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Waste electrical and electronic equipment (WEEE) handbook

Edited by Vannessa Goodship and Ab Stevels

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Waste electrical and electronic equipment (WEEE) handbook

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Preface

Waste electronic and electrical equipment (WEEE) has been on the agenda of governments, industry and non-governmental organizations for more than 20 years. In the early 1990s it seemed a relatively straightforward issue to deal with. The consistent application of the ‘producer responsibility’and ‘polluter pays’ principles was expected to keep the societal debate simple and to quickly result in legislation which would be unambiguously applied in all member states of the European Union. Ecodesign and, in particular, design for recycling were supposed to assist in achieving high recycling rates and elevated levels of toxic control. Simultaneously this would result in a reduction of the waste processing costs to almost zero. Current experience shows that take-back and treatment systems for WEEE have in practice a high degree of complexity. Therefore, organizations struggle with the development and implementation of these systems, irrespective of whether the organizations deal with legal, technical or economic aspects of take-back and treatment. This rapidly became clear when the European WEEE Directive first began to be transposed into national laws. It was then that the first divergences in interpretation of the directive occurred. In the nation states when implementation rules had to be agreed among stakeholders, even more varied ‘rules of the game’ developed. Although the intent and the spirit of the WEEE Directive are quite clear and are also broadly supported, the very complexity of the matter made it extremely difficult to effectively balance all the environmental, technical, economic and social interests in all the states involved; in spite of the fact that the physics and economics are in principle identical all over the globe.

Since the material composition of electronic and electrical products varies widely, there is also no ‘one size fits all’ model in terms of technical solutions. Moreover many variables must be taken into account when optimizing take-back and treatment systems that vary with time. The discarding behaviour of users changes, legal or illegal exports to outside the EU change and this affects the volume of WEEE to be treated inside the EU. Logistics and sorting costs gradually increase, industrial infrastructures develop, treatment technologies become more sophisticated, energy and secondary materials prices fluctuate (and have the tendency to go up). Also the volume and cost of disposal of the fractions left over after treatment changes as a function of time. Parallel to such developments, knowledge and know-how about take-back systems has increased tremendously as regards science and technology as well as economic aspects. Large amounts of data which can underpin sensible policy and business decisions have become available as well.

The purpose of the current WEEE handbook is to assist the reader in dealing better with those issues of WEEE which are relevant in their particular situation. For this purpose the book gives a comprehensive review of all items which could be applicable. The organization of the material in 30 chapters and the division of each chapter into a large number of sections will allow the reader to navigate quickly to the items which are of direct relevance to them.

The editors are happy that a vast number of leading experts have contributed to this book. This is the essential reason why it will be such a valuable and powerful resource. We would also like to thank Woodhead Publishing for their initiatives, for their continuous support and for their meticulous execution of the publishing tasks.

The material presented in this handbook has a global significance. The editors hope therefore that its contents will thoroughly and universally support the achievement of higher environmental gains at lower cost in the implementation of take-back and treatment systems throughout the world. For ease of use the chapters are divided into six sections:

Part I: Legislation and initiatives to manage WEEE
Part II: Technologies for refurbishment, treatment and recycling of waste electronics
Part III: Electronic products that present particular challenges for recyclers
Part IV: Sustainable design of electronics and supply chains
Part V: National and regional WEEE management schemes
Part VI: Corporate WEEE management strategies

Part I (Chapters 1–6) covers the problems of e-waste from a strategic perspective covering both legislation and international initiatives. Whilst Chapter 1 takes a global approach, Chapters 2–6 focus on examples of EU legislation and conformity approaches. These chapters consider successes in policy, failures, and future areas of research. Chapter 6 also considers the economic impacts of such legislation and how this relates to future policy development.

Part II (Chapters 7–12) takes a more technical approach. It begins with an introduction to the materials found in WEEE and then mirrors a best practice approach to waste management by considering in turn reuse and refurbishment (Chapter 8), mechanical recycling (Chapters 9 and 10), and finally thermal methods of waste disposal (Chapters 11 and 12). Each of these chapters discusses both current practice and future trends.

Part III (Chapters 13–17) highlights some waste streams that present particular challenges due to complexity, toxicity, lifetimes and technological developments. This covers relevant chapters on printed circuit boards, liquid crystal displays, fridges, batteries and, with an eye to the future electronic waste stream, the likely impacts of printed electronics.

Part IV (Chapters 18–21) looks at how design can reduce the cost and environmental impacts of electronic products, and includes a chapter on the European legislation on ecodesign (Chapter 18), sustainable design for products (Chapter 19), options for reducing hazardouns substances (Chapter 20) and the economics attached to different material flows within a disposal plant (Chapter 21).

Part V (Chapters 22–26) looks at e-waste from a regional perspective with individual chapters considering practices in Europe, China, India, Japan and Africa.

Finally Part VI (Chapters 27–30) looks at waste management from a company perspective with valued contributions from Hewlett Packard, Siemens and Philips. These chapters highlight the many difficulties faced by international companies operating within this arena, facing global disparities in terms of legislation, local facilities and environmental costs. The book ends with a chapter for those looking to create their own environmental strategies. This highlights the current best practice/considerations in dealing with electronic waste streams.

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1
Global e-waste initiatives

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Abstract: This chapter analyzes how far the e-waste problem is hindering the realization of sustainable societies. It looks into how far existing initiatives such as the Solving the E-waste Problem (StEP) Initiative, Mobile Phone Partnership Initiative (MPPI), Partnership for Action on Computing Equipment (PACE), Global e-Sustainability Initiative (GeSI), Further work under the International Telecommunications Union (ITU) and the Strategic Approach to International Chemical Management (SAICM) address the e-waste problem and its multitude of dimensions, also describing a way ahead towards reaching the vision.

Key words: E-waste, StEP, Basel Convention, UNEP, UNU, MPPI, PACE, SAICM, GeSI, ITU, transnational, local.

1.1 Introduction

The production, consumption and final disposal of electrical and electronic equipment (EEE) without waste and harmful emissions; hardly any idea is more convincing and challenging. Though this appears more like a crazy dream or simply impossible considering the current situation, it could be the visionary statement of many initiatives working towards a sustainable solution to the e-waste problem. It would take for granted the final decoupling of the world's energy demand from non-regenerative and uncontrollable sources due to, for example, remaining wastes; it would also be based on a closed system for supply and its reverse, not allowing any losses and leakages of resources. The digital divide would be successfully closed, allowing all and everybody to benefit from the speedy innovations in technology, making our life and work easier, healthier and more enjoyable, without revoking the future of coming generations.

Harsh critics of such a vision became more careful when it turned out that some governments and international organizations, together with industry, science sectors, non-governmental organizations (NGOs) and local governments strongly support the development of concepts towards sustainable societies and are substantially investing in the pertinent research that will explore if and how it could become a new standard and a model for a sustainable society.[1]

The e-waste problem is increasingly attracting interest in politics, media and initiatives around the globe. But what is the e-waste problem about?

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And what problems would the realization of this vision solve? How far do existing initiatives address the e-waste problem and its multitude of dimensions? What is the forecast for the way ahead toward reaching this vision?

1.2 Problems associated with e-waste

1.2.1 Transnational

At least in the past five years, e-waste has become a catchword covering almost all types of EEE that have or could enter the waste stream. This is also because e-waste is growing exponentially simply because the markets for EEE are booming and many parts of the world are developing quickly and therefore crossing the so-called 'digital divide'. Rapid product innovation and replacement, especially in information and communication technologies (ICT) and office equipment, combined with the migration from analog to digital technologies and to flat-screen TVs and monitors, to give a few examples, are fuelling the increase. Economies of scale have led to lower prices for many electrical goods, which have increased global demand for many products that eventually end up as e-waste.

On the general level e-waste is a term covering all end-of-life (EoL) products with either a battery or cord/circuitry. Hence, it includes TVs, computers, mobile phones, white goods (refrigerators, washing machines, dryers, etc.), home entertainment and stereo systems, toys, toasters, kettles – almost any household or business items including medical devices such as magnetic resonance tomography, etc. A snapshot into the knowledge management tool C2P illustrates that thousands of definitions of e-waste in policies, regulations, decrees, guidelines, guidance documents, etc. exist.[2] Based on the numerous definitions, the number of types of e-waste included in government-initiated analyses and collection programmes differ across the world. The US, for example, does not include any white goods in its statistical number, whereas these are included in the ten categories in the e-waste legislation of the European Union and Japan. In consequence, the national e-waste figures are not easily comparable and the accumulation of all figures does not necessarily reflect the actual amount of global e-waste. Moreover, the categorization of EEE as 're-usable' is used as a loophole in international shipments in order to make money from what formally often should be classified as 'e-waste' – a clear break of the Basel Convention which controls the transboundary movements of hazardous wastes including e-wastes and their final disposal.[3] In addition large amounts of EoL EEE are kept in closets, cellars or lofts, not entering the recycling chain. Because of the above large quantities of the planet's e-waste is unaccounted for as it is not entering the appropriate e-waste recycling processes.

Hence, a widely agreed upon approach to estimate national and global e-waste is based on EEE put on the market. The lifetime of the product categories, in addition to other determinates, helps to derive the total e-waste generation.[4] The EEE put on the global market has increased from 19.5 million tons in 1990, to 34 million tons in 2000 and 57.4 million tons in 2010 and is estimated to reach 76.1 million tons in 2015.[5] In consequence, the global e-waste amount has increased from 20 million tons in 1998 and is likely to reach 50 million tons in 2014/2015, whereas the actual arising in 2011 is estimated to be 41 million tons ±10%.[5] This is enough to fill a line of dump-trucks stretching half way around the globe.

E-waste is usually regarded as a waste problem, which can cause environmental and health damage if not dealt with in an appropriate way.[6] However, there are additional dimensions which are often overlooked: e.g. the enormous environmental footprints and hence resource impact of EEE throughout its lifetime resulting out of their production, consumption and disposal,[7] the implications of global supply chains and their reverse in an appropriate recycling process at the end-of-life and enormous social relevance of having access to EEE allowing people to benefit from access to information and globalization.

1.2.2 Local

In addition to various hazardous materials, e-waste also contains many valuable and precious materials. In fact up to 60 elements from the periodic table can be found in complex electronics. Using the personal computer (PC) as an example – a normal cathode ray tube (CRT) computer monitor contains many valuable but also many toxic substances. One of these toxic substances is cadmium (Cd), which is used in rechargeable computer batteries and contacts and switches in older CRT monitors. Cadmium can bio-accumulate in the environment and is extremely toxic to humans, in particular adversely affecting kidneys and bones. It is also one of the six toxic substances that has been banned in the European Restriction on Hazardous Substances (RoHS) Directive.[8]

Beyond CRT monitors, plastics, including polyvinyl chloride (PVC) cabling is used for printed circuit boards, connectors, plastic covers and cables. When burnt or land-filled, these PVCs release dioxins that have harmful effects on human reproductive and immune systems. Mercury (Hg), which is used in lighting devices in flat screen displays, can cause damage to the nervous system, kidneys and brain, and can be passed on to infants through breast milk. Electrical goods contain a range of other toxic substances such as lead (Pb), beryllium (Be), brominated flame retardants and polychlorinated biphenyls (PCB) just to name a few. Lead plays an important role in the overall metal production processes and while attempts to design-out lead from

EEE does not necessarily mean that it is no longer used. Even the lead-free solder elements are co-produced with lead. This illustrates the need for a holistic view to be taken in analysing the e-waste situation for working out possible solutions.[8, 9]

Because of this complex composition of valuable and hazardous substances, specialized, often 'high-tech' methods are required to process e-waste in ways that maximize resource recovery and minimize potential harm to humans or the environment. Unfortunately, the use of the these specialized methods is rare, with substantial quantities of the world's e-waste traveling great distances, mostly to developing countries, where crude techniques are often used to extract precious materials or recycle parts for further use. These local 'backyard' techniques pose dangers to poorly protected workers and their local natural environment, made visible to the general public through recent media campaigns.[6, 10] Moreover, these approaches are very inefficient in terms of resource recovery as recycling in these instances usually focuses on a few valuable elements like gold and copper (with often poor recycling yields), while most other metals are discarded and inevitably lost.[6] In this sense it can be demonstrated that resource efficiency is another important dimension in the e-waste discussion in addition to the ecological, human security, economic and societal aspects.

1.3 Global e-waste management initiatives

1.3.1 Solving the E-waste Problem (StEP) Initiative

The development of the Solving the E-waste Problem (StEP) Initiative was initiated during Berlin's Electronics Goes Green Conference in 2004 and formally launched in 2007. This was in response to United Nations University's work on Information Technology and Environment, supported by the United Nations Environment Programme (UNEP) and the United Nations Conference on Trade and Development (UNCTAD), co-initiated with Hewlett Packard and Promotionteam Wetzlar. With prominent members from industry, government, international organizations, NGOs and academia, StEP's overall aim is to develop strategies to solve the e-waste problem – globally. StEP was founded to offer an impartial global platform for information exchange and developing sustainable solutions for e-waste management. Today the more than 55 StEP institutional members from industry, academia, governments, NGOs and international organizations work to reduce environmental and health risks and increase resource recovery worldwide from a holistic and science-based but nevertheless applied viewpoint.[8]

StEP's prime objectives are:[8]

- to act as a knowledge hub on e-waste for industrialized and industrializing countries;

- to increase re-use of electrical and electronic equipment;
- to increase materials recovery from e-waste;
- to support the safe processing of e-waste;
- to encourage life-cycle thinking;
- to develop clear policy recommendations.

StEP envisions a future in which societies have reduced to a sustainable level the e-waste-related burden on the ecosystem that results from the design, production, use and disposal of electrical and electronic equipment. These societies make prudent use of lifetime extension strategies in which products and components – and the resources contained in them – become raw materials for new products.[11]

To realize this vision StEP acts as a network of actors, sets forth clear and achievable objectives that are broad in scope but aim to solve concrete issues. Toward these:

- StEP conducts cutting-edge research and undertakes activities assessing the e-waste problem from a holistic perspective in order to optimize the entire life cycle of EEE, from policies to design to refurbishment to capacity building. Such activities are also in the form of pilot projects, which aim to improve supply chains, close material loops and reduce contamination.
- Because of the adverse ecological and economic impacts associated with mismanagement of resources and the exponential increases in (waste) electrical and electronic equipment, StEP strives to increase utilization of resources, focusing and steering many activities on safe and proper re-use and recycling of (waste) EEE.
- An overarching theme in all of its activities, StEP exercises concern about disparities between industrializing/developing and (post-)industrialized countries, such as the digital divide which hinders people from accessing technology and acquiring the resources to effectively use it.
- StEP also concentrates on increasing public, scientific and business knowledge about current e-waste challenges and developments through its interdisciplinary composition of actors and dissemination and capacity building activities.[8]

Membership in StEP is open to all accepting the StEP principle and the agreement of cooperative work. Also, since 2010 the participation of representatives from developing countries has also been increasing, due to a growing number of projects in Africa, Asia and Latin America. Until then StEP's work mainly concentrated on Europe and North America.

1.3.2 United Nations Environment Programme

A number of United Nations Environment Programme (UNEP) organizations are actively working on the e-waste issue. These include, among others, the Basel Convention, the Second International Conference on Chemical Management, the International Environmental Technology Centre (IETC) as part of the Division for Trade, Industry and Economics (DTIE).

1.3.3 Basel Convention

In order to obtain the latest and most relevant information on environmentally sound management of e-waste in the Asia-Pacific region, a regional partnership was launched in 2005. Such a partnership was developed to explore existing know-how on cleaner technologies or processes used in the repair, refurbishment, recycling or recovery of used or EoL EEE. The goal of this partnership was to enhance the capacity of parties in the region to manage electrical and electronic waste in an environmentally sound way through the building up of public–private partnerships. As part of this partnership, Dowa Eco-System Co. Ltd. substantially financed a pilot project on Transboundary Movements of End-of-Life Mobile Phones in South East Asian countries involving initially Malaysia, Thailand and Singapore. The objective of this activity was the establishment of a scheme for the collection and environmentally sound management of EoL mobile phones from these three countries.

The 8th Conference of Parties to the Basel Convention also guided the Nairobi Ministerial Declaration on the environmentally sound management of electrical and electronic waste calling for urgent global action on e-waste. It was agreed to accelerate efforts to reduce the risks posed to human health and the environment by the dramatic worldwide growth in electronic wastes; priorities should include launching pilot projects to establish take-back systems for used electronic products, strengthening global collaboration on fighting illegal traffickers and promoting best practices through new technical guidelines.

However, the most prominent seems to be Basel Convention's former Mobil Phone Partnership Initiative (MPPI) and the Partnership for Action on Computing Equipment (PACE). The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal came into force in 1992 and has 175 Parties of this UNEP Convention.[3]

Mobil Phone Partnership Initiative (MPPI)

The MPPI was launched during the 6th Conference of the Parties to the Basel Convention in 2002, when 12 manufacturers such as LG, Matsushita

Panasonic, Mitsubishi, Motorola, NEC Europe, Nokia and Philips and shortly after three service providers signed a Declaration to develop and promote the environmentally sound management of EoL mobile phones.[12]

The objectives of the partnership[12] were to:

- achieve better product stewardship;
- influence consumer behavior toward more environmentally friendly actions;
- promote the best disposal/recycling/refurbishing options,
- mobilize political and institutional support for environmentally sound management;
- create an initiative that could be replicated to build new public–private partnerships for the environmentally sound management of hazardous and other waste streams.

Within MPPI's work five guidelines have been completed that address:

- refurbishment of used mobile phones;
- material recovery and recycling of end-of life mobile phones;
- collection of used mobile phones;
- transboundary movement of collected mobile phones;
- awareness raising on design considerations.

In addition an overall guidance document on environmentally sound management of used and EoL mobile phones was prepared. The guidance document, together with the MPPI guidelines, was designed to help raise awareness and further the implementation of best practices associated with the different stages of the environmentally sound management of used and EoL mobile phones. It provides information that can be used by the parties, the Basel Convention regional centers and other stakeholders to develop training materials and awareness-raising workshops on the issues that are covered in the guidance document. However, these documents are not legally binding.

Partnership for Action on Computing Equipment (PACE)

Following the experiences from the MPPI, PACE was launched at the 9th Conference of the Parties to the Basel Convention, which took place in Bali, Indonesia in June 2008. Similar to StEP, PACE sees itself as a multi-stakeholder partnership that aims at providing a forum for governments, industry leaders, non-governmental organizations and academia to tackle the environmentally sound management, refurbishment, recycling and disposal of used and EoL computing equipment.[13] But contrary to StEP PACE is governed by the political negotiations, rules and developments within the Basel Convention; hence, all decisions must be made in consensus of the members.

The Partnership is intended to increase the environmentally sound management of used and EoL computing equipment, taking into account social responsibility and the concept of sustainable development, and promoting the sharing of information on life-cycle thinking. Hence PACE aims to:

- promote sustainable development for the continued use, repair and refurbishment of used personal computers in developing countries and countries with economies in transition;
- find incentives and methods to divert EoL personal computers from land disposal and burning into commercial material recovery/recycling operations;
- develop technical guidelines for proper repair, refurbishing and material recovery/recycling, including criteria for testing, labelling of refurbished used equipment and certification of environmentally sound repair, refurbishing and recycling facilities;
- end shipment of personal computers that cannot be refurbished and re-used to developing countries and countries with economies in transition.[13]

PACE also intends to develop pilot demonstration projects to assist developing countries and countries with economies in transition in assessing the current situation of used and EoL computing equipment in their countries, and to achieve partnership and Basel Convention objectives.

Within four project groups of PACE, the following documents were finalized and approved:

- Report on Environmentally Sound Management (ESM) criteria recommendations.
- Glossary of Terms.
- Guideline on Environmentally Sound Testing, Refurbishment, and Repair of Used Computing Equipment.
- Guideline on Environmentally Sound Material Recovery and Recycling of End-of-Life Computing Equipment.
- Guidance on Transboundary Movement (TBM) of Used and End-of-Life Computing Equipment.

These documents were submitted for consideration by the Basel Convention's last Conference of Parties, which took place in October 2011 in Colombia. Plans are in development that these guidelines will be tested in practice to see if any changes are required to the recommendations contained in them.

1.3.4 Strategic Approach to International Chemicals Management (SAICM)

The 2nd International Conference on Chemical Management (ICCM2), which took place under the auspices of the Strategic Approach to International

Chemicals Management (SAICM) in Geneva in 2009, invited the participating organizations of the Inter-Organization Programme for the Sound Management of Chemicals (IOMC) and the Secretariats of the Basel Convention and the Stockholm Convention on Persistent Organic Pollutants to realize a workshop to consider issues in relation to electrical and electronic products, based on a life-cycle approach. This workshop took place during March 2011 at the United Nations Industrial Development Organization (UNIDO) headquarters in Vienna and developed a road map for possible global action regarding green chemistry, including elimination and substitution of toxic substances; information exchange on chemicals in EEE and e-waste, recycling and disposal of the toxic substances as contained in EEE, for consideration by ICCM3, the IOMC participating organizations and the chemicals and waste conventions and programs, other initiatives including the future mercury convention.[14]

1.3.5 International Environmental Technology Centre (IETC)

UNEP's Division for Technology, Industry and Economics, the Japan-based International Environmental Technology Centre (IETC), is assisting member countries on Integrated Solid Waste Management (ISWM) including e-waste issues as part of its Global Partnership on Waste Management (GPWM). In order to build the capacity of practitioners and decision makers to guide and handhold them to understand, plan, design and implement e-waste take-back schemes, the IETC produced a manual. This manual was prepared as a guidelines document to support e-waste inventory and assessment of risks involved. Earlier UNEP DTIE supported a city level e-waste assessment study for Mumbai and Pune in India.[15, 16]

1.3.6 Global e-Sustainability Initiative (GeSI)

As part of the response to the UN Millennium Development Goals (MDG) signed by 189 countries in 2000,[17] GeSI, the Global e-Sustainability Initiative, was initiated in 2001 to further sustainable development in the ICT sector. The GeSI brings together leading ICT companies – including telecommunications service providers and manufacturers as well as industry associations – and NGOs committed to achieving sustainability objectives through innovative technology. The UNEP was among the initiators of GeSI and functioned for several years as its Secretariat. Today GeSI is an international non-profit association with its Secretariat in Brussels. GeSI activities are thus far focused on the following six areas:

- Climate change: To develop a methodology and standards to measure and cut the carbon footprint of the ICT sector and enable other industries to reduce their emissions through innovative technology.

- Supply chain: To promote good conduct and develop or improve tools, management practices, processes or systems to assist each participant and their supply chain in dealing with supply chain risks.
- E-waste: To promote take-back and create tools to ensure electrical and electronic equipment is disposed of responsibly at end-of-life and materials are re-used or recycled wherever possible.
- Standardization: To work with others to develop common industry standards in key areas such as energy efficiency.
- Public policy: To engage with policy-makers to promote the contribution ICT can make to sustainability.
- Communication: To raise awareness of GeSI and the ICT sector's contribution to sustainability among external stakeholders and inform them about our activities.[18]

GeSI's e-waste working group's vision is for the ICT sector to move from managing risks to encouraging more efficient use and more extensive re-use of materials by viewing e-waste as a valuable resource. Recycling more of the materials in used equipment – including precious metals – reduces environmental impacts from its disposal and reduces the need to extract more raw materials from the ground. This, in turn, reduces the associated environmental and social impacts of mining, tying in with our supply chain work on extraction. The ICT industry does not have direct control over a lot of equipment – such as computers and mobile phones – when it reaches the end of its useful life. Some of the GeSI member companies already have take-back schemes in place; yet they rely on consumers to return products for recycling and are working on incentives encouraging them to do so.[19]

ICT companies can make a difference with their own waste disposal contractors and in 2008 GeSI developed an EoL management tool that can be integrated into their existing E-TASC self-assessment questionnaire for suppliers. Specific criteria cover collection, recycling, re-use and disposal. This is intended to help GeSI member companies ensure e-waste from their own operations is handled responsibly.

GeSI also plans to promote take-back schemes to reclaim more e-waste from consumers for re-use and recycling. Its e-waste working group will increasingly focus on management of material resources as well as risk associated with end-of-life.

1.3.7 International Telecommunication Union (ITU)

The International Telecommunication Union (ITU) is the UN specialized agency for information and communication technologies. Currently it has membership of 172 countries and more than 700 private sector entities and academic institutions. In addition to ITU's work on radio communications, it also focuses its work on development and standardization. Being increasingly asked by a growing number of customers, investors, governments and other stakeholders to report on sustainability performance, ITU is aiming to fill the lack of an agreed-upon standardized measurement that would simplify and streamline this reporting specifically for the ICT sector by developing sustainability standards. Sustainable ICT products and appropriate EoL management are among the topics the developed public–private partnership initiative is working on.

Moreover ITU is also increasingly looking into climate change aspects associated with the production, consumption and final disposal of ICT. In late 2011 the ITU, the Secretariat of the Basel Convention and the United Nations University (UNU), launched a large international survey whereby the data will ensure better quantification and qualification of the e-waste problem.

1.4 Synergizing e-waste initiatives

The above described initiatives are of global character being in one way or another under the umbrella of the UN, though partly with certain regional foci due to existing funding schemes, which are in the majority of cases not global. However, as all initiatives are depending on voluntary contributions – both in cash and in kind – and successful project acquisitions, the avoidance of duplications and emphasis of synergizing efforts is not only a prerequisite of its contributing members but also the supporters.

The snapshot into the above initiatives might convey a lot of overlaps and duplications of activities. Aware that these initiatives share substantial areas of mutual interests and undertake complementary activities, StEP through the United Nations University has initiated close cooperation with all UNEP Initiatives, GeSI and ITU. This was laid out in a Memorandum of Understanding (MoU) between the Secretariats of StEP and the Basel Convention through which the coordination of their work is already enhanced and cooperation strengthened to facilitate the discharge of their respective responsibilities. These organizations have even started joint project work in researching the global e-waste situation, developing recommendations for standards and conducting joint events. A similar MoU has been signed between GeSI and StEP. Presently, joint activities between GeSI and StEP are mainly concentrated on the development of an e-waste academy to offer a platform for exchange of best practices and continued dialog on e-waste management systems among policymakers and representatives of small and medium-sized companies (SMEs); the first e-waste academy will target Western Africa and will take place in Accra, Ghana in June 2012. Moreover, StEP through UNU is also actively participating in UNEP's Integrated Solid Waste Management activities and Global Partnership on Waste Management (GPWM) e-waste work headed by UNIDO and UNEP is represented in StEP's Steering Committee.

Nevertheless, given the high interest of many in the e-waste issue, future coordination attempts also beyond StEP, the various UNEP activities, GeSI and ITU but among, for example, donors in certain regions are going to be necessary. The e-waste business has become lucrative for many, even trying to be paid twice for their contribution towards a possible solution highlighting the urgent need for close coordination. Moreover, a close multi-stakeholder and transnational coordination is also necessary to ensure the progress towards sustainable solutions. Owing to its science-based multi-stakeholder approach, StEP appears well positioned for these assignments and provides the necessary recommendations for international and national policy-making, as it takes into consideration the complexity of the e-waste issue. A big challenge for all initiatives is obviously a successful integration of players from the South in cooperative work substantially driven by digital cooperative work via the Internet, conference calls, etc.

1.5 Future trends

The global e-waste issue is increasing in both numbers and visibility. There is, without question, a growing penetration of electrical and/or electronic components into all goods. Intelligent clothes are increasingly winning market shares in the same way as electrical vehicles and photovoltaics are gaining importance in the developed world. Certainly, transition and developing countries still have a long way ahead to reach a certain market saturation of EEE, which is annulled in the (post-) industrialized countries by the speedy product innovations. But as all the products substantially depend on the limited resources of the Earth's crust, conflicts for these resources might also be on the rise, going beyond a certain dictation through prices. In consequence, to maintain a certain autonomy, states and companies ought to develop further strategies to maximize the return of the equipment, further improve the component and material recovery, and harmonize action beyond the border lines as the associated problems will only be solved transnationally through concerted action.

In light of this, more and more states around the world are starting to develop their respective e-waste management policies and legislations. Moreover, certain adaptation of present systems will be required, moving away from linear to holistic thinking, also allowing tests of the unthinkable in solving the problem, because this was and is the driver of innovation. Dematerialization and hence purchasing the services EEE provide instead of purchasing the product as such are regarded as one possible future trend. In this way, the EEE loops will be closed, avoiding leakages through low return rates, illegal shipments of e-waste will be substantially reduced, a design supporting the refurbishment and final material recycling will be further developed and the digital divide further closed through offering the services for a special price for those in need. In addition, a smart separation of work in the reverse supply chain and especially the various recycling steps might also allow developing countries to successfully contribute to the appropriate treatment of their domestically generated e-waste.[6] This approach, introduced by StEP as 'the best of two worlds', is commonly seen as a possible way ahead.

Awareness raising and hence psychological, cultural and behavioral aspects must move much more in the focus of e-waste related activities, because not all technical and technological solutions receive the necessary acceptance and support from the consumers. Thus far, most efforts have concentrated on recycling aspects substantially neglecting up-stream issues such as re-use and design and the drivers behind the low return rates of consumers even in countries with proper e-waste management systems in place.

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2

EU legislation relating to electronic waste: the WEEE and RoHS Directives and the REACH regulations

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Abstract: A series of Environment Action Programmes spanning the last 30 years has shaped the way in which the EU manages its waste. Legislation in the form of regulations and directives for dealing with waste such as waste electrical and electronic equipment (WEEE) is just one of a number of tools the European Union has used to try and manage specific waste streams. Since EEE, and therefore WEEE, may contain hazardous chemicals it is subject to the requirements of not only the WEEE directive but also the Restriction on Hazardous Substances (RoHS) Directive and the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations. Owing to the wording of the founding treaties of the EU on which legislation is made, existing law in these areas has been widely interpreted across member states. This has led to highly varied practice across the EU and patchy implementation of the directives. The end result has been poor collection rates, low enforcement and continued illegal exports of WEEE. To address this, the European Commission decided to recast both the WEEE and RoHS Directives and propose amendments to the REACH regulations. The proposed changes seek to reduce the ambiguities in the existing legislation and impose even greater responsibility on producers to manage the products and the waste they produce.

Key words: WEEE, RoHS, REACH, waste management, legislation, EU directives, regulations.

2.1 Introduction

The majority of legislation covering the control and management of waste, not just of waste electrical and electronic equipment (WEEE), flows from the European Union (EU). Legislation and also policies are then implemented through domestic law in each EU member state. Thus, it is worth starting the chapter with an outline of the legislative structure of the EU with regards to environmental matters. The procedures and processes of the EU are complex and this chapter seeks to provide only a broad outline of how legislation and policies are formulated; it will then focus on the provisions of the relevant waste directives and regulations.

2.1.1 Legislative structure of the EU

At the core of the EU are the founding treaties which are a series of international agreements between the EU and its member states. The treaties set out the operation of the EU and its constitution as well as setting up four institutions (Commission, Council of Ministers, Parliament, Court of Justice) to oversee various functions through agreed terms of reference. Under the treaties the EU institutions can adopt legislation which is then implemented by member states.

The original founding Treaty was signed in Rome in 1957 between six member states and established the European Economic Community (EEC) [Treaty Rome 1957] and the European Atomic Energy Community (Euratom) [Treaty Rome 1957]. The Treaty provided for an economic internal market and a common agricultural policy and also permitted the free movement of goods and people. The Treaty was amended a number of times and in 1992 the Treaty on European Union (TEU) was signed in Maastricht [Treaty Maastricht EU 1992]. This treaty renamed the EEC as the European Union. Further amendments have been made including those signed in Amsterdam in 1997 [Treaty Amsterdam 1997] and Lisbon in 2007 [Treaty Lisbon 2007]. When the Lisbon Treaty came into force in 2009 the Treaty was renamed as the 'Treaty on the Functioning of the European Union' (TFEU) and a consolidated version was published in the *Official Journal of the European Union* in 2010 [Treaty FEU 2010].

Each member state has to ratify a treaty individually and this is done by agreement with each country's Prime Minister or President who will then go on to seek ratification by their respective parliaments. In addition to setting out the roles and functions of the EU institutions, the treaties also set out the fundamentals for law in Europe which are based on specific Articles contained within a Treaty. After significant expansion of the EU, most recently by Bulgaria and Romania in 2007, there are now 27 member states.

2.1.2 The European Parliament

The European Parliament is the only body in the EU to which EU citizens directly elect members (MEPs) to represent them. A Parliament has a term of office for five years and the next elections will be held in 2014. Together with the Council of the European Union they are the main legislators of the EU. The Parliament has supervisory powers over the Council and in particular the Commission.

2.1.3 The Council of the European Union

The Council represents each member state and is made up of one minister from each of those member states. Each member state will select a minister dependent on the issue at hand, meaning the composition is not fixed but there are overall nine configurations, one of which is specifically for dealing with environmental issues.

The Council takes a joint role with the Parliament in making decisions but in practice the Council is the main decision making body. The Council holds the executive power in the EU which it confers to the European Commission and usually the Council will only act on proposals from the Commission and does not, in general, itself make any proposals.

2.1.4 The European Commission

The Commission is independent of any member state government. It is the executive of the EU and is responsible for its day-to-day running. The Commission is composed of a Commissioner from each member state who is appointed for a five year term in order to represent and act in the interests of the EU rather than those of their member state.

The Commission has four main areas of responsibility:

- To draft and propose legislation to the Council and Parliament.
- To ensure that the regulations and directives passed by the Council and Parliament are being implemented by the member states and to manage the budget.
- To enforce law passed by the Council and Parliament with recourse to the European Court of Justice (ECJ) if necessary. The ECJ is the highest court in the EU and has final say over all other courts on matters to do with EU law. It is completely independent of the other EU institutions and has the ability to impose penalties on member states.
- To represent the EU in international forums.

The Commission is assisted by a civil service made up of 46 directorate generals, one of whom specifically deals with the environment. The Commission is also responsible for ensuring that consultation with appropriate stakeholders takes place.

The Council and the Parliament pass legislation on the environment using the ordinary legislative procedure (formerly known as the co-decision procedure). Under this procedure the Parliament and the Council have equal rights when it comes to passing legislation on a number of important issues with the environment specifically being one.

Initially, the Commission proposes a piece of legislation to both the Parliament and the Council whilst also consulting with national governments and other stakeholders. This will be followed by a first reading in the Parliament where a position, rather than an opinion, will be given. If the Council agrees with the Parliament's position at its first reading then the act is adopted. If the Council does not agree and has a different position then this is relayed back to the Parliament.

The legislation will then be heard at a second reading and the Parliament can accept the Council's wording, in which case the act is adopted; it can reject the Council's position, in which case the act fails; or it can propose amendments to Council. Should the Parliament propose amendments these will be considered by a second reading of Council. At this stage, the Council can accept the Parliament's amendments and the act is passed or if it does not accept it the Council and the Parliament enter into a conciliation process. The Commission has published a useful flowchart of the process at http://ec.europa.eu/codecision/stepbystep/diagram_en.htm.

2.1.5 The relationship between the EU and member state laws

The primary source of European laws are the founding and amending treaties already discussed. However, in and of itself, a ratified treaty does not have a legal standing in member state laws and for it to have any legal force it has to be passed by an act of government. The treaties instruct domestic courts that priority is given to EU law over national law, which means that member state legislators have to modify domestic laws to align with EU laws if there is a conflict between the two.

The secondary sources of EU law transposed from the treaties consist of regulations and directives which are characterised as follows:

- *Regulations* – These are binding and are directly incorporated into member state law without that member state having to use national legislation to incorporate them into law. If there is a conflict between a regulation and an existing national law, the regulation takes precedence.
- *Directives* – A directive sets out the requirements that the legislation should achieve. While there is an obligation on the member state to change its national laws, a directive then leaves it to the member state to implement as it sees fit to meet the requirements. The directive will provide for a set period of time within which implementation has to be achieved via nation state legislative processes.

Article 249 (prev 189) of the Treaty of Rome [Treaty of Rome 1957] permits member states to implement directives using an individual approach and just sets out minimum requirements while granting member states the ability to improve on these. In practice, the ability to implement as a member state sees fit (subject to achieving the minimum requirements) leads to wide and varied interpretations of law and practice. Consequently, across the EU there is, in reality, little uniformly applied law made in this way and this has led to a number of pieces of legislation such as the Waste Electrical and Electronic Equipment Directive, WEEE (Directive 2002/96/EC), and the Restriction of the use of certain hazardous substances in electrical and electronic equipment Directive, RoHS (Directive 2002/95/EC) being amended and recast to address the disparity in practices between member states.

2.2 The EU and the environment

The EU founding treaty, the treaty of Rome [Treaty Rome 1957], does not contain any reference to environmental legislation and so a number of amendments, including the Maastricht Treaty [Treaty Maastricht 1992] and the Amsterdam Treaty [Treaty Amsterdam 1997] have been necessary to bring forth environmental legislation across Europe. It was in 1972 that the European Community (now the EU) determined that a community environmental policy was needed. The framework which developed and shaped environmental legislation was provided by the Environment Action Programmes (EAP). There have been six programmes of work to date and the current programme, EAP6, expires in July 2012 [EAP 1–6]. Each programme is specific to a particular environmental issue and spans a 5 to 10 year time frame. During their course they have become the main driving force behind current and future environmental policy. The recommendations of the EAPs are not legally binding but they do clearly set out the aspirations of the EU.

The first environment action programme [EAP1 1973] set out the principles and priorities that would inform future policy. There were 11 principles listed worthy of repeating as many of these have been carried forward to subsequent programmes:

1. Pollution is better prevented at source.
2. In decision making processes, environmental effects should be taken into account as soon as possible.
3. Exploitation of natural resources is to be avoided if it can cause significant harm to the ecological balance.
4. Scientific knowledge should be advanced to help in the protection of the environment.
5. The ‘polluter pays’ principle.
6. Countries’ activities should not degrade the environments of others.
7. The environmental policy of member states must take into account the interests of developing countries.
8. The community should participate in international organisations to promote global environmental policy.
9. Environmental education should be promoted throughout the community.
10. Pollution control should be established at all levels (local, regional, national, community, international).

11. National environmental policy to be harmonised within the community.

Each EAP was a building block on the previous one but much of the focus of the first three programmes was devoted to developing the policies and little attention seems to have been actually given to whether or not the policies were effective or indeed being implemented at all [Hawke 2002]. It was not until EAP4 that meaningful consideration was given to implementation. EAP5 began to set longer-term objectives and the concept of sustainable development was introduced as well as management of waste.

The outcomes and recommendations influenced the current EAP which runs until July 2012 (EAP6 2002). The Sixth Environment Action Programme, entitled 'Environment 2010: Our Future, Our Choice' was adopted by the European Parliament and the Council of the European Union in 2002. The treaty of Amsterdam [Treaty Amsterdam 1997], signed previously in 1997, fed into EAP6 with its requirement to give consideration to sustainability. Article 6 of the treaty states that 'environmental protection requirements must be integrated into the definition and implementation of the Community policies… in particular with a view to promoting sustainable development'. Consequently, there is a greater drive towards achieving sustainability and an emphasis on extending the bottom up approach, i.e. more stakeholder cooperation and less of a focus on relying on legislation to tackle the environmental issues targeted. Programme 6 proposed a focus on four priority areas:

- climate change – cuts to global emissions of 20–40% by 2020;
- biodiversity – reduce threats to habitats and the survival of a number of species;
- environment and health – water, noise and air strategies;
- sustainable management of resources and wastes – improve recycling rates and waste prevention strategies.

2.2.1 EAP6 and the shape of future legislation

The Environment Action Programmes have been setting the EU's agenda for environmental protection for over 30 years and much legislation has subsequently been created. Regulation is just one of a number of methods that have been employed in trying to implement environmental policies and is generally a means of last resort when voluntary agreements, taxes and subsidies fail to have the desired effect.

Although regulation is an important tool in bringing about environmental change it also has its limitations as it can be a lengthy process to implement and amend and often has low enforcement rates. In light of such slow progress in some areas EAP6 seeks to toughen up the EU's approach to how it regulates and enforces environmental regulation by, for example;

- developing and amending existing legislation;
- developing new legislation;
- encouraging more effective implementation and enforcement for instance by better inspection procedures;
- systematically reviewing how legislation is being applied across member states and better exchanges between member states on best practice for implementation.

Article 8 of EAP6 echoes Article 3's strategic approach and deals specifically with the priority areas for sustainability and waste management which states the following objectives:

> – achieving a significant overall reduction in the volumes of waste generated through waste prevention initiatives, better resource efficiency and a shift towards more sustainable production and consumption patterns;
> – a significant reduction in the quantity of waste going to disposal and the volumes of hazardous waste produced while avoiding an increase of emissions to air, water and soil;
> – encouraging re-use and for wastes that are still generated: the level of their hazardousness should be reduced and they should present as little risk as possible; preference should be given to recovery and especially to recycling; the quantity of waste for disposal should be minimised and should be safely disposed of; waste intended for disposal should be treated as closely as possible to the place of its generation, to the extent that this does not lead to a decrease in the efficiency in waste treatment operations.

The objectives are to be achieved by:

- development and implementation of a broad range of instruments including research, technology transfer, market-based and economic instruments, programmes of best practice and indicators of resource efficiency;
- developing and implementing measures on waste prevention and management by, *inter alia*:
  - (a) measures aimed at ensuring source separation, the collection and recycling of priority waste streams;
  - (b) further development of producer responsibility;
  - (c) development and transfer of environmentally sound waste recycling and treatment technology;
- developing or revising the legislation on wastes, including, *inter alia*, construction and demolition waste, sewage sludge, biodegradable wastes, packaging, batteries and waste shipments.

2.2.2 The future direction of waste management

It is evident that while further legislation to deal with waste management is inevitable, it is only one of a number of methods that will be employed to implement the EU environmental policy. The current Environment Action Programme expires in July 2012 and the European Commission published its final assessment report in August 2011 [COM (2011) 531]. This report was informed by stakeholder consultations [Meeting report 2011] and an independent review the Commission requested in 2010 [Homeyer *et al*. 2011]. The Commission's final report also drew on assessments reported in *The European Environment – State and Outlook* produced by the European Environment Agency [SOER 2010].

The Commission's report sets out to what extent it believes the aims and objectives of each of the priority areas in EAP 6 have been met. In terms of waste, the Commission's report highlights some important findings;

- Taken as a whole, during the last 10 year period European waste generation has been stagnant and possibly even increasing, suggesting that existing waste prevention methods have been less effective than hoped.
- The modernisation and simplification of waste legislation and waste management legislation has resulted in substantially fewer harmful electronic products being placed on the EU market. However, there is still a general problem with implementation and enforcement of legislation.

In October 2011 the Council of the EU called for the Commission to come forward with proposals for the 7th EAP by January 2012 [Doc 15384/11]. However, the Commission has advised the Council that its final proposals are not likely to be published until much later in 2012. In the meantime, the Commission has communicated its proposals to both the Parliament and the Council on measures that would see better implementation of existing environmental legislation [COM (2012) 95]. These proposals seek to improve the knowledge base across member states that currently hinder implementation and will lead to more comprehensive data collection and reporting on waste.

Although this chapter has thus far spent some time in outlining the EU waste management strategy, the background is important to an understanding of the likely direction of future trends in specific waste streams such as WEEE especially as much WEEE contains hazardous materials. The rest of the chapter will now focus on regulations/directives dealing with this specific waste stream.

2.3 The Waste Framework Directive

The Waste Framework Directive has been amended a number of times since its introduction in 1975 [Directive 75/442 EEC] and following lengthy consultations in response to the thematic strategies adopted in the 6th Environment Action Programme [EAP6], a review of the Waste Directive commenced and a proposal was put forward by the Commission in 2005 [COM (2005) 667]. After public consultation, the proposal was adopted by the European Council as a directive in October 2008 and member states had until 2010 to transpose it into domestic law [Directive 2008/98/EC]. The effect of the new directive will be to repeal the existing waste directive but also the directives on hazardous waste [Directive 91/689 EEC] and waste oils [Directive 75/439 EEC], thereby simplifying the legislation.

A major problem with the original directive was the lack of clarity in the definitions used, for example fundamentally identifying precisely what was meant by the term ‘waste’. The differing interpretations of a number of terms resulted in variable implementation practices between member states. These differing interpretations had to be settled by the Court of Justice of the European Communities and they mainly centred around the definition of waste and the distinction between the terms recovery and disposal [COM (2005) 667].

The intention of the directive is to promote waste as a secondary resource so that landfill levels can be reduced even further, bringing about a greater reduction in greenhouse gas emissions. There is a strong emphasis on waste prevention and the amended directive sets even more ambitious recycling targets of 50% of household waste (including compostable waste and 70% of construction waste by 2020).

The terminology used in the directive has been harmonised with other directives and it seeks to promote product life-cycle thinking by encouraging producers to prevent waste generation in the first instance. The 1975 directive set out a waste management hierarchy with the first priority being to prevent waste in the first place, then to recycle and reuse it. This hierarchy is the core of sustainable waste management and has thus been embedded into legislation. The amending directive extended this thinking further and introduced two further measures into the hierarchy based on their environmental impact. Member states are now required to adhere to the new hierarchy in order of priority:

1. prevention of waste
2. preparation of waste for reuse
3. recycle waste
4. other recovery (for example energy recovery)
5. disposal

The regulations now state agreed definitions with the aim that this will reduce the varied practices between member states due to differing interpretations:

Waste: any substance or object which the holder discards or intends or is required to discard.

Waste management: the collection, transport, recovery and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker.

Prevention: measures taken before a substance, material or product has become waste.

Recovery: any operation the principal result of which is waste serving a useful purpose.

Recycling: any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.

The directive also requires member states to set up 'competent authorities' to be responsible for the planning, organisation, authorisation and supervision of waste disposal operations. Once established, the authorities were required to make waste management plans which set out the type and quantity of waste for disposal as well as associated costs and technical requirements for doing so. The competent authorities were given responsibility for granting permits to any undertaking or holder processing waste. To obtain a permit, the waste operator had to demonstrate how the waste would be disposed of without causing harm to human life or the environment.

This obligation meant providing technical details and safety precautions undertaken to protect human health and the environment but also a requirement to provide the competent authority with information on the origin, destination, treatment, type and quantity of the waste. To ensure waste operators complied with the criteria detailed in the permit they would be subject to inspection by the authority. In turn, the competent authority would have to report back to the EU Commission on how it was implementing the directive.

The burden of costs associated with disposing of waste were placed upon the waste producer and the 'polluter pays' principle was firmly retained: the more waste a producer created, the more they would pay to have it disposed of.

2.4 The WEEE Directive

The objective of the WEEE Directive [Directive 2002/96/EC] is to prevent and minimise WEEE in line with the waste hierarchy principles established in the Waste Framework Directive (reuse, recycling, recovery). A responsibility is put on producers and distributors to pay for the costs associated with the collection, treatment, recycling and recovery of WEEE. To ensure this takes place, the directive requires producers to set up individual or collective schemes which will finance the collection and treatment of WEEE.

The directive is set out over 19 articles and the main requirements can be summarised as follows.

Article 2 – Scope

The directive applies to electrical and electronic equipment as described in the accompanying Annex IA unless it is contained within a piece of equipment not listed in Annex IB. Military equipment and equipment used by member states as part of their national security systems are also excluded from the directive.

Ten categories of WEEE are covered by Annex IA:

- Large household appliances
- Small household appliances
- IT and telecommunications equipment
- Consumer equipment
- Lighting equipment
- Electrical and electronic tools
- Toys, leisure and sports equipment
- Medical devices
- Monitoring and control instruments
- Automatic dispensers.

Annex IB then goes on to specify specific types of equipment that are covered by the directive within each of these categories. For example, under the large household appliances category established by Annex IA, Annex IB expands on this to specify equipment such as dish-washing machines, refrigerators, microwaves etc.

Article 3 – Definitions

This article lists 13 definitions through which the directive should be read. It provides a definition for the important terms listed:

1. EEE – this only applies to equipment up to 1000 volts alternating current or 1500 volts direct current
2. WEEE as described by the Waste Framework Directive
3. prevention
4. reuse
5. recycling
6. recovery

7. disposal
8. treatment
9. producer – includes sellers, distance sellers, resellers, manufacturers, importers and exporters
10. distributor
11. WEEE from private households which includes commercial WEEE if it is similar in quality and quantity to private WEEE
12. dangerous substance or preparation – this ties up closely with the provisions set out in RoHS [2002/95/EC]
13. finance agreements – this definition seeks to make clear who is responsible for the WEEE where equipment may not be sold but leased or hired, for example.

Article 4 – Product design

In order to facilitate efficient dismantling, recovery, recycling and reuse of WEEE the article encourages member states to pay attention to design and production techniques which aid this. Clearly, as there is no specific requirement, member states are at liberty to determine to what extent they enact this article.

Article 5 – Separate collection

Member states are instructed to adopt techniques that achieve a high level of separate collection of WEEE from other waste to prevent it forming part of any unsorted municipal waste stream. To assist this with respect to private households, the directive requires member states to set up systems so that the final holders of WEEE can return it free of charge to a collection facility. There is a further requirement for distributors who must also take back WEEE for free from private households when providing another of similar specification. Producers can also set up their own collection and take-back operations to comply with the directive. For private households, this article sets a collection target of 4 kg per head of the population per year.

Article 6 – Treatment

This article clearly makes producers, and third parties acting on their behalf, responsible for setting up systems for the treatment of WEEE using the best available methods for recycling and recovery. Producers can either make these arrangements individually or they can act collectively with other producers to set up treatment facilities. Each member state is responsible for the oversight of any treatment operator through a system of permits which carry with them a number of onerous reporting and inspection obligations as well as technical standards for treatment processes. Standards are also laid down for the treatment of exported WEEE outside the member state concerned. Annex II of the directive sets out some minimum treatment requirements such as the need to remove certain substances, preparations or components. An example of this is the minimum requirement to remove components containing radioactive material or removing the fluorescent coating from cathode ray tubes.

Article 7 – Recovery

Not only are producers responsible for the treatment of WEEE but Article 7 also makes them responsible for setting up systems that enable WEEE to be recovered with priority given to the reuse of whole appliances. Article 7 also lays out specific targets that producers must meet by three years post-implementation:

- For WEEE described in categories 1 (large household appliances) and 10 (automatic dispensers) of Annex IA of the directive a minimum recovery of 80% and for component, substance reuse, recycling and material a minimum of 75%, both being based on the average weight of each appliance.
- For WEEE in categories 3 (IT and telecommunication equipment) and 4 (consumer equipment), recovery needs to reach a minimum of 75% with component, substance reuse, recycling and material a minimum of 65%, both being based on the average weight of each appliance.
- For WEEE in the remaining categories recovery needs to reach a minimum of 70% with component, substance reuse, recycling and material a minimum of 50%, both being based on the average weight of each appliance.
- For gas discharge lamps, component, substance reuse, recycling and material a minimum of 80%, based on the weight of lamps.

In order to demonstrate the above, producers must keep records of the mass of WEEE treated along with records of their components, materials or substances both on entry and exit to the treatment facility.

Article 8 – Financing in respect of WEEE from private households

An obligation is placed on producers to finance the collection, treatment, recovery and disposal of WEEE which private households have taken back to the collection facility established under Article 5. Any products put on the market after August 2005 will remain the financial responsibility of each individual producer. As with the take-back schemes already mentioned, producers can either do this individually or they can act collectively to set up a system which achieves this. Article 8 states that the financial costs associated with the collection, treatment and environmentally sound disposal should not be shared with purchasers when they buy new products.

This situation is different for WEEE that was on the market before August 2005 where all producers from that period contribute to the collection, treatment and disposal of historical WEEE based on their share of the market. This is the 'polluter pays' principle in action whereby the more a producer puts on the market the more they pay towards a scheme which deals with the waste. Article 8 allows producers to share these costs with the purchaser for historical WEEE. In contrast to new WEEE, producers can tell purchasers the costs associated with collection, treatment and disposal but only for an 8 or 10 year period depending on the category of WEEE.

Member states must also make sure that distance sellers are bound by the requirements of this article. Therefore, if the producer of the equipment is in member state A and the purchaser is in member state B then the producer must comply with the arrangements for member state B rather than member state A where the producer is located. This is an important point as the directive provides for member states to improve on the minimum standards set out and also encourages rather than requires progress in areas such as product design and technologies. This means that the requirements in each member state will be different and there is an obligation on the producer to know this and set up systems to comply.

Article 9 – Financing in respect of WEEE from users other than private households

Producers are responsible for the financial costs of collection, treatment, recovery and disposal of both new and historical WEEE. However, each member state is at liberty to make users of EEE responsible for these costs so long as it is free to private households. Article 9 also gives the flexibility for producers and users to come to their own financial arrangements.

Article 10 – Information for users

Member states need to ensure that private householders are provided with sufficient information about how WEEE should be dealt with when the end user no longer has a need for it. The information needs to include how and where it can be collected separately, how the general public can contribute to reuse and recycling and what effects hazardous substances found in WEEE can have on the environment.

Since August 2005 producers of EEE have had an obligation imposed on them by Article 10 to mark their products with a crossed-out wheelie bin symbol and a registration number from which the producer can be identified.

Further obligations are placed on producers/distributors to provide information to consumers on the environmental impact of the products they purchase.

Article 11 – Information for treatment facilities

To maximise the correct treatment and reuse of WEEE, member states are tasked with ensuring that producers provide this information for all EEE they put on the market so that reuse centres and recycling and treatment facilities have information on the type and location of hazardous substances as a minimum. Producers must also make sure that they mark any EEE they put on the market so that the producer can be clearly identified. Furthermore, the producer needs to mark the EEE clearly to show if it was put on the market after August 2005.

Article 12 – Information and reporting

The requirements on member states and producers for providing information on collection activities to the European Commission are both onerous and stringent. Member states need to set up registers of all producers, including distance sellers, putting EEE onto the market in that member state. The member state needs to collect information annually on the quantities and categories of WEEE collected and to be broken down by how it was collected, whether that be by reuse, recycling or recovery even if the collected waste is exported. Article 12 also lays down how often the information is communicated to the Commission.

Article 13 – Adaptation to scientific and technical progress

Article 13 explores possible future amendments to the annexes of the directive which may allow additional items of WEEE to be included in the scope of the directive; examples are filament bulbs and solar panels.

Article 15 – Penalties

It is left open to each member state to determine how breaches of the directive will be enforced. The only advisory note given is that any penalties should be ‘effective, proportionate and dissuasive’.

Article 16 – Inspection and monitoring

In addition to the strict reporting requirements placed on member states as set out in Article 12, member states must additionally undertake inspections and monitor all parties involved for compliance with the directive.

Article 17 – Transposition

Apart from Greece and Ireland, member states were given until August 2004 to implement the directive.

Amendments to the WEEE Directive came into force in 2008 at the end of the first compliance period [Directive 2008/34/EC]. The amendments include counting of whole appliances for reuse and providing for private households to return WEEE to the system free of charge even where they do not replace it with an equivalent.

2.5 The WEEE Directive in operation

The WEEE Directive is legislation based on Article 175 of the founding treaty of the European Union [Treaty Amsterdam 1997] and, as discussed earlier in the chapter, member states are afforded a certain degree of flexibility in how the directive can be implemented as they have the ability to improve on the minimum standards should they wish to and have the technology to do so. In practice this has meant that there have been widely varying practices and implementation timetables across all member states. Despite member states being required to implement the WEEE Directive by August 2004, only Greece and the Netherlands were actually in a position to do so. It took until the start of 2008 before all member states had actually implemented the directive, with Italy being one of the last. The Commission has not published any implementation maps as such but good accounts are given by Magalini and Huisman [2007] who also look at some of the reasons behind the differing timetables (such as the differences in pre-existing infrastructure and technology between member states and the complexity of the legislation itself as well as financing issues). Cahill *et al*. [2011] have also discussed implementation timetables across the EU. As with the Waste Framework Directive discussed earlier, there have also been differences in the interpretation of certain terms used in the directive which has contributed significantly to the lack of uniform implementation. An example of this is the practical interpretation of ‘put on the market’.

In order to assess the implementation of the directive the Commission ordered three reports from independent consultants [Savage *et al*. 2006, Sander *et al*. 2007, *Huisman et al*. 2008]. All three of the reports highlighted the vast differences in practices between member states in a number of key areas and questioned whether some member states were actually complying with the directive at all. These reports also made a number of suggestions for tackling the problems. It was also apparent that enforcement rates were also low, reporting procedures and practice were confusing, and the problem of illegal exports of WEEE persisted. To address these problems, the Commission put forward new proposals for a recast of the directive in 2008 [COM (2008) 810].

2.6 The recast of the WEEE Directive

As suggested by the reports obtained by the Commission, the recast proposal cites the grounds behind it as being:

> …technical, legal and administrative problems that result in unintentionally costly efforts from market actors and administrators, continuing environmental harm, low levels of innovation in waste collection and treatment, a lack of a level playing field or even distortion of competition and unnecessary administrative burden.

Unpacking this a little further, the proposal cites a number of specific issues which were also raised in the consultants' reports:

- Lack of clarity on the different products and their associated categories identified by the directive which has caused differing interpretations and therefore practices and provisions not just between member states but also stakeholders more widely.
- Despite 65% of EEE placed on the market being collected separately, only roughly half of this is actually subsequently treated and reported in accordance with the directive. This means that the missing WEEE is potentially being treated out of sight below the minimum requirements or else is being illegally exported outside the EU. Clearly the risks of this happening are the release of toxic substances and the loss of the materials themselves as resources. The Commission also identifies that the collection target of 4 kg from private households may be inappropriate since for some member states this is far too low and for others it is difficult to achieve.
- The existing directive has no set targets for the reuse of whole appliances.
- Poor enforcement rates may be attributed to the lack of firm enforcement guidance and requirements set out in the directive.
- Differing requirements for producer registration schemes between member states has created the potential for 'economic actors' needing to comply with the requirements of up to 27 different schemes across Europe. Undoubtedly, this has led to an onerous administration burden and cost.

The Commission intended from the outset to review the directive and the collection rates in 2008 and through the Waste Framework Directive had already committed itself to improving regulation.

2.6.1 Summary of the main proposed revisions

- *Article 2* – The scope of the WEEE Directive should be the same as the scope of the RoHS Directive [2002/95/EC] as discussed further later in the chapter. There are also some clarifications given about the exemptions from the proposed recast directive and a new statement on the classification of WEEE.
- *Article 3* – Some terms are better defined to provide both clarity and coherence with other community legislation, examples of this are the definitions of reuse, prevention, recycling, recovery, disposal, treatment, placing on the market, collection etc.
- *Article 5* – Member states must prioritorise and maximise the separate collection of cooling and freezing equipment that contains ozone-depleting substances and fluorinated greenhouse gases.
- *Article 6* – Disposal of untreated WEEE that has been separately collected must be prohibited. Any WEEE that is collected and transported has to be done in a way that will optimise its ability for reuse and recycling and must also ensure that hazardous substances are contained.
- *Article 7* – Producers, or third parties acting on their behalf, must achieve a minimum collection rate of 65%. This is to be based on the amount of EEE that the producer has put on the market in the preceding two years and producers need to achieve this rate annually from 2016. This rate will be re-examined in 2012 and there is some flexibility if member states can demonstrate they have an exceptional reason due to national circumstances for not being able to comply by the deadline or the rate. When reviewing the collection rate targets in 2012 the Council and the Parliament will also consider setting separate collection rates for freezing and cooling equipment.
- *Article 11* – Member states need to ensure that producers achieve new targets for all separately collected WEEE for the categories of equipment set out in Annex I of the RoHS Directive (previously Annex IA of the WEEE Directive). The targets are based on the weight percentage of separately collected WEEE sent to recovery facilities rather than the simple 4 kg per person weight based approach in the original directive. The new targets had to be implemented by 31 December 2011.
    - Categories 1 and 10 – 85% for recovery and 80% for reuse and recycling.
    - Categories 3 and 4 – 80% for recovery and 75% for reuse and recycling.
    - Categories 2, 5, 6, 7, 8 and 9 – 75% for recovery and 55% for reuse and recycling. Note the addition of a target for category 8 which are medical devices.
    - Gas discharge lamps – 85% for reuse and recycling.

- *Article 12* – producers should be encouraged by member states to finance the entire financial costs incurred by collection facilities for WEEE arising from private households.
- *Article 14* – producers will now be able to show consumers the so-called ‘visible fee’ when they make their purchases. This will mean that producers can show the costs of collection, treatment and environmentally sound disposal costs with the proviso that the costs shown to the consumer do not exceed the actual costs of doing so.
- *Article 16* – Under the previous directive, a huge administrative burden was put on producers and the recast attempts to reduce this by simplifying the registration process. Member states can create a national register of producers, including distance sellers, whereby the producers can provide details of all their activities across other member states. By making the registers harmonised and interoperable the burden should be substantially reduced and negate the potential need to register separately in all 27 member states.
- *Article 19* – Member states will need to set out their national rules on penalties and infringements of the directive. Further, member states are expected to take steps to enforce the rules.
- *Article 20* – Minimum inspection requirements are set out, including for shipment of WEEE outside the EU, and member states must monitor and verify that the directive is being properly implemented. The proposals warn that further measures on inspections and monitoring will be forthcoming. Annex I of the original directive has been deleted and a new Annex has been created which deals with the minimum requirements for monitoring shipments of WEEE.

2.6.2 The Parliament’s and the Council’s response to the Commission’s proposal

The ordinary or co-decision procedure means that both the European Parliament and Council have an opportunity of hearing and suggesting amendments to the Commissions proposals on the WEEE recast.

The Parliament’s views

The position adopted by the Parliament at its first reading in February 2011 made the following recommendations, among others [EP Resolution 2011]:

- All operators involved in product life cycles should be required to improve their environmental standards.
- The directive should apply to all electronic and electrical equipment other than:

    - large-scale fixed installations
    - large-scale stationary industrial tools
    - non-road mobile machinery intended exclusively for professional users
    - means of transport for persons or goods
    - photovoltaic modules.

  The Commission is asked to report every five years on whether or not the scope should be widened to include photovoltaic cells.
- Member states should ensure that WEEE from private households, especially mercury-containing lamps and small appliances are collected separately and that no untreated WEEE is sent to landfill or is incinerated.
- As of 2016 the rate of collection of WEEE should be at least 85% as opposed the 65% proposed by the Commission.
- As of 2012 the requirement to collect 4 kg per person should be a minimum or at least the same as the amount that each member state collected in 2010, whichever is the greater.
- Harmonised standards should be adopted for the collection, storage, transport, treatment, recycling and repair of WEEE.
- Exporters should provide evidence before and after shipping WEEE that shows the treatment and recovery standards are equivalent in the receiving country.
- The number of categories of WEEE should be reduced from the current number of 10 to only 6 and that the collection rates should be 75–85% for recovery and 50–75% for recycling depending on the category. Reusable equipment should be separated and a target of 5% of this for reuse should apply.
- To help increase collection rates from private households, waste operators should run awareness-raising campaigns and door-to-door collection events. These activities should be funded using the 'polluter pays' principle, with responsibility falling to producers, retailers and consumers but not on general taxpayers.
- Distributors should set up and promote collection schemes especially for small volumes of WEEE. End users should be able to dispose of items in the retailer's shop at a visible and accessible point and the retailer should be obliged to take back small volumes of WEEE for free when supplying small volumes of EEE even if the consumer makes a purchase which is not on a like-for-like basis.

The Council's position

The Council had its first hearing of the proposals in March 2011 [Presse 58 2011] and disagreed with the Parliament's position in a number of key areas. In summary the Council's amendments are as follows:

- The Council would prefer to see member states make annual collections of 45% of the average weight of EEE placed on their national markets, effective from four years after the directive is reintroduced. This would rise to 65% after a further four years. The Council also proposes flexibility for countries where the use of EEE is lower and a collection rate of 40–50% by 2016 is suggested, rising to the full collection target rate by 2022. This would apply to the Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Latvia and Lithuania.
- The scope of the directive was widened by the Council's decision so that all EEE will be covered six years after reintroduction. In opposition with the Parliament's position, the Council specifically includes photovoltaic panels.
- The Council proposes that the targets previously set out for recovery and recycling are increased by 5% but that the reuse of whole appliances can count towards that target taking effect three years after entry into force of the recast directive.
- Producers must pay for the collection and treatment of waste but this should extend to include its preparation for reuse, recycling or recovery.

Next steps

After considerable and lengthy negotiations, the Council and the Parliament finally reached agreement in January 2012 after the second reading in the Parliament [Doc P7-TA (2012) 0009]. The final text now has to be ratified by the Council after which it will be published in the *Official Journal*. Once this has occurred, member states have 18 months to implement it. A summary of the agreed text is given in a press release by Commissioner Potočnik [Memo 12/20]. The key elements of the agreement are as follows:

- Member states will be required to collect 45% of electrical and electronic equipment placed on their markets by 2016, rising to 65% by 2019, or may opt for the target of 85% of all waste generated.
- Consumers should be allowed to return for free small items (such as kettles and toasters) to any larger electrical goods supplier, without needing to buy a new product.
- Producers will continue to contribute towards the financial costs of meeting processing targets but will be subject to less complex registration and reporting requirements. Producers will be permitted to appoint representatives to act on their behalf in other member states instead of having to set up business in each member state in which it trades.
- There will be tighter controls on illegal shipments of WEEE to prevent it from being processed in countries where practice is less rigorous than set out by the EU. The burden of proof moves from customs officers

to exporters, who must test and properly report that goods are being transported for repair or reuse etc.

2.7 Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)

The Directive on the Restriction of Hazardous Substances [Directive 2002/95/EC] is companion legislation to the WEEE Directive. Unlike the WEEE Directive, the RoHS Directive is enacted by Article 95 of the Treaty establishing the European Community [Treaty Amsterdam 1997] which has much less flexibility that those enacted by Article 175 such as the WEEE Directive. The intention is that legislation made on the back of Article 95 should be uniformly applied across the EU. However, along with the WEEE Directive, RoHS has also been recast. Before discussing the changes, an overview is given of the original provisions.

The RoHS Directive is set out in ten articles and an associated annex and should be read in tandem with its sister legislation the WEEE Directive. The objectives of the directive are to protect human/animal health and ensure the environmentally sound recovery and disposal of WEEE. The main provisions of the directive can be summarised as follows.

Article 2 – Scope

The directive applies to EEE which falls within categories 1 to 7 and 10 of Annex IA of the WEEE Directive and also to electric light bulbs and other forms of household electric illumination. Categories 8 (medical devices) and 9 (monitoring and control equipment) of Annex IA of the WEEE Directive are not covered by the RoHS Directive. Note that batteries are also not covered by the RoHS directive but by the separate legislation in the form of the Batteries Directive [Directive 2006/66/EC].

Article 3 – Definitions

The definitions of electrical and electronic equipment and producer are identical to those set out in the WEEE Directive. EEE is similarly defined as

> electrical and electronic equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields falling under the categories set out in Annex IA to directive 2002/96/EC (WEEE) and designed for use with a voltage rate not exceeding 1000 volts for alternating current and 1500 volts for direct current.

Article 4 – Prevention

Member states were given until July 2006 to ensure that after this date no EEE put on the market would contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ether (PBDE). In light of scientific advances the Commission may propose further substances that should be banned or give a view on any substitutions of the banned chemicals with ones less environmentally harmful.

The Annex of the directive sets out a number of situations where the use of the banned chemicals lead, mercury, cadmium and hexavalent chromium are exempt from Article 4(1). Examples of this are mercury in straight fluorescent lamps for special purposes and lead in glass of cathode ray tubes, electronic equipment components and fluorescent tubes. Other uses are exempt if they contain only a given concentration of the chemical; for instance, mercury in compact fluorescent lamps not exceeding 5 milligrams per lamp.

Article 5 – Adaptation to scientific and technical progress

The annex to the directive setting out the exempt uses of the banned chemicals should be reviewed in light of scientific and technical progress. The legislative procedure for doing this is set out in Article 7. Any amendments should include consideration of three issues:

1. Laying down maximum concentration values of the banned chemicals in specific materials and components of EEE.
2. Granting exemption for materials and components of EEE from Article 4-(1) if removing them or substituting them, through design changes for example, is technically or scientifically not practical or if by doing so the impact on health and safety or the environment outweighs the benefit.
3. A review of each exemption in the annex every four years as a minimum or four years after the item is added to the list in the annex. The aim of the review is to determine whether or not the item should be deleted in line with the analysis of the ability or desirability of doing so as set out in (2).

Article 6 – Review

The Commission committed to a review of the directive in 2005 and resolved to give consideration to including equipment that falls in categories 8 (medical devices) and 9 (monitoring and control equipment) of Annex IA of the WEEE Directive.

Article 7 – Penalties

Each member state is left to determine its own penalties for breaches of the directive provided that any penalty is effective, proportionate and dissuasive.

Article 9 – Transposition

Member states were given until August 2004 to implement the directive.

Since its introduction, the RoHS Directive has been amended many times before the Commission submitted its proposal for a recast in December of 2008 [COM 2008/809/EC]. In 2005, Article 5 of the directive was amended when the Commission established maximum concentration values of the six chemicals listed in recognition that it was not always practically possible to eliminate them altogether [COM 2005/618/EC]. The maximum concentrations were established to be 0.1% for lead, mercury, hexavalent chromium, PBB and PDBE by weight of homogeneous material and 0.01% by weight of homogeneous material for cadmium. The list of exempt equipment given in the annex of the directive has been added to significantly and the list of exempt equipment has grown from 10 in the original directive to the current 39 and to reflect the changes the annex was reissued in 2010 [COM 2010/571/EU]. The list expanded largely as a result of lack of technical progress in the early stages but the amendments in 2010 also reflected the change in technology and scientific advance and so a number of exemptions were reviewed. The Commission also set expiry dates for exemptions where it believed that technology and science were close to providing an alternative. The maximum concentration values of the chemicals permitted was also under review.

Like the WEEE Directive the initial implementation of the RoHS Directive was variable across Europe and one reason was due to the differing interpretations of 'homogeneous material' which was introduced in the amending regulations in 2005 [COM 2005/618/EC]. The directive also did not set out any advice or instructions governing compliance and the producers' responsibilities so there was considerable confusion about proving product compliance in practice. As with WEEE, enforcement rates were very low.

In line with Article 6 of the original directive, the Commission was committed to reviewing the directive and in particular whether or not equipment listed in categories 8 and 9 of Annex IA of the WEEE Directive should be included. The Commission then put forward a proposal to recast the RoHS directive at the same time as the WEEE Directive [COM 2008/809/EC] to promote harmonised and coherent legislation. Going one step further, the recast will also put RoHS in line with legislation on Registration, Evaluation, Authorisation and restriction of CHemicals (REACH) [Regulation 1907/2006 EC] which will be discussed in the Section 2.9.

2.8 The Commission's proposal on a recast RoHS

In summary the main changes proposed by the Commission are as follows.

Article 2 – Scope

The directive will apply to all ten electronic and electrical equipment listed in its Annex I and so will now apply to the two categories previously excluded (medical devices and monitoring and control equipment). A new Annex II provides a binding list of products that fall within the scope of the categories set out in Annex I.

New exclusions to the directive are added and in line with the WEEE Directive include equipment necessary for the protection of member state security, equipment designed as part of a larger piece of equipment falling outside the scope of the directive and equipment not intended to be put on the market as a stand alone item.

Article 3 – Definitions

The list of definitions has been modified and significantly added upon to ensure that the potential for varying interpretations is minimised such as that around 'homogeneous material'. Definitions relating to the new category of medical devices are also given.

Article 4 – Prevention

The maximum concentration limits imposed by the 2005 amendment [COM 2005/618/EC] are listed as a new Annex IV to the directive. The requirement for member states to ensure that no EEE is placed on the market containing the banned substances is extended to include spare parts. However, as medical devices and monitoring and control equipment are new to the list in Annex I, this rule will apply to such equipment placed on the market after January 2014. It applies to *in vitro* medical devices from January 2016 and to industrial monitoring and control instruments from January 2017. The reason behind the staged implementation is to ensure that the requirement for spare parts to be compliant does not result in equipment covered by these categories being prematurely withdrawn from the market.

Exemptions from Article 4(1) are listed in new Annexes V and VI and a means of introducing new substance bans is outlined.

Article 5 – Adaptation of the annexes to scientific and technical progress

The Commission will have the ability to amend the binding list of products given in Annex II and the exemptions listed in Annexes V and VI of the directive where a number of criteria are fulfilled. Both materials and components are included. The new criteria includes taking into account the availability and reliability of substitutes and the socio-economic impacts on environmental health or consumer safety.

Exemptions are also time limited to a four year maximum period and the Commission has the ability to delete them from the list. New criteria for applying for an exemption are introduced and include consideration of reliability and availability.

Article 6 – Implementing measures

This is a new article which allows the Commission to adopt new rules for applications for exemptions, compliance with the maximum concentration of substances and procedures for renewing exemptions.

Article 7 – Obligations of manufacturers

It is the responsibility of the manufacturer to ensure that products comply with the relevant requirements of the directive and they have a duty to draw up a declaration and mark their products with the CE mark [Directive 93/68/EEC and Decision 93/465/EEC]. Manufacturers must then keep the technical documentation and the declaration for ten years from placing the EEE on the market. Conditions for the declaration and the CE marking are dealt with in new Articles 13–16. The CE mark is placed on a product by a manufacturer to demonstrate that the product complies with all the relevant requirements of an EU directive. CE means 'Conformité Européenne' which simply means 'European conformity'.

Manufacturers will also now need to ensure as much uniformity of their products as is feasible and have to undertake sampling and testing of any they place on the market to make sure they do conform. There is an onus on the manufacturer to take steps where non-conformity is identified. Consumers will need to be given much more information about the EEE they purchase including the manufacturer's name, trademark and address, model and serial numbers. The competent authority of any member state can also demand the information and it has to be provided in a language that can be understood by that particular authority. Most of these obligations are also placed on importers and distributors through new Articles 9 and 10.

Article 8 – Authorised representatives

Manufacturers have the ability to appoint an authorised representative to draw up and maintain the technical documentation required in Article 7.

The response of the Parliament and the Council to the Commission's proposals

The Parliament had its first reading of the Commission's proposals in November 2010. After making a number of compromises with the Council, the Parliament adopted its position which amended the Commission's proposals in a number of ways:

- Any WEEE outside the scope of the original RoHS Directive but which would be non-compliant within the scope of the recast RoHS Directive, can continue to be available on the market for eight years after the recast comes into force.
- The directive does not apply to;
    - equipment concerned with member state security including arms, munitions and war material intended for military use;
    - equipment designed to be sent into space;
    - equipment that is specifically designed for and forms part of a larger piece of equipment excluded from the scope of the directive provided it can only function as part of that larger equipment;
    - large stationary industrial tools;
    - large fixed installations;
    - Transport for either people or goods other than non type-approved two-wheelers;
    - professional machinery not intended for use on roads;
    - active implantable medical devices;
    - photovoltaic panels if their intended use is in a professionally installed and permanent place and for energy generation by solar power in public, commercial, industrial or residential applications;
    - research and development equipment between businesses only.
- New definitions should be added including a definition of 'dependent' with regards to 'electrical and electronic equipment' to add clarification for products where more than one characterisation is possible.
- Annex II of the directive should also include cables and spare parts for the repair, reuse or upgrade of equipment. However, this should not apply to reuse of spare parts recovered from historical EEE (put on the market before July 2006) and put into equipment placed on the market before July 2016. Any such instances will need to be adequately audited.
- In the light of technical and scientific progress Annexes III (list of substances in Article 4) and IV (allowable concentrations of substances

in article 4) should be reviewed so that the REACH regulation is not weakened. There should also be a review to determine if other substances such as nanomaterials should be added.
- Distributors should be obligated to ensure that products have the CE mark, documents are provided that can be understood in the relevant member state and that manufacturers and importers are compliant with the directive.
- After three years in force, the Commission should review the scope of the directive and within ten years carry out a general review.

The Council adopted Parliament's amendments and agreement was reached in May 2011 [Council Press Release 156]. Member states will have 18 months to transpose into domestic law from the date that the recast Directive is published in the *Official Journal*.

2.9 Registration, Evaluation, Authorisation and restriction of CHemicals Directive (REACH)

REACH is a lengthy and complex EU Regulation [Regulation 1907/2006 EC] which seeks to protect human health and the environment while also supporting competition within the chemicals industry. The regulations were published in 2006 along with amendments to its sister legislation the Dangerous Substances Directive [Directive 67/548/EEC]. The Regulation is set out in 141 articles and 17 annexes, spanning 849 pages, so this section simply attempts to give an overview of the main highlights.

The REACH Regulation brings about regularisation of the chemicals industry and therefore also the EEE industry, and is managed by the European Chemicals Agency (ECHA) to ensure consistency across the EU. Prior to REACH, the risks associated with chemicals were characterised according to a number of different directives and regulations which were repealed and replaced with the REACH system to try to harmonise practice across the EU – see article 139 of REACH.

Under previous regulations such as Regulation EEC 793/93, chemicals were identified as either 'existing' or 'new' chemicals depending on whether or not they were on the EU market between 1971 and 1981 or after. All existing chemicals had to be recorded in the European Inventory of Existing Commercial Chemical Substances (EINECS) but it was not a requirement that they had to be tested before being placed on the market. New substances however, were required to be tested prior to being placed on the market. The previous practices had many problems, including the different reporting and control mechanisms between existing and new chemicals, making it very difficult to obtain coherent and comprehensive information about the risks and uses of chemicals. Further, the responsibility for implementing the regulations between public authorities, manufacturers, importers etc. were unclear.

2.9.1 Brief summary of REACH

Like many of the other directives discussed in the chapter, REACH places responsibility on the manufacturer/producer for ensuring that any chemicals they put on the market are properly assessed and managed in terms of their risks. Public authorities are tasked with ensuring the industry meets this obligation.

The REACH regulations still apply to the previous definitions of 'existing' and 'new' substances but they are now termed 'non-phase in' and 'phase in' substances.

Title I Scope

The scope of REACH is very broad and covers all substances in quantities with a usage of more than one tonne per year and are:

- manufactured;
- imported;
- used as intermediates;
- placed on the market on their own;
- placed on the market in preparations;
- placed on the market in products.

Specifically exempt from REACH are;

- radioactive substances;
- transport of substances;
- waste;
- certain natural substances that are low hazard;
- non-isolated intermediates (chemicals that are manufactured with the sole purpose of being transformed into another substance);
- substances subject to customs supervision;
- substances covered by other specific provisions such as human and veterinary medicines (Annexes IV and V of the regulations set out these exemptions in full).

Title II Registration of substances

All manufacturers and importers must provide the ECHA with information about their substances which will be stored in a central database. All individual substances must be registered with the agency if they are made or imported in quantities over one tonne and if a company fails to register any substance then it cannot be manufactured or imported to the EU at all. The information that is provided for the central database needs to be used by the manufacturer or importer to determine the risks and management associated with the use of that substance. The registration documents need to include a technical dossier outlining the properties, uses, classification and guidance on safe use as well as a chemical safety report (if over 10 tonnes). A priority for registration are those substances that are harmful to health and the environment, carcinogens, mutagenic and toxic to reproduction substances among others.

There is a separate requirement to register substances in articles such as EEE owing to the potential harm they may cause due to the chemicals they contain if there is the potential for them to be released during normal use. Otherwise, safety instructions need to be issued.

Title III Data sharing and avoidance of unnecessary testing

In order to reduce the amount of testing on vertebrate animals, the regulations stated that industry had to share data on testing of any phase in substances (those already on the market before REACH) and non-phase in substances (those not on the market when REACH was implemented). It is permissible to charge a fee for data sharing.

Title IV Information in the supply chain

REACH places an obligation on manufacturers and importers to provide information on the safe use of their substances to downstream users, i.e. their customers and distributors. The information that should be provided includes that relating to health and safety, environmental risks and measures for the management of risks. The obligation is not just to be passed down the supply chain but also back up it as well. The mechanism for communicating the information will typically be in the form of safety data sheets which are likely to evolve as greater information results from the registration process.

Title V Downstream users

Any industrial user of chemicals, including those manufacturing articles such as EEE, have to make a safety assessment and implement appropriate risk management techniques. Generally, this will be informed by the safety data sheets provided by the manufacturer or importer but there is also the obligation to assess in the light of the downstream users' particular circumstances.

Title VI Evaluation

The regulation sets out two different types of evaluation carried out by the ECHA. The first type is a dossier evaluation and the second is a substance evaluation.

- Dossier evaluation involves the agency checking the registration dossiers that applicants submit when initially registering a substance to ensure they comply with the information requirements of the regulation. The dossier evaluation will also consider whether or not unnecessary animal testing has taken place.
- Substance evaluation by the agency is carried out in conjunction with the competent authority of a member state to investigate any concerns over risks to human health or the environment and can ask industry for further information to clarify any concerns over a particular substance. The ECHA will develop guidance at member state level on the prioritorisation of substances that should be evaluated further.

Title VII Authorisation

If there is a high concern to human health or the environment posed by a particular substance then the agency can mandate that it can only be placed on the market if it is authorised by the agency first. Substances that fall into this category, are for example, carcinogenic, mutagenic or reproductive (CMR) toxic substances and persistent, bioacumulative toxic (PBT) substances. If an authorisation is granted then the applicant will need to clearly demonstrate that all possible controls necessary have been put in place and that there is no safer alternative substance.

Title VIII Restrictions

Certain substances and preparations which pose a threat to human health or the environment, may be strictly regulated across member sates so that conditions for their manufacture and use are controlled and harmonised and if necessary prevented.

Title XI Classification and labelling inventory

REACH adds to the existing requirements to classify and label dangerous substances and preparations by introducing an inventory system. The inventory keeps a central log of all classifications and labels arising from them on substances that are either manufactured or imported to the EU. Industry will be required to provide their classifications to the agency for subsequent entry on the inventory. The aim is that differences in classifications of the same substances by various industries will be identified and removed in favour of a harmonised set of classifications. In furtherance of this aim, the Commission put forward a proposal [COM 2007/355] which would see the introduction of a globally harmonised system (GHS) of classification.

Article 126 Enforcement

As with WEEE and RoHS Directives the REACH regulations leave each member state to determine the penalties that would apply to the infringement of the regulations. They also have to take all measures necessary to ensure that they are implemented. The penalties should be 'effective, proportionate and dissuasive'.

Article 141 Implementation

Titles II (registration of substances), III (data sharing and avoidance of unnecessary testing), V (downstream users), VI (evaluation), VII (authorisation), XI (classification and labelling inventory), XII (information) and Articles 128 (free movement) and 138 (review) came into force in June 2008, Article 135 (transitional measures) in August 2008 and the remaining Title VIII (authorisation) along with Annex XVII (restrictions) in June 2009.

2.10 Review of REACH

The REACH regulations require a number of reviews to be carried out which will examine the scope of the regulations and also a number of the annexes. Article 138 requires a review of the scope to be carried out by June 2012 and provide an assessment on the extent of overlap between REACH and other legislation. Stakeholder consultations closed in December 2010 but until the review is completed it is not possible to say if it will result in the Commission bringing forth more legislative changes. The Commission is also mandated to reviewing the annexes of the regulations and several reviews have been completed or are ongoing [http://ec.europa.eu/environment/chemicals/reach/reviews_en.htm].

In addition to the required reviews there have also been a number of amendments to the regulations:

- EC 1354/2007 – A new definition of 'phase in' substance has been added to reflect the fact that Bulgaria and Romania did not join the EU until 2007.
- EC 987/2008 – Amendments to Annexes IV and V.
- EC 134/2009 – Amendments to Annex XI.
- EC 552/2009 – Amendments to Annex XVII.

2.11 Summary

This chapter has looked at the EU Directives on WEEE and RoHS and also the REACH regulations which are three key pieces of legislation relating to both EEE and WEEE. Owing to differing interpretations arising from the legislation and also differences in technological advancement across the EU, widely varying implementation practices have emerged between member states. On the whole, collection rates of WEEE have been poor and enforcement powers have had little impact. To address these problems the legislation has been reviewed and/or recast to make it simpler and better defined. A key theme of the revised legislation is that much more responsibility is put on producers to deal more effectively with the waste and products they produce. The waste hierarchy has been extended and prioritorised as prevention, reuse, recycle, recovery and, as a last resort, disposal of waste. Producers are tasked with extensive reporting and monitoring procedures to demonstrate compliance with the regulation and new collection targets will be implemented based on individual member states' ability rather than to a set amount per head of population as under previous rules. A number of future reviews of the recast legislation are set in place and it is likely that there will be further amendments coming on stream in the next five years, in particular with regards to the position of photovoltaic cells.

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3
The present recast of the WEEE Directive

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Abstract: This chapter primarily describes the drivers which have led to the current waste electrical and electronic equipment (WEEE) recast process. These range from more scientific and technical insight into take-back and treatment systems, and increased environmental ambition of stakeholders, to difficulties in implementation due to operational complexities. Also different interpretations of the Directive by member states and the large variety of products to be considered have added to the necessity of a recast. The present situation in this respect is analysed in three study reports commissioned by the European Commission; a summary of their recommendations and policy options is given in this chapter. In its present proposals for the recast of WEEE, the European Commission has only partly followed up on these. Amendments in the first reading by the European Parliament will bring several enhancements but simultaneously often do not bring more eco-efficiency. At the time of writing, it remains to be seen what the final outcome will be. Apart from continuation of the present process, there are also signals that a much more radical overhaul is being considered.

Key words: WEEE Directive, recycling.

3.1 Introduction

Recasting means literally that something is being brought into a new form. This means that the basics on which the Waste Electrical and Electronic Equipment (WEEE) Directive is based are there to stay, whereas the way take-back and treatment systems are to be organized and implemented is subject to change.

One might wonder why so soon after its introduction a recast of WEEE is necessary. The reason for this is that the essential parts of the Directive were written in 1996 and hence the political process to get it approved took almost ten years. In fact the Directive was out-dated or at least old-fashioned from the very beginning. At that moment there was a focus on control of toxics in e-waste by means of smart design for recycling and manual disassembly. In later versions material recycling was brought in more explicitly but the language of the Directive remained unbalanced.

In the meanwhile, practical experiences as well as scientific research showed that the WEEE Directive could and should serve multiple and broader environmental goals, not only waste reduction and toxic control but in particular saving resources. A significant development towards this end was that effective shredding and separation technologies were developed. Recovery of valuable materials (prevention of new material extraction) and energy preservation were shown to be of primary importance for the environmental success of the WEEE Directive. Such developments have meant that in one decade thought patterns about electronic waste have substantially changed. This is summarized in Table 3.1, in which the chief elements of the WEEE Directive have been addressed. It can be concluded from this Table that in all respects 'times have really changed'. For instance, weight based recycling targets, a single collection target of 4 kg per inhabitant and an origin-oriented categorization of products are no longer adequate.

Moreover the framework for transposition of the Directive was rather simple – it was left to the EU member states because the WEEE Directive had a '175 character' which means that its requirements are minimum ones and individual member states have the option to formulate additional ones. Practice showed that governments and the various other stakeholders involved in the member states had substantial difficulties in agreeing on implementation. The 175 character opened in practice the avenue for 27 completely different compromises on transposition.

Also the financial issues were dealt with in different ways. The core item is here that for some categories there is a structural deficit in recycling costs which cannot be phased out by smart design. Reducing these deficits

Table 3.1 Trends in approaches to managing electric waste (1996–2006) (Source: UNU *et al.*, 2007)

Item	1996 status/focus	2006 status/focus
Starting point	Solve waste issue	Optimize waste management and save resources
Principle	Producer as main responsible party should get things started	Chain optimization is a matter of responsibility of all stakeholders
Scope	'Origin based' product categories	'Destination based' waste treatment categories
Environmental issue	Waste prevention and toxicity control	Toxicity, resource efficiency, energy preservation, health and safety
Economic issue	Design for recycling will reduce recycling costs	Maximize environmental performance as cost efficient as possible
Technology	Manual disassembly is the way to remove hazardous substance and make purer fractions	Shredding and separation has become more effective, toxic control depends much more on destinations of fractions

by achieving economies of scale (for instance by collective take-back and treatment) and asking fees from consumers at purchase clearly conflicts with the principles of individual producer responsibility and cost internalization (at producers). Financial issues are also linked to a variety of issues; reimbursement of municipalities taking part in collection, free riders and (il)legal exports to third world countries. In practice, the EU member states show a big variety in the way these issues are addressed.

In general it can be concluded that the environmental, technical, organizational and financial complexity of implementation of a WEEE Directive has been underestimated. The very goal of the European Union is to come to common approaches. Member states tend to the opposite due to differences in their industrial, socioeconomic and political structures. The WEEE recast should therefore better balance principles and practice, environment and economy and maximize communality and allow differentiation where necessary. This process has not come to an end yet. The sections below sketch the situation as of May 2011.

3.2 Review studies proposing options for the recast of the WEEE Directive

3.2.1 Overview

In order to generate an overview of options for the recast of the WEEE Directive the DG Environment of European Commission has contracted two review studies. One focuses on the producer responsibilities and has the title ‘The Producer Responsibility Principle of Directive 2002/96/EC on Waste of Electrical and Electronic Equipment’. The study contract 07010401/2006/449269/MAR/G4 has resulted in a report of 285 pages which has been made public through http://www.ec.europa.eu/environment/waste/weee/pdf/final_rep_okopol.pdf. The contractors are Ökopol GmBH in Germany, the International Institute for Industrial Environmental Economics at Lund University, Sweden and Risk&Policy Analysts of the UK.

The second study considers a review of six items of the Directive: its scope, the collection targets, the recycling targets, targets for reuse and the treatment requirements in particular the Annex II Requirements. Under study contract 07010401/2006/442493/ETU/G4 a 345 page report has been published supported by 265 pages of Annexes. This publication is on the website http://ec.europa.eu/environment/waste/weee/pdf/final_rep_unu.pdf. The United Nations University in Bonn, Germany has been the chief contractor, supported by AEA Technology, Didcot (UK), Gaiker, Bilbao (Spain), the Regional Environmental Centre for Central and Eastern Europe in Szentendre (Hungary), and the Design for Sustainability Lab of Delft University (the Netherlands).

On top of the two studies, DG Industry of the European Union has commissioned a 230 page report on the effects of implementation of the WEEE and the RoHS Directive in industry. The study has been carried out by Arcadis Ecolas from Belgium and Risk&Policy Analysts of the UK under contract number 30-CE-0095296/00-09. It is available from http://ec.europa.eu/environment/waste/weee/pdf/rpa_study.pdf. The report on one hand makes recommendations, while on the other hand it consults stakeholders in particular individual producers and their industry associations about their opinions.

3.2.2 The report about producer responsibility for WEEE

The core of this report by Ökopol *et al.* (2007) is a well-documented overview on how the producer responsibility principle as embedded in WEEE has been implemented in the 27 member states of the EU. This overview makes clear that there is a broad variety of implementation practices pointing to sometimes quite opposing interpretations of the WEEE Directive.

An obvious conclusion is therefore that practices in the member states should be brought more in line. The report discusses extensively pros and cons of directions to go as regards for instance more or less individual responsibility of producers, financing mechanisms, registration systems, definitions (producers/sellers, consumer items/business to business items but also for weight and percentage recycled), reporting obligations (who does what, frequency). However, in most cases the preferred direction cannot be selected because there is insufficient quantitative environmental and/or economic evidence of what is best.

The conclusion is therefore that the producer responsibility principle has in practice given insufficient guidance to come to harmonized implementation of the WEEE Directive. A top-down approach to achieve this will most likely be very sensitive. The author of this chapter therefore sees strengthening of the role of Technical Adaptation Committee as one of the preferred options. This Committee has representatives of all member states and has so far addressed a number of technical issues as regards implementation of the Directive. Extending its scope to administrative and even financial matters seems to be justified by the large disparities among member states as specified below (data taken from the producer responsibility report, the figures refer to the number of member states taking a certain position):

- Definition of who is considered to be a producer: 21 definitions on a national level, 3 on a European level, 3 ambiguous definitions.
- Distance sellers registration: 7 member states, in country of seller; 5 in country of customer; 5 mixed system; 5 unclear.
- Responsibility for collection: 4 member states, Distributor/Municipality

and Producer; 7 Distributor and Municipality; 6 Producer; 6 Distributor and Producer; 3 Municipality; 1 Distributor.

- Responsible for treatment: in 26 member states the producer, in one member state this responsibility has not been assigned.
- Fees from consumers permitted: in 24 member states, allowed (of which in 3 member states, mandatory and in 10 cases not applied in practice).
- Guarantees: in 10 cases collective schemes exempted, in 10 member states, collective schemes not exempted, in 7 member states only to be given by individual companies.
- Financing mechanism: 9 member states obligation to finance own waste; 16, pay based on current market share.
- Information to consumer: big variety in obligations.
- Registration: 15 member states, can be done by (collective) compliance schemes; 12 member states, individual producers/sellers only.
- Registration fees: big variety of tariffs.
- Reporting: big variety (monthly, quarterly, yearly).
- Business to consumers versus business to business: three chief approaches – (basically) self-declaration, definition by member states what categories are considered to be B2C and B2B (respectively) or compliance scheme declares.
- Registration and clearing house: in 5 member states both are privately run; in 3 member states, register is publicly run, clearing house is private; 13 member states, register is public, no clearing house; 3 member states, register is private, no clearing house; 4 member states, no register.
- Big variety in formats for reporting, certification of (accepted) recyclers, rules and control for export and appliance lists (what belongs to what categories).
- Monitoring of compliance of depollution (Annex II): big variety.

Although the Producer Responsibility Report spends the vast majority of its pages on the harmonization issues as specified above, it rightly concludes that with the recast of the WEEE more intrinsic issues are (or should be) at stake:

- Promoting design for recyclability.
- Increasing the amounts of waste collected and treated.
- Achieving economies of scale so that costs can be decreased.
- Better dealing with free riders and orphan products.
- Creating incentives for producers and other operators for better performance.

3.2.3 An overview of the WEEE Review Report

The core of this report (UNU *et al.*, 2007) is formed by an extensive set of data which has been collected per member state and per product category

– some categories have even been subdivided. Larger household appliances have been split into three (washing machines, etc., cooling and freezing, smaller items).

The IT and telecoms category has been split as well: cathode ray tube (CRTs) and liquid crystal display (LCDs) monitors are separate subcategories; all remaining IT/telecom items have been put in a 'general' subcategory. An identical pattern has been followed for consumer electronic products. Here the subcategories are CRT TVs, LCD TVs and all other CE products.

Data collected include amounts of products sold, amounts discarded and amounts (properly) treated. Combined with extensive data sets about environmental impacts, economy (costs), administrative burdens/issues, quantitative analyses can be made of the effects of the policy options proposed. Per item the options are grouped as regards their environmental effectiveness, cost efficiency, social impact, simplification of legal framework and other relevant items.

The general conclusion of the report is that in 2005 on average in the EU only 40% of the large items discarded were properly collected and treated. For medium sized products this percentage was 25%, for appliances with a weight less than 1 kg it was very low. With this performance the requirement to collect 4 kg/per inhabitant is fulfilled. Apparently this is not an ambitious target. Although there are indications that in the years after 2005 these amounts are increasing, there is still substantial room for improvement here. This will result in big environmental improvements both in the domain of recycling (metal and precious metal dominated products) and toxic control (cooling and freezing, LCD monitors).

Simultaneously however the costs of collection and treatment will go up. This leads to the core question about the WEEE Directive: how to create systems in which there is an incentive to collect and treat more – the current systems based on extended producer responsibility tend to have the opposite effect.

Another important (general) conclusion of the report is that now the recycling target as formulated in the Directive has been met, more attention should be paid to the secondary streams resulting from the treatments. However, for the recycling part, current definitions and requirements do not foster going for the highest level of reapplication. This is particularly relevant for secondary glass and plastics. In the Annex II (toxics removal) there is a lack of a proper definition of 'removal'. In fact a wording 'control of toxics' is more appropriate here since 'removal' does not guarantee adequate control. Irrespective of semantics, calculations in the report demonstrate that setting more precise targets would contribute substantially to environmental improvement while keeping costs under control.

As a general conclusion the report advocates realigning the most important provisions of the Directive in such a way that the two chief goals of collecting more and treating better can be achieved more easily. The following areas have been identified:

- Address multi-stakeholders responsibilities, clarify the extended producer responsibility definition (or replace extended producer responsibility by something else).
- Financing mechanisms working out positively on collection and treatment performance.
- Give design for recycling a proper position both as regards life cycle design and the requirements of the Energy-using Product (EuP) (Design) Directive.

Apart from this, it is advocated to make the WEEE Directive a Waste Management Framework. The legal framework and operational standards should be split so that a quicker adaption to changes in technology, market prices and costs and last but not least 'learning by doing' are possible.

3.2.4 The six chief items addressed in the WEEE Review Report

Scope

No major changes in the scope of the Directive are suggested. The options that will have a major positive impact by simplifying the implementation of the directive are:

- Define more clearly what is inside or outside the scope of the Directive, for instance by making detailed product lists. This would mean that a large number of small products for which there is little environmental potential could be excluded.
- Make no distinction between WEEE from consumers and business (last named category only forms 6% of the total amount) and between 'historic' and future waste. These simplifications will require changes in the financing mechanisms but these will have to be addressed anyway (see 'Collection').
- Change the categorization of the waste streams from being application oriented (the current 10 categories) to one which corresponds to collection and treatment.

Collection

The report shows evidence that increasing collection is the major way to increase the environmental effectiveness of the Directive. Currently, amounts are increasing at a pace which is not good enough to make a major step forward. All major avenues to achieve this will require that the cost problem associated with more collection (and treatment) will be solved:

- Getting more back from consumers will most likely imply that return premiums have to be offered.
- Preventing collection intermediaries like municipalities from selling WEEE with positive value to third parties will require that they get more reimbursement for their services.
- Reducing (il)legal export of WEEE not only requires more controls in, for instance, harbours but could also imply that recycling organizations in Europe will have to compete more actively in (informal) WEEE markets.

Recycling

The report shows that current treatment of WEEE is satisfactory when assessed by the requirements of the Directive. Nevertheless there is environmental potential in the domain. Chief options include referral to the best available technologies both as regards treatment itself and as regards upgrading of secondary material streams. Most options mentioned in the report refer to this issue. It is noticed that member states use different definitions about what is considered to be recycled and to be recovered respectively. Depending on whether more 'strict', most 'popular' or 'wider' definitions are used, outcomes will be different. Coming to harmonized definitions will become more relevant when more ambitious recycling targets are in place.

Reuse

The report concludes that there is not enough meaningful data to have a sound basis to propose reuse options for appliances that are discarded as a complete unit. A proposal is to establish a clear set of definitions for the reuse of appliances that are still in their original form. It is further observed that in some product categories much more product reuse takes place. This depends on how the technology cycle of a product compares with its wear and tear (see also Chapter 30). Also the consumer demand for products with greater functionality may play a big role as regards the feasibility of meaningful reuse activities. An option mentioned in the report is to make – on the basis of the considerations above – a list of reusable products/products with reuse potential and to connect targets to be developed to this list.

Treatment requirements (Annex II)

In this field there is a large uncertainty about how the intent of this clause ('to get toxics under control') is to be translated into operational practices.

The report advises establishing a clear definition of the key wording 'to remove' for instance by making official the definition as developed by the Technical Adaptation Committee of the member states.

Equally important is to align Annex II with the Restriction on Hazardous Substances (RoHS) and Batteries Directives and to introduce concentration and system limits for the incoming streams. In this respect it is noted that RoHS exemptions need special attention under WEEE (not only as regards Annex II requirements but possibly also in the form of specific – high – collection targets). Under the other options mentioned, the introduction of concentration and systems limits for outgoing streams is highly environmentally relevant as well.

Differentiation in the rules for implementation of the WEEE Directive

The report contains throughout its sections suggestions to allow more differentiation in the implementation rules of the WEEE Directive. A plea is made to organize collection according to the material composition of the products concerned. Four categories are specifically mentioned: precious metal-dominated products, metal-dominated products, glass-dominated products and plastic-dominated products – the wording 'dominated' is to be understood here as the type of material responsible for the chief environmental effects. When properly treated, precious metal-dominated products show the most positive environmental effect on recycling, followed by metal-dominated products and glass-dominated products. Plastic-dominated products generally show the lowest environmental gains on recycling.

For collection, the present 'one size fits all' target of 4 kg per inhabitant is neither well matched to the amounts of EEE equipment sold in the past and at present in the various member states nor with the amounts actually discarded. Amounts placed in the market in the 2008–2014 period are estimated between 12–14 kg per inhabitant (lowest in Bulgaria) and 27–29 kg (highest in Austria) – generally there is a pretty good correlation between amounts sold and income/head.

Current amounts of WEEE range between 9 kg/head (Bulgaria, Romania) and 21–27 kg/head (Austria, Belgium, Finland, Germany, Ireland, the Netherlands, Sweden and the UK), in all cases well above the current 4 kg/head required (see also 'Collection'). In the current WEEE there is for treatment no link between the environmental relevance of recycling of a product with a certain material composition with importance of control of its toxics (see also 'Recycling').

For reuse there are currently no targets. If such targets were to be introduced differentiation among product categories would add to environmental relevance and economic effectiveness (see also 'Reuse'). For Annex II requirements, the formulation of a proper definition of the core wording 'removal' will be decisive whether suitable differentiation in treatments to control toxics will be allowed or stimulated.

3.2.5 The study on implementation of RoHS and WEEE Directives

On top of the two extensive reports discussed in Sections 3.2.2 and 3.2.3, the WEEE part of the study by Arcadis Ecolas *et al*. (2008) has little to add. In view of the fact that a limited number of stakeholders have been interviewed, outcomes seem to represent rather a trend than a strongly underpinned conclusion. Observations (not mentioned in the reports of Sections 3.2.2 and 3.2.3) include:

- The WEEE Directive has led to a very marginal increase of R&D in the sustainability field.
- The Directive is also felt as a weak driver for EcoDesign.
- Producers consider customer requirements as the primary drivers for their environmental activities. In the field of legal requirements, the RoHS Directive ranks first, followed by WEEE.
- Most producers (there are, however, noted exceptions) see collective schemes as the best approach to limit efforts and cost to comply with the directives.
- There is widespread fear that concentration of operators in the recycling sector will lead to quasi-monopolization of the market.
- Free riders are thought to form 5–10% of the volume in the B2C category and 10–15% in the B2B category.
- Among producers there are many complaints with the implementation of WEEE.

3.3 The current proposals for the recast of WEEE

The proposals of the European Commission for the recast of WEEE so far do not entail big changes in the structure of the directive; although the EuP Directive is now in place, the WEEE Directive has not been transformed into a waste directive only, paragraphs about design stay in place.

Also no more detailed guidance is given to how the principle of extended and/or individual producer responsibility has to be put into practice. As regards environmental performance there is a new clear ambition: the collection target is increased to 65% of the products put on the market (to be achieved in 2016). This is an increase by a factor of of 2 for a few member states but a factor of 3–4 for most of them. The positive effect for the environment will be enormous: in this respect the slight increase in recycling targets which is in the proposals has a much more limited effect (in the present Directive the recycling targets are pretty ambitious already).

Furthermore, the proposals stick to the ‘not-to-landfill’ character of the directive, also the proposals from the studies for more differentiation (recycling or toxic control focus, collection and treatment requirements more tailored to the material composition of products) generally have not been followed.

The Annex II (considering removal of toxics) has not been changed. This is remarkable because the member states have agreed on a definition of ‘removal’ which is very practical.

The Commission comes up with very few suggestions for administrative simplification or about stimulating standardization of operational procedures among member states. Combined with the absence of a financial system which will encourage more collection and better treatment, this means that in the opinion of the author, the implementation difficulties today are here to stay. In view of the much higher collection rates which will have to be realized in the future, it might even be that the problems will increase, also because fees paid by consumers will no longer be allowed after 2011.

In the first reading of the Commission proposals, the European Parliament (EP) has formulated a lot of amendments aiming at more harmonization and standardization across the EU. As regards responsibility including financial responsibility there is a strong focus on the producers who have to pay all costs including collection and transportation. Other stakeholders (municipalities, retailers) are obliged to hand in collected waste in the systems set up by the producers. For the scope of the Directive, the Parliament asks the Commission whether solar cells should be included – this would fit into the request of the EP that recuperation of strategic materials should be included as one of the goals of the WEEE Directive.

In the field of collection, the EP wants to link an ambitious target to WEEE discarded rather than to EEE sold (85% of WEEE discarded). In terms of kg/head this is slightly more than the Commission’s idea (in relation to EEE placed on market) and the closer link with actual waste streams is likely to make the WEEE discarded option the most relevant. A new element is that special attention, including a separate target, is requested for the collection of products in which the amounts of toxic substances are environmentally dominant (freezers, mercury lamps). Also, the amendment to forbid any landfill of WEEE is to be placed in this context. Limiting exports of WEEE to products which have certified reuse potential has the intent to increase the amounts collected inside the EU as well (and to prevent informal recycling elsewhere).

Recycling targets have been amended to be slightly higher than the proposal of the Commission. Moreover a target for reuse has been introduced (5%). Other amendments consider guarantees, treatment of products containing nanomaterials, the position of smaller and medium sized enterprises (SMEs) and information/data collection requirements. At the time of writing, the discussion between the Commission and the Parliament is still going on;

a session for a second reading in the EP has been planned for October or November 2011 but will possibly move to a later date. In the meanwhile, there has been strong criticism of the proposals, in particular by industry, which sees a lot of operational and financial problems in the future. It could be that a much more radical overhaul of the WEEE Directive is being considered. Whether this will lead to tangible proposals remains to be seen.

3.4 Further developments (July–September 2011)

After the initial writing of this chapter in May to June 2011, further developments in the field of the recast of the WEEE Directive have taken place. The report supporting the second reading of the Commission proposals in the European Parliament has been published. Also the Council of Environmental Ministers of the Member States – this Council has to support a recast Directive as well – has published its views. In the meanwhile, the Commission itself has not yet come up with a set of revised proposals.

In the report for the second reading, the spirit of the amendments of the first reading (80 in total) has been emphasized further:

- Open scope (categories, no product lists); however, six categories instead of ten, closer to current collection practice.
- European approach for registration, administration (including administration fees) and reporting.
- Collection targets to be based on 85% of WEEE generated.
- Responsibility expanded to all actors in particular to ensure ambitious collection rates. More collection responsibility for trade (not just ‘one for one’ collection).
- Possibility to ask fees for WEEE treatment from consumers completely excluded.
- Provision that collective schemes should charge differentiated fees from producers based on how easily products can be dismantled and how easily ‘critical’ new materials can be recycled.
- Reuse targets to be included in recycling and recovery targets.

On the other hand, the views of the Council of Environmental Ministers of the member states go in an opposite direction:

- Scope allowed to be more specific (not completely open).
- National approach for registration, administration (and administration fees) and reporting.
- Collection targets to be based on 65% of EEE currently sold in the market.
- Member states have the freedom to allow fees to be charged to consumers for WEEE take-back and treatment.

- ‘Minimum’ standards and requirements. Individual member states allowed to make detailed/ambitious rules.
- Reuse issues clearly separated from recycling and recovery targets.

Revised proposals from the European Commission are not available yet, however publication is said to be close from now. In view of the quite opposing views of the Parliament and the Council, it is expected that the reconciliation process to come to one recast Directive will be cumbersome. It will be the task of the Danish presidency (first half of 2012) to deal with this process. If it has to continue in the second half of 2012, the Cypriotic presidency has to guide the process further. When necessary, the Irish have to take over in the first half of 2013.

3.5 Conclusions

The analysis in this chapter of the implementation of the current WEEE Directive in the member states shows that there is an urgent need for a recast. This conclusion refers both to a more clear and harmonized attribution of technical and financial responsibilities as well as a higher environmental ambition as regards collection/recycling and toxic control. The latter will require more differentiation among product groups.

The current proposals by the European Commission only very partially fulfil these needs. The amendments in the first reading by the European Parliament will bring – if accepted by the Commission – several enhancements but simultaneously often do not bring more eco-efficiency of take-back and treatment systems. The second reading proposals do not essentially change this situation.

The Council of Environmental Ministers of the member states has – in the meanwhile – published its views: a number of them are quite opposed to those of the Parliament. So far it is not known where the European Commission will position itself between these proposals. It is expected, however, that a quite complicated and lengthy reconciliation process to come to an agreed recast WEEE Directive lies ahead.

3.6 References

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4 The WEEE Forum and the WEEELABEX project

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Abstract: The chapter explains the essentials of the WEEELABEX project which is laying down a set of European standards with respect to the collection, sorting, storage, transportation, preparation for re-use, treatment, processing and disposal of all kinds of WEEE, and, additionally, a harmonised set of rules and procedures that will provide for conformity verification. The chapter begins by explaining what the WEEE Forum is and what its main activities are. It then reviews the context of WEEELABEX, including its ambition, key deliverables, why it is unique and the project's business economics. It concludes by focusing on the project's two main phases (standardisation and conformity verification).

Key words: WEEELABEX, WEEE, producer responsibility organisations, WEEE system, standards, normative requirements, conformity verification, audit, operators, directive, label.

4.1 Introduction

In August 2008, the European Community awarded funding under its LIFE programme to a WEEE Forum project (LIFE07 ENV/B/000041[1]) that aspires to take WEEE management in Europe to the next level by laying down, on the one hand, a set of European standards with respect to the collection, sorting, storage, transportation, preparation for re-use, treatment and disposal of all kinds of WEEE, and, on the other hand, a set of rules and procedures that will guarantee harmonised conformity verification. The project is expected to be concluded by 31 December 2012. Its key deliverables are uniform conformity verification procedures related to monitoring and auditing, standards (including technical requirements and documentation, and reporting obligations), the 'auditor's toolbox', i.e. manuals, checklists and audit forms, a pool of auditors familiar with WEEE processing technologies and trained to perform audits corresponding to the standard, a WEEELABEX Office and a visual identifier to identify physical operations that conform with the standards.

4.2 What is the WEEE Forum?

4.2.1 Mission of the WEEE Forum

The WEEE Forum (www.weee-forum.org) is a European non-profit association speaking for 39 electrical and electronic equipment waste (WEEE) collection and recovery organisations – alternatively referred to as 'producer responsibility organisations' (PRO) and 'WEEE systems') – all of them run on behalf of producers. It was set up in the early 2000s. The 39 PROs are based in Austria, Belgium, Czech Republic, Denmark, Italy, Germany, Greece, France, Hungary, Ireland, Lithuania, the Netherlands, Norway, Portugal, Poland, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom. It is the largest organisation of its kind in the world.

WEEE Forum members in 2010 were: Amb3E, Appliances Recycling, Asekol, Eco-asimelec, Ecodom, Ecofimatica, Ecolec, Ecologic, Ecoped, Eco-RAEE's, ecoR'it, Eco-systèmes, Ecotic, Eco Tic, EEPA, ElectroCoord, ElektroEko, Elektrowin, El-Kretsen, elretur, el retur, Envidom, ICT Milieu, Lightcycle, Lumicom, RAEcycle, Recupel, Re.Media, Repic, Retela, RoRec, SENS, SEWA, SLRS, SWICO, UFH, Wecycle, WEEE Ireland and Zeos.

The WEEE Forum's mission is to provide those WEEE systems a platform for cooperation, the exchange of experiences as well as a set of standards and benchmarking tools (see Section 4.2.2), which in turn results in optimisation of the effectiveness of their operations and in a continual search for excellence and improvement in environmental performance. 'WEEELABEX' is the WEEE Forum's most important standardisation project, both in terms of financial resources and scope, since its inception.

Based on the growing body of know-how, the WEEE Forum also seeks to be a centre of competence that allows member organisations to make constructive contributions to the general debate on electrical and electronic waste policy matters. The association assists its members in the development of their activities in a sustainable manner within the existing regulatory and legislative framework.

4.2.2 The WEEE Forum key figures benchmarking tool

In the past few years, the WEEE Forum developed a set of 'key figures' (KF) and a web-based KF tool that allow its member organisations to benchmark their operations with their peers. Each year the membership of the association submits quantitative data describing the tonnages of electrical and electronic equipment that the producers, associated in those organisations, put on the market, the quantities of WEEE that the member organisations collected, and the costs related to WEEE system management. All data are collected confidentially through a secure web-based application and all overviews are generated anonymously. Each WEEE Forum member can use the KF tool to generate overviews of the data range that it is interested in. The data is statistically analysed, averages are calculated and minimum/maximum ranges are provided to external interested parties. In 2010, the 38 member organisations properly collected and secured proper treatment of a total of more than 2 million tonnes (Mt) of WEEE.

Considering the huge potential environmental impact of some types of WEEE – for example of cooling equipment containing ozone-depleting substances and/or global warming gases (CFC, HCFC or HFC) – or the presence of critical raw materials – for example, though not exclusively, in categories 3 (consumer electronics) and 4 (information and communication technologies (ICT)) – it is important to ensure proper collection of those categories. In 2009, organisations representing a large majority of the WEEE Forum properly collected and secured proper treatment for more than 350 000 tonnes of cooling equipment (approximately 7.8 million units) which amounts to more than 10 Mt of CO_2. This is the equivalent of 50 bn kilometres, driven by an average car (over a distance of 10 000 kilometres, one car releases around 2 tonnes of CO_2 on average, meaning that through the environmentally sound recycling of a single refrigerator up to 2 tonnes of CO_2 can be saved). They collected almost 95 000 tonnes of small household appliances, more than 310 000 tonnes of consumer electronics and ICT equipment, and more than 13 000 tonnes of lamps. For more information on the WEEE Forum's 'key figures benchmarking tool' see http://www.weee-forum.org/services/quantitative-key-figures.

4.3 Context of WEEELABEX

4.3.1 Birth of a project

Despite a large array of European laws, primarily directives, developed since the early 1970s and aimed at harmonisation of national legislation, environmental policy in Europe is to a very large extent in the hands of member states. Solutions to environmental problems typically arise at national level. Austria, Belgium, the Netherlands, Norway, Sweden and Switzerland were among the first jurisdictions, in Europe as well as globally, to develop producer responsibility legislation addressing the growing mountain of electrical and electronic waste. As a direct result of these bodies of legislation, producers established, at national level, 'WEEE systems', i.e. organisations that took on WEEE collection and management responsibility on behalf of producers. As time went by, and starting in earnest with the entry into force of Directive 2002/96/EC on WEEE[2] (hereinafter referred to as 'the Directive') in February 2003, WEEE compliance schemes – the generic term for organisations that provide compliance with the Directive and are not all run on behalf of a collective grouping of producers – were set up in all 27 member states. Consequently, before long, Europe ended up with about 150 compliance schemes. As they were being set up, each PRO in the WEEE Forum developed its own set of 'normative requirements' in its contracts with operators, notably logistics companies and electronic waste processors. Each of them required their business partners to meet certain pre-determined technical specifications and levels of compliance, both based on national (or sub-national) legal requirements and arising from business needs. Needless to say, operators in Europe ended up facing a patchwork of different (types of) requirements from a huge range of compliance schemes.

It did not take long for the PROs of the WEEE Forum to realise that it would make sense, both for themselves and for processors and producers, to harmonise these requirements. In the second half of the 2000s, the WEEE Forum started to develop standards for the proper collection and management of cooling equipment containing ozone-depleting substances and/or global warming gases (CFC, HCFC or HFC) and later, in collaboration with CECED (the association in Europe of household appliance makers) and EERA (the European electronics recyclers association) of standards related to cooling equipment containing hydrocarbons (HC).

In 2007, PROs in the WEEE Forum made the suggestion of harmonising contractual requirements for all 10 WEEE categories. A project plan was developed and submitted with the European Commission under the LIFE programme, a European Union financing instrument that promotes, among other things, environmental governance. The multi-annual project was dubbed 'WEEELABEX' (short for 'WEEE LABel of EXcellence').[3] On 28 July 2008, the LIFE committee, an EU body composed of representatives of the member states and of the European Commission, approved the plan. The cost of the project is estimated at €1 064 600. The EU has agreed to finance 50% of the total eligible budget. After five months of pre-project preparations, the project took a swift start on 1 January 2009. EU financing of the project is supposed to end on 31 December 2012.

Various working groups were created, and stakeholders from the producers and processors community were involved in their activities. Early 2010, CECED, DIGITALEUROPE (ICT and consumer electronics makers in Europe), ELC (the European Lamp Companies federation), and EERA took a seat in the project's steering group.

4.3.2 Ambition of WEEELABEX

The WEEELABEX project aims to design, on the one hand, a set of European standards (or 'normative requirements') with respect to the collection, sorting, storage, transportation, preparation for re-use, treatment and disposal of all kinds of WEEE, and, on the other hand, a set of rules and procedures that will guarantee harmonised conformity verification. The project affects all parties with whom the PROs of the WEEE Forum have contractual relationships, essentially logistics companies and electronic waste processing firms. Compliance with the WEEELABEX set of normative requirements obviously does not infer immunity from legal obligations. The standards are not intended to create trade barriers.

The WEEELABEX standards and the harmonised conformity verification scheme will make environmental performance more transparent and will level the playing field. It will create incentives for operators to meet high standards, and disincentives for dishonest companies to dodge 'the system'. Operators that have not been 'WEEELABEX approved' due to failure to comply with the standards will be subject to easier scrutiny by the authorities. WEEELABEX standards, as opposed to the legislative requirement laid down in Annex II of the Directive, allow for a more flexible toolbox; laws and decrees are too inflexible as tools to address this constantly changing landscape.

In August 2009, the WEEE Forum signed a contract of cooperation with CENELEC, one of the three official EU standards bodies. In time, the standards may be turned into formal EN standards or alternative deliverables, i.e. standards that confer a set of rules for all operators on the market to comply with the Directive.

4.3.3 The scope of WEEELABEX

Globally, and in Europe in particular, there exist many different types of standards, certification programmes, markings, labels and so forth. In order to avoid misunderstandings, a clarification about the project's scope is therefore due.

- The project concerns all steps in the product and material flow, including collection and preparation for re-use.
- The requirements related to collection activities are supposed to be implemented, to the extent that they can be contractually enforced, by all the WEEE systems of the WEEE Forum and those who have contracted to do so. They will be designed to encourage collection points to play their important role in the WEEE stream.
- Operators processing WEEE that are subject to the standard will ultimately undergo conformity verification and audits.
- The requirements laid down in the standard are minimum requirements. WEEE systems are entitled to stipulate requirements that go beyond the standards' requirements if they are environmentally more ambitious.
- Only sites of operators – as opposed to companies or legal entities as such – will be identified as being 'WEEELABEX approved'.
- Operators will have to be in a position to assess conformity of their

activities with the standards and to demonstrate that they have contracted with WEEELABEX (or WEEELABEX-equivalent) partners.

- Auditors performing audits in view of conformity verification will be trained in accordance with the standard and will join a pool of auditors.
- The project can be considered of an open nature in the sense that any organisation that accepts the rules of governance of WEEELABEX and its constituent obligations can join the scheme.
- The standards are expected to be, at least, acknowledged by the various administrative bodies in Europe in charge of implementation and enforcement of the provisions in the Directive transposed in national (and sub-national) regulation. The member states will be called on to integrate them into their permitting policy.

4.3.4 The WEEELABEX deliverables

By the end of 2012, the project will have produced, among other things:

- A set of governance rules specifying terms and conditions for organisations to join the WEEELABEX community.
- Standards or 'normative requirements', including technical requirements and documentation and reporting obligations.
- Uniform conformity verification procedures related to monitoring and auditing, and the sanction and cancellation procedures.
- The 'auditor's toolbox', i.e. manuals, checklists and audit forms.
- A pool of auditors, familiar with WEEE processing technologies, trained to perform audits corresponding to the standard.
- A referencing item of some sort to identify physical operations that are in conformity with the standards.

4.3.5 WEEELABEX breaks new ground

One legitimate and obvious question is to what extent WEEELABEX breaks new ground, i.e. in what terms the project is novel and adds value to the WEEE market.

- For the first time ever, a uniform set of normative requirements affecting all parties involved in WEEE operations and covering all 10 WEEE categories, i.e. the legal scope of the Directive, is laid down, and will be implemented by parties that represent approximately two-thirds of officially reported WEEE collection in Europe and are in a position to do so. In other words, it is not an academic, descriptive or partial exercise; it will have – and is already having – an immediate and significant impact on the entire WEEE chain, from collection to disposal.

- The set of standards is not only likely to be acknowledged by authorities but will probably resonate globally as well. Operators in other parts of the world will likely wish to adhere to the same set of principles.
- The project started off to produce requirements to be integrated into contracts of WEEE systems with operators. Yet (some of) those requirements will end up becoming formal EN standards, affecting all operators on the market, not just those with whom the PROs of the WEEE Forum have entered contractual terms.
- At the time of writing, the current Directive is being recast. The future recast Directive might introduce the specific and legally defined concept of 'harmonised standards', produced by one of the three standards bodies who are mandated to do so. Those harmonised standards are expected to result from the WEEELABEX set of standards. In the event the future recast Directive lays down the principle of harmonised standards, it will likely affect the project and conformity verification schemes. Operators may decide to follow those harmonised standards in order to acquire presumption of conformity with the provisions in the Directive and they may unilaterally declare conformity with the harmonised standards.
- The WEEELABEX requirements are not systematically going beyond the Directive's provisions in environmental terms. Yet WEEELABEX expects parties to be in a position to monitor downstream operations and lays down uniform, specific and comprehensive reporting and documentation obligations, most of which are not, as such, legally required. The reporting will follow the principles and reporting format provided by WF_RepTool, the WEEE Forum's web-based tool that allows operators to calculate in a consistent manner and to communicate recycling and recovery quotas to WEEE systems.
- Also for the first time ever, a European scheme is being constructed that harmonises the rules for the verification of conformity with the normative requirements. The scheme is of a private and *sui generis* nature, i.e. it will affect the WEEE Forum and other contracting parties, yet is expected to demonstrate how European rules can be enforced in a harmonised manner.

4.3.6 The business economics of WEEELABEX

The WEEELABEX project would not be worth the trouble if the business model were shaky or no financial or commercial return on investment were expected. The best environmental projects are those that marry environmental values with genuine commercial principles.

It goes without saying that costs are involved in setting up and running a European scheme of this nature and scope. However, overall costs are expected to be outweighed by benefits. Costs that have typically been borne by WEEE systems will shift to the newly set-up WEEELABEX entity, but due to economies of scale, those costs are expected to be, on the whole, less significant than the individual costs of all WEEE systems taken together.

The benefits for WEEE systems:

- lower costs related to audits (batches, audits, analyses...);
- no direct costs related to update of standards;
- better quality of operations;
- clearer benchmarks;
- quality mark to WEEE systems and hence to affiliated producers.

On the cost side for WEEE systems:

- investments to be in compliance with the normative requirements;
- reporting and monitoring requirements.

The benefits for WEEELABEX operators:

- lesser administrative burden (harmonised standards and tools);
- time savings for those offering services to various WEEE systems;
- quality mark, improving corporate brand;
- economies of scale.

On the cost side for operators:

- audits (conformity verification) commissioned by the WEEELABEX Office;
- investments to be in conformity with the normative requirements.

The benefits for the WEEELABEX Office:

- monitoring of one set of standards and harmonised tools (rather than many different tools).

On the cost side of the WEEELABEX Office:

- governance, supervision and monitoring, involving analyses, benchmarks, coordination of the verification system, training sessions and workshops with the auditors, limit values...;
- Update of the standards.

4.4 WEEELABEX phase I: standards

The four-year project can be nicely divided into two phases: the first two years focused on the development of standards, while the second, mainly covering 2011–12, is focusing on the uniform set of conformity verification rules. The standards aim to:

- achieve effective and efficient treatment and disposal of all WEEE in order to prevent pollution and minimise emissions;

- promote high level and high quality recovery of secondary raw materials;
- prevent inappropriate disposal of WEEE and fractions thereof;
- ensure protection of human health and safety;
- prevent illegal (cross-boundary) shipments of WEEE and fractions thereof;
- prevent shipments of WEEE and fractions thereof to operators that fail to comply with this standard or an equivalent set of requirements;
- create a level playing field for fair competition of all actors in the WEEE chain.

The standards are based on the objectives of the Community's environment policy which are aimed at preserving, protecting and improving the quality of the environment, protecting human health and utilising natural resources prudently and rationally. That policy is based on the precautionary principle and principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay. The requirements are also based on the presumption that operators adhere to the principle of due diligence with all activities. Due diligence includes understanding of all obligations to which the company is subject and transparency with business partners.

The WEEELABEX standards package structurally consist of three documents, one aimed at operators performing collection of WEEE, one aimed at logistics operators and one on treatment operators.

4.4.1 General normative requirements

The normative document on treatment consists of part I concerning general normative requirements, i.e. pertaining to all types of WEEE, part II concerning specific normative requirements pertaining to specific types of WEEE, and, finally, a set of annexes stipulating de-pollution guidelines and monitoring principles, requirements concerning batches and rules concerning the determination of recycling and recovery quotas.

Part I concerning general normative requirements in the normative document on treatment distinguishes, apart from clauses with provisions concerning scope, definitions and normative references, between administrative and organisational requirements, on the one hand, and technical requirements on the other.

Administrative and organisational requirements:

- legal compliance;
- technical and infrastructural conditions;
- training;
- downstream monitoring;

- preparation for re-use;
- shipments.

Technical requirements:

- handling;
- storage;
- de-pollution;
- de-pollution monitoring;
- further treatment;
- storage of fractions;
- recycling and recovery;
- disposal of fractions;
- documentation.

The other two normative documents, on collection and logistics, contain equivalent provisions as those specified in the document on treatment.

4.4.2 Specific normative requirements

Part II concerning specific normative requirements in the normative document on treatment pertains to specific types of WEEE, in particular appliances containing cathode ray tubes (CRT) (old-fashioned TV sets), flat panel displays (FPD), lamps and cooling equipment. More information can be accessed on the WEEELABEX pages on www.weee-forum.org.

4.4.3 Roll-out of the standards

At its meeting in Amsterdam on 1 April 2011, the General Assembly of the WEEE Forum approved the standards and decided that they will not be subject of modifications for a period of 18 months (until 1 October 2012). In those 18 months, a number of producer responsibility organisations of the WEEE Forum will 'test' (parts of) the standards, they will gather experience on their implementation on the ground by the operators. The know-how will be fed back into the project management. The organisations that commit to be part of this 'vanguard of early adopters' in 2011 and 2012 are: Ecodom and Re.Media (Italy), Ecolec, Ecofimática, EcoAsimelec, Ecotic and Eco-RAEE's (Spain), SENS, SLRS and SWICO (Switzerland), Eco-systèmes (France), Wecycle (The Netherlands), RoRec (Romania), Recupel (Belgium) and Lightcycle (Germany).

By 31 December 2013, PROs in the old member states – essentially Western Europe – must have the standards integrated into their contracts. By 31 December 2014, PROs in the new member states – essentially Central and Eastern Europe – must have the standards integrated into their contracts. All WEEE systems in the WEEE Forum are expected to require the operators with whom they have a contractual relationship to put all requirements in place.

4.5 WEEELABEX phase II: conformity verification

Laying down a set of principles and normative requirements that operators are supposed to meet is one thing, but enforcement and monitoring of implementation of those requirements is another. All monitoring activities fall under the heading of ‘conformity verification’. Even though the project has not yet issued definitive guidance on how the conformity verification architecture will look, the main principles have been agreed on.

4.5.1 WEEELABEX scheme

A ‘WEEELABEX scheme’ will be set up. This scheme (or WEEELABEX Office specifically) will:

- be based on a ‘WEEELABEX charter’ establishing governance rules, principles of reporting and conformity verification, all other types of WEEELABEX guidance material and terms of entry into and exit out of the community;
- lay down and update, at regular intervals, the WEEELABEX standards;
- provide guidance for operators on how to perform internal conformity assessment;
- define limit values and chemical analysis protocols, conduct weighing protocols and de-pollution efficiency measurement methods;
- select WEEELABEX auditors on the basis of defined profiles;
- organise WEEELABEX training sessions and workshops for auditors.

4.5.2 WEEELABEX auditors

Not just anybody will be entitled to verify conformity of operations. Those parties that express an interest in being involved in WEEELABEX conformity verification will be subject to a uniform training programme and to confidentiality and impartiality rules (ISO 17020). They will perform audits of operators with the WEEELABEX standards as spelled out in a harmonised contract. Since conformity verification covers different operational areas, principally environment, management, finance and operations, an auditor may be accompanied by another auditor with a different specialty, competence or focus. Scorecard audits will be performed and reported to the WEEELABEX Office. Inspection could at least partly be performed before tendering takes place.

4.5.3 Operators

The operators are the parties in the WEEE market that will be subject to conformity verification. They will be expected to internally assess and declare contractual conformity with the normative requirements. They will be free to decide to entitle WEEELABEX auditors to disclose conformity verification report. If, for whatever reason, the operator decides not to allow disclosure of the conformity verification report, then they will have to agree to be subject of a new conformity verification. In the event they fail to meet the requirements, they will be expected to implement corrective actions, subsequent to the provisions laid down in the scorecard. The operator is not entitled to refuse or select a WEEELABEX auditor, e.g. for specific types of activities, but has the right to make suggestions and the right of appeal if the operator is deemed to have an unfair attitude.

4.6 Conclusions

Even though the project has not run its course yet and many sub-projects remain under discussion, the key deliverable that is finalised, the WEEELABEX standards, are expected to resonate in the WEEE marketplace, both in Europe and globally. The standards are creating a new ‘benchmark’ for all operators involved in WEEE activities. In addition, a uniform set of conformity verification procedures will be put in place. For more information, see the WEEELABEX pages on www.weee-forum.org, including frequently asked questions.

4.7 References

1. European Community LIFE programme (‘L’Instrument Financier pour l’Environnement’ – financing instrument for the environment) financing the WEEE Forum project (LIFE07 ENV/B/000041).
2. Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE).
3. WEEELABEX pages on www.weee-forum.org, http://www.weee-forum.org/weeelabexproject

5

Conformity assessment of WEEE take-back schemes: the case of Switzerland*

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Abstract: In order to assure conformity with quality requirements of recycling operations and in order to minimize environmental impacts caused by the processing of WEEE, take-back schemes often maintain internal or external conformity assessment bodies. SENS, Swico Recycling and SLRS are three WEEE take-back schemes established in Switzerland in 1992, 1994 and 2005 respectively which have created a conformity assessment strategy based on a common technical standard. This chapter describes the scope of monitoring and auditing, the approach and important elements of this activity. It furthermore outlines reporting requirements, additional aspects and future trends.

Key words: WEEE, e-waste, recycling, conformity assessment, WEEE standard, control, monitoring.

5.1 Introduction

5.1.1 WEEE take-back schemes in Switzerland

Three producer responsibility organizations (PRO) for electrical and electronic equipment, the Swiss Foundation for Waste Management (Sens), the recycling section of the Swiss Association for Information, Communication and Organization Technology (Swico Recycling) and the Swiss Lighting Recycling Foundation (SLRS) are in charge of take-back operations of end-of-life (EoL) electrical and electronic equipment in Switzerland. Sens started operations in 1992 and nowadays pools 700 affiliates. The organization handles waste electrical and electronic equipment (WEEE) categories 1, 2, 6 and 7. Swico Recycling started in 1994 and today has 640 affiliates and is responsible for the WEEE categories 3, 4 and 9. Category 5 is handled by the Swiss Lighting Association which was founded in 2005 in order to set up a system for the recycling of lamps and luminaires. The non-profit activities of the PRO are financed through an advanced recycling fee (ARF) charged on new appliances, which has been introduced progressively for a wide range of electrical and electronic equipment categories. The ARF is added to the sales price of any

*This chapter is based on the experience gained by the group of auditors from Swico Recycling and Sens.

new appliance in order to finance the non-profit part of the current WEEE collection and treatment, so that consumers can return their old appliances to retailers, manufacturers and importers free of charge.

In 2010 Swico Recycling processed 56 600 tonnes of information and communication technology (ICT), consumer electronics and dental equipment. Sens processed 64 900 t of large and small domestic appliances, toys and tools. In addition 3100 t of illuminants were processed by SLRS. With an overall collection quantity of around 125 000 t, Switzerland reaches almost 16 kg per capita, which is among the highest collection rates in Europe. This high rate is mainly due to the high convenience level for returning EoL products by the consumer to the take-back schemes: Swico Recycling maintains around 650 and Sens around 440 collection sites. In addition to the collection sites thousands of retailers are obliged by law to take back EoL products they sell, independent of the brand, free of charge.

All over Switzerland, and in some cases abroad, 30 treatment operators contracted by SENS and Swico Recycling process the collected WEEE. A major share, 70–80% depending on the type of equipment, of the fractions resulting from the different recycling process steps gets recycled. Around 90 manual dismantling centers work under contracts with the treatment operators and dismantle the EoL equipment for either direct end processing or further mechanical processing. Most of the mixed fractions resulting from mechanical processing in the treatment facilities undergo an end processing in specialized facilities outside Switzerland. Printed wiring boards and highly concentrated metal fractions get final processing in specialized precious metal refineries in Europe. Table 5.1 displays the main features of the three take-back schemes.

A recent study on the Swiss take-back schemes for WEEE (Wäger *et al.*,

Table 5.1 Main characteristics of the WEEE take-back schemes in Switzerland

	Year	SENS	Swico Recycling	SLRS
Start of operation		1992	1994	2005
Number of affiliates	2010	700	640	230
Number of recycling partners	2011	21	8	10
Number of manual dismantling centers	2011	58	63	0
Number of collection sites	2010	436	650	436
Number of auditors for conformity assessments	2010	6	4	3
WEEE categories according Directive 2002/96/EC	2010	1/2/6/7	3/4/9	5
WEEE collected	2010	64 900 t/y	56 600 t/y	3100 t/y
	2010	124 600 t/y (15.8 kg/inhabitant/y)		

2011) has shown the clear environmental benefit of recycling compared with incineration in a municipal waste incinerator or landfilling. The main environmental impacts of the take-back scenario come from metal treatment, followed by cathode ray tube (CRT) device treatment and plastics treatment, whereas collection and pre-processing only contribute marginally to the environmental impacts. The highest share of the environmental benefits from a take-back scheme can be achieved with secondary production from battery treatment, metals treatment, cables treatment, and printed wire board (PWB) treatment. The recycling of plastics results in clearly lower total environmental impact compared with incineration and landfilling, similar to the diminution for the metals.

5.1.2 Conformity assessment

Conformity assessments of collection, logistics and treatment operations with regard to specified requirements have been considered paramount from the start of the system operations in 1992. Whereas conformity assessments of the collection sites are realized as second party assessment, the treatment operators get audited by means of a third party assessment.

Swico Recycling has chosen the Swiss Federal Institute for Materials Science and Technology (Empa) as its conformity assessment body. Empa forms part of ETH's domain, which comprises the two federal technical universities, ETH in Zurich and EPFL in Lausanne, and four external research centers, Empa being one of them. Empa provides to Swico Recycling an audit team currently of four auditors and additionally delivers services and research activities in the area of WEEE management to Swico Recycling and other public and private institutions. Sens and SLRS have mandated different service providers which conduct the conformity assessments with six auditors.

The three systems have joined forces in developing, coordinating and implementing the conformity assessment system and have formed a technical committee which holds regular meetings in the course of the year and which reports directly to the management of the respective system. Amendments to the specified requirements need prior consent, whereas the operation of the conformity assessment scheme falls under the responsibility of the respective technical committee.

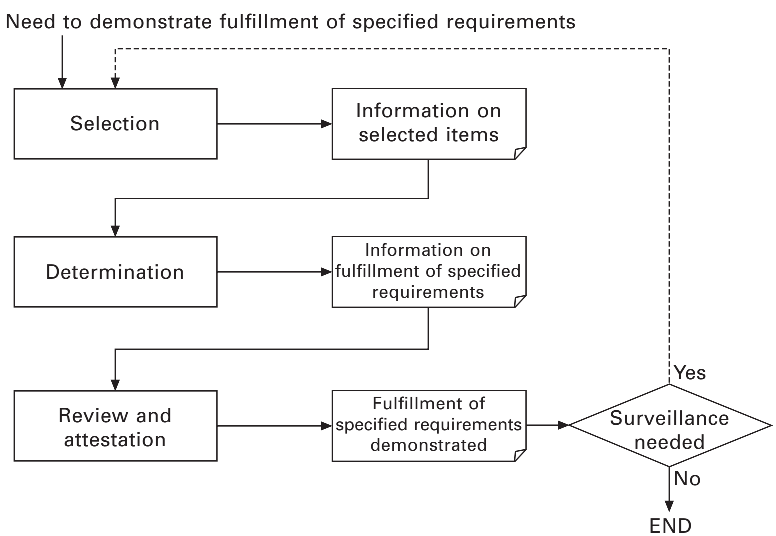
5.1.3 Aims and subject of the conformity assessment of treatment operators

The aim of the conformity assessment is to assess whether a treatment operator adheres to the prescribed quality standards and the environmental aspects of the operation and to determine the performance against prescribed recycling and recovery quotas stipulated for the different WEEE categories. The quality standard is formulated in the 'Technical regulations on the recycling of electrical and electronic appliances from Swico Recycling and SENS' (Sens, Swico Recycling, 2009). The main elements of the conformity assessment are a control of documentation, treatment processes, fraction qualities and legal compliance. Additionally, the material flows which are to be reported by the treatment operators on an annual basis to Empa are verified and evaluated in a material flow accounting system.

5.2 Approach of the conformity assessment

The conformity assessment approach is functional according to ISO 17000 (2004, 2010) covering three different phases (Fig. 5.1). Prior to the on-site conformity assessment it starts with a *selection phase* which includes planning and preparation activities in order to enable the subsequent determination phase. In this phase the assessment is planned and relevant documents are requested from the treatment operator. Reported mass flows and batch results are verified. At this stage, the choice for the most adequate procedures for the determination phase is made. This might include the decision on specific measures or samples to be taken in the course of the determination phase.

The *determination phase* is equal to the on-site audit or inspection. It involves completing the information required to verify if specified requirements formulated in the technical guidelines are met. On-site audits at the treatment operator's installations are scheduled annually, usually for



5.1 Functional approach to conformity assessment (according ISO 17000: 2004).

a duration of one day. They are implemented by a team of two auditors. In almost all cases the visits are preannounced; however, surprise visits take place exceptionally, either when information provided through the operator's own or external sources indicates the existence of deviations from normal business operations, or as a matter of second control when previous audits have revealed relevant non-conformity aspects and corrective measures have been taken by the treatment operator.

The *review and attestation phase* constitutes the verification of all collected information in order to decide whether conformity is met or not. The result of the conformity assessment is reported to the treatment operator in the form of a conformity assessment report (audit protocol). Owing to changes in treatment operations, variation of input streams or changes in administrative or legal requisites full conformity is only exceptionally achieved. In most cases the deviations are of a minor nature. Corrective measures are formulated in the conformity assessment report which the treatment operator has to fulfill and document in a given period of time. If major deviations occur or even non-compliance is concluded in relevant areas of the operation, an additional audit can be required in the course of the same year in order to verify the correct implementation of the corrective measures and the compliance with the specified requirements. If the additional audit continues to reveal non-conformity with the specified requirements, the contract between the take-back scheme and the treatment operator can be ceased or resigned on request of the audit team to the take-back scheme.

The conformity assessment report is handed over to Sens and SLRS, whereas Swico Recycling does not request a full report but only a reporting on non-conformity.

5.3 Scope and elements of the conformity assessment

5.3.1 Technical regulations of Swico Recycling and SENS

The technical regulations (Sens, Swico Recycling, 2009) are stipulated as an integral part of the contract between the take-back scheme and the treatment operator. They have been formulated, harmonized and continuously developed further by the systems in the course of several years of experience in processing WEEE.

The regulations cover the following aspects:

- *General part:* It defines aim and scope and provides the definition of terms used in the regulations.
- *Legal compliance:* This part makes reference to the relevant legal

framework and outlines the way compliance has to be verified and demonstrated by the treatment operator.

- *General rules on treatment:* Principles for data destruction, manual disassembly and mechanical treatment are formulated. WEEE has to be processed separately from other wastes. A prohibition of mixing different fractions with the aim to lower the resulting concentrations of hazardous substances below legally regulated limits (limit values) is stipulated and the disposal path for non-recyclable fractions is prescribed. All combustible fractions have to be incinerated; non-combustible fractions have to be treated prior to landfilling if they do not reach the conditions for landfilling formulated in the national legislation.
- *De-pollution:* The de-pollution procedures encompass the removal of batteries, accumulators, capacitors, plastics, asbestos, radioactive elements and mercury-containing components. Plastics need to be removed and incinerated if they do not comply with limit values set forth in the legislation for new products. Limit values are given for heavy metals (Cd, Cr-VI, Hg, and Pb) and brominated flame retardants (PBB, PBDE) (814.81 Ordinance 2005).
- *Recovery:* Recycling partners have to accomplish the recycling and recovery targets set forth in the WEEE Directive. This is verified with batch tests. Changes in processes which influence recycling and recovery targets have to be reported to the conformity assessment body within one month. In particular cases the fulfillment of recycling and recovery targets can be calculated based on the annually reported mass flow data.
- *Storage, handling and transport:* WEEE has to be stored in non-accessible areas; the storage quantity is limited to 20% of the average annual processed quantity. Equipment, components or fractions which are not detoxified need weatherproof covering unless the treatment operator can prove that the rainwater is properly collected on a sealed surface and that the rainwater runoff is regularly controlled and analyzed. Lamps and other contaminant-containing fractions such as batteries, capacitors, cathode ray tubes (CRT) and their components, flat screens (liquid crystal display, LCD) and their components, printed circuit boards, photoconductor drums, asbestos-containing components, toner cartridges, phosphor powder from lamps and mercury-containing fractions may not be stored outdoors.
- *Documentation:* Documentation requirements comprise the company organization and responsibilities, work instructions and flow charts, materials accounting, proof of material flows and monitoring and checking of de-pollution quality. The material accounting system is a standardized recording of all material flows, and an annual compilation and reporting to the conformity assessment body, taking into account the stocks at the

beginning and the end of the reporting period. Material flows to third parties have to be controlled by the treatment operator who must assure compliance with the technical regulations at all times. The conformity assessment explicitly includes checking downstream flows by means of a standardized format for documenting treatment operations by the downstream vendor. The quality of de-pollution is monitored and checked through key figures derived from the materials accounting, internally calculated key figures, and, in the event of mechanical processing, through chemical analyses of light-weight fractions (dust, shredder light-weight fractions, etc.). An internal monitoring system has to be established which allows monitoring de-pollution performance by the management and a self-control by the employees.

The regulations are complemented by five directives which cover (1) recycling and recovery quota, (2) ICT and consumer electronics equipment, (3) lamps and illuminants, (4) cooling appliances and (5) dental appliances.

5.3.2 Main elements of the on-site audit

The elements and their sequence during the on-site audit are standardized. The workflow can be adapted in case of a specific situation regarding a certain WEEE category, such as flat screens, or regarding the treatment operator's installations, such as new machineries or new processes.

The on-site audit covers operational aspects (organizational chart, training plan, treatment processes and infrastructure), legal compliance (authorizations check, internal processes to verify legal compliance, health and safety), decontamination (benchmarks batteries and condensers), process efficiency (recycling and recovery rates), material accounting and mass flow control (control of records, shipment to and further treatment by downstream vendors), emission and immission control and ends with an on-site inspection of the installations and processes.

5.3.3 Measuring recycling performance

The treatment operators have to fulfill recycling and recovery quotas prescribed in the technical regulations which are verified by the auditors on an annual basis through batch tests. These tests are performed each year determining one of the WEEE streams which is processed by the respective treatment operator. Batch tests are differentiated into small or large household appliances, cooling appliances, IT equipment without screens, screens and consumer electronics. Table 5.2 indicates the recycling and recovery quota to be accomplished.

The calculations of the recycling performance are realized in the standardized reporting tool (Rep-Tool) which has been developed by the WEEE Forum

Table 5.2 Recycling and recovery quota according to Swico, Sens (2009)

WEEE Directive category	Appliance category	Recycling quota (%)	Recovery quota (%)
1	Large household appliances incl. refrigeration appliances	75	80
2	Small household appliances	50	70
3	IT and telecommunication equipment	65	75
4	Consumer electronics	65	75
5a	Luminaires, light fittings	50	70
5b	Lamps, gas discharge lamps	80	80
6	Electrical tools, building, garden and hobby appliances	50	70
7	Toys, as well as sporting and recreational appliances	50	70
8	Medical equipment	No information	No information
9	Monitoring and controlling instruments	50	70
10	Automatic output appliances	75	80

on a pan-European level. The Swiss version has been slightly adapted as regards to the allocation of the different recycling technologies to material recycling, energy recovery, thermal disposal, landfill disposal or re-use. The Rep-Tool allows the calculation of the processed WEEE stream including all downstream operations undertaken by downstream operators. In the case of non-conformity the treatment operator has to adapt the process technology and/or change downstream operators.

5.3.4 De-pollution control

The de-pollution control follows a double approach. As a first step benchmarks for the removal of batteries and capacitors have to be monitored and reported by the treatment operators, which are then verified as part of the conformity assessment with the help of the material accounting tool (see Sections 5.3.5). As a second step for mechanical treatment processes limit values for Cd (100 mg/kg), PCB (50 mg/kg; PCB-congeners in accordance with DIN 51 527 Part 1 are determined and assessed) and Cu (10 000 mg/kg) are prescribed for dust and the shredder light fraction, which have to be undershot in daily treatment operations. The latter are monitored in the course of the batch tests and in addition have to be reported by the treatment operator, drawing a mixed sample during a predefined period of time.

5.3.5 Material accounting

On an annual basis the treatment operators have to report the input material differentiated into the main groups ICT and consumer electronic equipment ('Swico material'), large domestic appliances, cooling equipment and small domestic appliances, toys and sports equipment ('Sens goods') and lamps. The treatment operators in addition have to report the destinations of all equipment categories and all produced fractions to downstream vendors. The information provided by the treatment operators is processed in a web-based reporting tool to which only the conformity assessment bodies have access.

The information provided by the treatment operators helps to understand the operations, the valuable and the hazardous fractions produced as well as the de-pollution performance. It gives a clear picture of the activities performed by the treatment operator and allows the conformity assessment body to follow the treatment chain further to the downstream vendor. In addition the information provided on a material level is counterchecked with the quantities indemnified by the take-back schemes. The data can be compiled in such a way that it also allows for comparing the treatment operators in terms of quantities, processes and efficiency. The information provided in the material accounting tool is an important element in the on-site audit and additionally helps the company to keep track of its operations in terms of received equipment, produced fractions, costs and benefits of the operation.

5.3.6 Control of downstream vendors

During the on-site audit high attention is given to information provided by the treatment operators as regards to the further processing by downstream vendors. Their operation is verified through a proof provided through a specified format by the downstream vendor to the conformity assessment body. In this form the downstream vendor has to report the type of material received and the fractions produced thereof.

In addition on-site conformity assessments at downstream operators' facilities are undertaken annually based on the information provided by the treatment operators. Focus is given to critical fractions, for example CRT or LCD treatment facilities, plastic recycling and mixed plastic/metal fraction treatment partners.

5.3.7 Reporting

The information revealed, derived and compiled in the course of the conformity assessment is summarized in the audit report. The major part of the report, although in a standardized format, has a descriptive nature. When it comes to technical or environmental information, organizational and legal aspects and performance data, template tables are to be filled in. It has been learnt in the course of more than 15 years of auditing that reports consisting only of checklists do not properly reflect the results of the conformity assessment of the treatment operator. Many of the aspects which form part of the conformity assessment need a dialogue and an expert discussion between the audit team and the company representatives. Therefore the audit team members need to have a good sense of proportion during the whole auditing process. The sense of proportion has proven to be a major need of the auditing process. The approach chosen for reporting reflects this need. The conformity assessment should not be seen as an inspection, but rather as a support of the treatment operator in its aim for continuous improvement. One-day spot-checks that end up with filling in long checklists are not a suitable way to establish a sense of cooperation. It will also not help to create confidence between the take-back scheme and the treatment operators, which is the basis for assuring that the performance level reached in the course of the spot-check reflects a typical situation during the whole year and not only at the occasion of the on-site audit.

5.3.8 Auditors

The requirements for auditors mandated by the take-back schemes are predefined. Auditors should have a university degree in either engineering or natural sciences. They should have prior experience in auditing either under ISO 9000 or ISO 14 000 schemes or have similar experiences and proof of knowledge on environmental legislation. If possible the auditors should bring first-hand experience in waste treatment and/or process engineering. They furthermore should come with a client-oriented attitude, good communication skills and highly developed analytical skills. Language skills should encompass German and English and preferably also French.

Indispensable requirements for auditors are impartiality and independence. Impartiality in the sense that observations and conclusions derived in the course of the conformity assessment process should be carried out in an objective and consistent way, disregarding the size, structure or importance of a treatment operator. Independence of the auditor is assured by the fact that they have to refrain from having individual mandates from treatment operators besides the auditing mandate given by the take-back schemes. The auditors have to fulfill confidentiality requirements in terms of disclosure of information provided by the treatment operators in the conformity assessment process. This information has to remain strictly confidential and cannot be used either for their own commercial purposes or against the competitors of the two take-back schemes. Only a high level of confidentiality prepares the ground for a conformity assessment process which is not a pure inspection but furthermore serves as a fruitful exchange and an open conversation between auditor and treatment operator.

Auditors are contracted individually or (in the case of Swico Recycling) as an institution which has to facilitate a number of auditors fulfilling the above-mentioned criteria. These auditors in addition to the auditing tasks have to participate in regular technical meetings, training and occasionally represent the take-back schemes towards public authorities on district or national level or in the technical groups of the European WEEE Forum.

The auditor usually audits the same company for a period of three years but then is subject to rotation with other auditors from the audit team. Some continuity in the auditing process is beneficial for both sides, the treatment operator and the auditor, and will make subsequent audits more efficient; however, in order to prevent too much closeness between the auditor and the treatment operator a change of auditor has proven to be a good way of optimizing continuity and independence.

5.3.9 Delegated law enforcement

The environmental authorities of three districts in Switzerland (Zurich, Aargau and Thurgau) have mandated Swico Recycling and Sens in the delegated enforcement of the legislation pertaining to WEEE. This implies that the control to be done by law through the environmental authorities is delegated to Swico Recycling and Sens who, as part of the conformity assessment, check legal compliance at treatment operator's site. This process results in a reduction or renouncement of the control previously realized by the public environmental authority, which in return decreases the control load on both the public authority and the treatment operator. Such public–private cooperations between authorities and private sector organizations already exist in different areas in Switzerland, as for example in the control of excavation sites, construction waste processing facilities and the painting sector. It has proven to be an efficient and effective means for reduction of costs of control and reduction of control overlaps by public authorities and private organizations. It furthermore shows the confidence in the professionalism of the auditing schemes of the private sector.

5.4 Future trends

5.4.1 WEEELABEX standard

The adoption of the pan-European WEEELABEX Standard by the WEEE Forum General Assembly on 1 April 2011 in Amsterdam will result in a new conformity assessment scheme for the participating collective take-back schemes (WEEE Forum, 2011). The introduction of the standard is foreseen for 1 January 2013 for those schemes which form part of the group of first movers. The procedures and formats in Switzerland will have to be adjusted to those established within the WEEELABEX Standard. This will particularly be the case for the on-site audit which will be based on new procedures and formats. However, experience from those systems which have operated conformity assessment procedures for many years will be brought in and the final approach will most probably not differ fundamentally from the one established.

5.4.2 Product stewardship standards

Different international standards have evolved in the last years related to the sound disposal of WEEE:

- The EPEAT Standard (Electronic Product Environmental Assessment Tool) operated by the Green Electronics Council started in 2005 and is now a widely recognized and accepted product standard for electronics (see: www.epeat.net). Over 1200 products are already EPEAT certified. The standard includes requirements for EoL waste management which follow the plug-in guidelines (US-EPA, 2004) based on the e-cycling initiative from the US-EPA. Certification procedures are based fully on a 3rd party approach.
- The e-stewards (www.e-stewards.org) launched by the Basel Action Network (BAN) is a standard on EoL-Management of WEEE (BAN, 2009a, 2009b). In comparison to WEEELABEX it requires full ISO 14000 conformity, occupational health and safety requirements and adherence to the Basel Convention and OECD trade rules. Conformance verification with the standard is following a third party conformity assessment approach. Auditors need to be qualified EMS auditors and need further qualification by the BAN designated training provider.
- The Responsible Recycling (r2) standard (John Lingelbach of Decisions & Agreements, LLC, 2008) from the US Environmental Protection Agency (EPA) is a third party certification scheme. It has been criticized for not banning export of WEEE or components of WEEE to developing countries. It also does not fix clear Work and Health Safety requirements.

In addition to these international standards on EoL management of WEEE, many original equipment manufacturers (OEM) have their own corporate standards like Hewlett Packard (Hewlett Packard Development Company, L.P., 2008). The increasing number of international standards asked for by OEMs, take-back schemes or national authorities makes it more and more cumbersome for recyclers to keep track with the different obligations and requirements which they have to fulfill. Various types of audits by different entities in different periodical cycles do not necessarily improve recycling performance and material yield. It would be beneficial if OEMs and take-back schemes (which mostly operate on their behalf) would come up with a harmonized set of standards applicable on a global scale, for example either established through the International Standard Organization or the OECD.

5.4.3 Recovery of critical metals

The occurrence of critical metals in EoL products as cited, for example, in OECD, (2010) and the increasing shift of these substances from natural resources into secondary commodities poses a new challenge which none of the existing standards addresses. The principal goal behind all standards is the reduction of the release of toxic substances from EoL equipment along the reverse supply chain into the environment, the achievement of predefined recycling and recovery quota and – in some cases – the prevention of illegal international trade. Recycling and recovery quota determine the recovery rate for bulk metals and plastics, the recovery of critical metals is not taken into consideration. This upcoming need will require a shift in policy orientation. Recovery of these metals is not incentivized by market rules; policy makers should therefore incorporate the prevention of loss of critical technological metals along the reverse supply chain as a claim in the legal framework. Financial compensation by take-back schemes to the treatment operators for those critical metals for which the economic benefit is not a key driver should be sought and developed. Plus, the technology chain from collection, logistics, manual and mechanical pre-treatment to end-processing should be optimized in a way that the material yield of valuable and critical substances can be optimized.

5.5 Conclusions

Driven by economic growth and changes in lifestyle the consumption of electric and electronic equipment has increased substantially and in parallel has catalyzed the generation of WEEE. In the mid-1990s producers, importers and distributors in Switzerland started to establish collective take-back schemes for EoL electrical and electronic equipment. Being a tourist hot-spot and due to the high level of environmental consciousness, which by itself is rationalized by the high population density and environmental education, return of these goods to the take-back schemes has increased and has reached more than 15 kg/capita/y in 2010. Although being a hilly and scattered country with small villages and remote areas, consumer convenience for product return is high, with on the one hand municipal collection points in almost all municipalities and on the other hand the possibility of returning these goods at points of sale of goods of the same type but not necessarily the same brand.

From the very beginning the take-back schemes have introduced a conformity assessment scheme for collection, logistics and treatment operations. The conformity assessment of treatment operators is realized as a third party assessment and adherence to technical, organizational, legal, and environmental and health and safety requirements is checked on an annual basis through external auditors. Technical regulations on the recycling of electrical and electronic appliances have been developed which ensure a level playing field for all services providers within the take-back schemes. Audit processes are well established and accepted by the treatment operators. They are designed in such a way that the auditing process serves as a basis for increasing system performance.

Driven by the pan-European WEEE Forum, future trends go towards standardized technical requirements and harmonized audit procedures all over Europe stipulated in the WEEELABEX Standard (WEEE Forum, 2011). On a global scale different non-governmental organizations (NGOs) and governments have initiated the formulation and implementation of standards on the management of EoL electronic goods. This trend will continue to contribute in making recycling of WEEE more sustainable worldwide. However the increasing number of actors in this field has made it more and more difficult for the treatment operators to keep track with the latest developments. Harmonization on a global scale through for example the International Standard Organization or the OECD might become necessary in the near future in order to assure a global level playing field.

One of the major challenges for the future of standard development and conformity assessment procedures will be how to address the recovery of critical metals present in different components of electrical and electronic goods. There is a need to develop resource strategies for take-back schemes which address not only de-pollution from hazardous substances and the recovery of basic and precious metals, but also the recovery of critical metals. Such substances are present in high dissipation and the economy will not in all cases be the driving force for increasing resource recovery and conservation. Take-back schemes and along with them the conformity assessment systems have to address this issue if sustainable material management should be realized.

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6
Eco-efficiency evaluation of WEEE take-back systems

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Abstract: E-waste or waste electrical and electronic equipment (WEEE) is one of the fastest growing and complex components of the global waste stream and one of the most troublesome. For the EU area the environmental impacts of WEEE were quantified in detail for all WEEE categories, illustrating the most significant aspects from various environmental perspectives. This impact assessment work resulted in improved environmental priority setting and shows also the variety of environmental themes like climate change effects, toxicity and intrinsic resource value related to WEEE take-back and recycling. The outcomes of the impact assessment work proved to be very valuable for the revision process of the WEEE Directive and specifically on where to differentiate and enhance legislative requirements related to, for instance, collection amounts, recycling targets and treatment standards.

Key words: global e-waste amounts, EU WEEE recast, impact assessment, eco-efficiency, policy development.

6.1 Introduction

The global amounts of new electrical and electronic equipment (EEE) products placed on the market are quantified as tripling from close to 20 million tonnes in 1990 towards over 75 million tonnes in 2015. So far, the amounts of WEEE being generated globally are highly uncertain. Moreover, the international flows are equally uncertain which combined with the contained environmentally damaging materials as well as valuable resources make waste electrical and electronic equipment (WEEE) a very complex waste fraction.

The environmental consequences of WEEE are related to many environmental themes at the same time. Besides significant amounts of toxic and environmentally sensitive materials, when not properly disposed of or recycled (cadmium, beryllium, lead, mercury, flame-retardants, etc.), also climate change substances (CFC's) in fridges and materials that are more and more regarded as critical from a resource depletion point of view (indium, gallium, etc.) are concerned. Although electronic products are intrinsically not toxic when left untouched or in use, the material recovery process itself

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in both the developed but especially the developing countries can pollute the environment severely (Huisman, 2003; Huisman *et al.*, 2008a; Stevels, 2009; Schluep *et al.*, 2009).

Various policies try to contain these environmental impacts, such as the Basel Convention and the European WEEE Directive (Commission of the European Communities, 2003). However, the intrinsic material and repair or reuse value in informal sectors constitute in an important market driver for trading outside of official and controlled channels (Yang *et al.*, 2008; Huisman, 2010; Sander and Schilling, 2010). In addition, solving the e-waste problem requires a comprehensive approach and cooperation of many different actors designing, consuming, collecting, recycling as well as in trading, financing, monitoring and researching the life cycle of EEE products. Unfortunately, most policies and legislation are to be regarded as national or a state by state patchwork and the solutions are limited due to lack of clarity of principles and responsibilities, implementation and enforcement. Subsequently the global WEEE situation is lacking market incentives to improve (Huisman *et al.*, 2008b; Yoshida and Yoshida, 2010).

A key contribution to this worldwide situation is the scientific task to provide the necessary fact finding and independent back-up of what is actually happening in these complex systems. More precisely: what means and interventions could be used to facilitate long-term system changes from a societal and general sustainable development point of view? This chapter addresses the following key parts needed for the sketched 'fact-finding' mission and some very basic questions underneath this:

- How much WEEE is there?
- How dangerous is it? How should different types of environmental impacts be prioritised?
- Who should pay for what?

These three questions are the starting point for the WEEE impact assessment building blocks presented in the next sections as well as for providing fact based guidance for developing take-back and recycling of WEEE.

6.2 How much WEEE is out there?

6.2.1 Background

In literature there are a few estimates presented for the amounts of WEEE being generated (Deepali *et al.*, 2005; Eijsbouts, 2008; Huisman *et al.*, 2008a; Nordic Council, 2009; Schluep *et al.*, 2009; Oguchi *et al.*, 2010; Walk, 2009; WEEE Forum, 2010). However, these estimates are either very rough when pinpointing total global quantities, or mainly related to sales data for specific appliances. The size of the actual global problem remains largely unclear. It is difficult to know exactly how much EEE is sold and generated on a global level and even more difficult to establish when and where it is ending up when disposed of. Moreover, of this, the amount that gets properly collected and treated is highly uncertain. In Europe, the United Nations University (UNU) found that at least 35% of the total weight of the EU's e-waste in 2005 was unaccounted for (Huisman *et al.*, 2008a). Astoundingly, that means there was no scientific data available at all to explain where roughly over 3 Mt of EU originating e-waste is going each year. In addition, the types of e-waste included in various government-initiated analyses and collection programmes differ across the world. The EU, for example, uses 10 distinct product categories, whereas in Northern America it is typically defined on a state by state basis and mainly limited to information and communication technology (ICT) products and TVs. Japan defined four product categories including TVs, air conditioners, refrigerators and washing machines, and as another example China defined its own limited list of affected products. Finally, for developing countries or countries in transition, only very limited data on e-waste arising is available in the first place, let alone data on collection and properly treated quantities.

Therefore, to answer the first impact assessment question: 'How much WEEE is actually out there?' this section will illustrate both previous and present quantification work of UNU and TU Delft. The starting point is the past work of the UNU WEEE Review study for the European Commission (Huisman *et al.*, 2008a) and the ongoing work in the UN-based StEP Initiative (www.step-initiative.org) in the so-called ADDRESS project (Huisman *et al.*, 2011). In this StEP meta-project supported by a large number of active research institutes and other organisations, the objective is to come to comprehensive detailing of EEE placed on the market, the amounts of WEEE generated, including international flows and the amounts properly collected and treated.

6.2.2 2007 EU quantifications

Predictions made during the 1990s estimated the tonnage of new EEE put on the EU15 market at 7 Mt. With the expansion from EU15 to EU27 and based on many sources and different estimation techniques, the UNU study (Huisman *et al.*, 2008a) points out that the amount of new EEE put on the EU27 market in 2005 is estimated at 10.3 Mt per year. This was done by analysing a variety of data sets such as: individual equipment sales, analysing amounts and numbers of equipment present in households and their average lifetimes, finding correlations with municipal solid waste (MSW) amounts and comparing amounts collected per country and per maximum amounts found per subcategory or collection category.

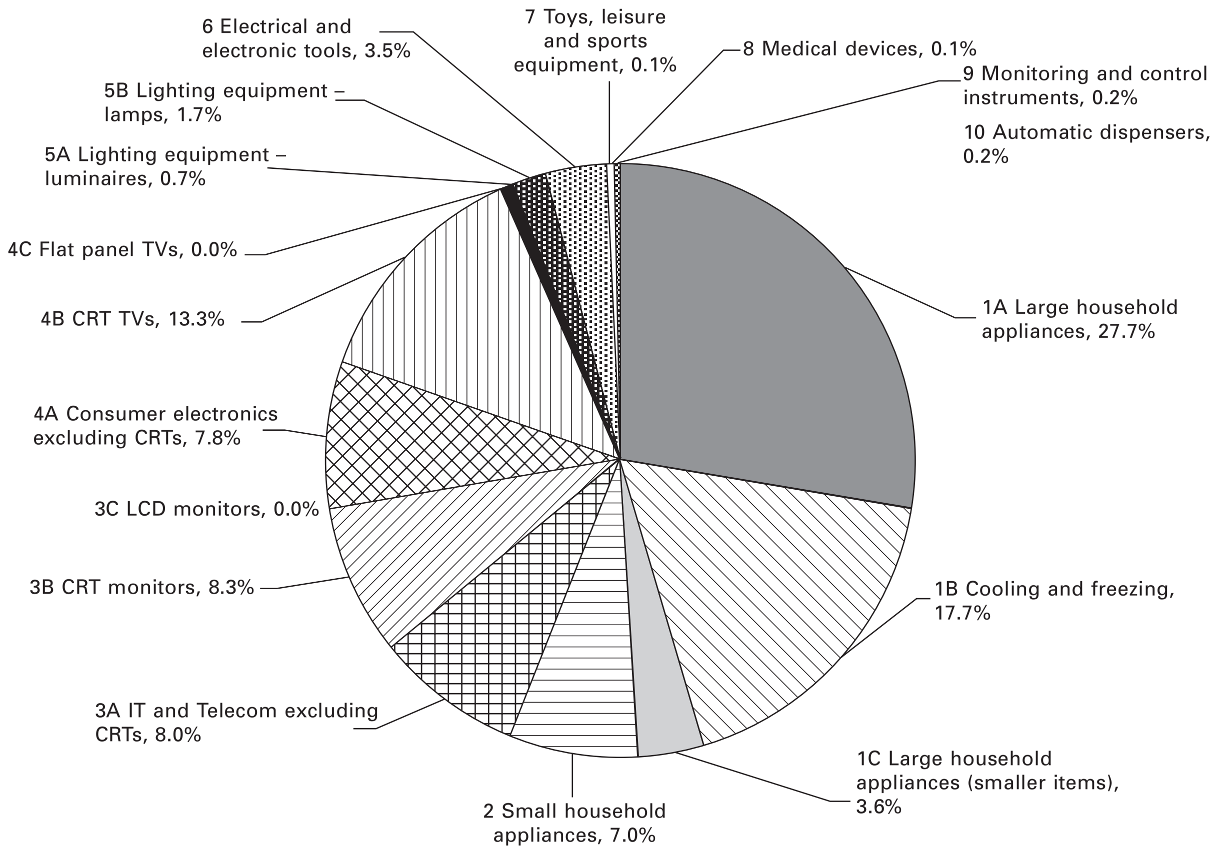
In the explanatory memorandum of the original WEEE Directive

(Commission of the European Communities, 2003), the amount of EEE becoming waste was estimated in 1998 for the EU15 to be 6 Mt. In the UNU study, the 2007 estimate of the WEEE generated across the EU27 was updated to between 8.3 and 9.1 Mt per year for 2005, from which approximately 7.2 Mt is household WEEE. In addition, the composition of WEEE was determined for the baseline year 2005 as well (see Fig. 6.1). This was done by extensive market survey of all European take-back systems (WEEE Forum, 2010) and input from the European Electronics Recyclers Association (EERA). The composition of the general WEEE breakdown can be used as a first order estimate for a certain category in developed countries when the size of other categories is known.

Table 6.1 shows the estimated amount of WEEE collected and treated as a percentage of the amounts of WEEE arising for the EU27 in 2005. The amounts are roughly in between 25% for medium sized appliances and 40% for larger appliances, showing substantial room for improvement. Based on more detailed assessment of data from various compliance schemes, it must be possible to collect around 75% of the large and 60% of the medium sized appliances in the long-term future (Huisman *et al.*, 2008a, 2008b). The analysis shows that returns of appliances lighter than 1 kg are very low.

Despite the low collection percentages, the original WEEE Directive collection target of 4 kg per inhabitant can easily be met by EU15 member states. It, however, remains a very challenging target for the new member states as their market input is much lower than the original EU15 members. The most interesting finding, however, is that there are very large differences in performance by different member states per sub-category. This indicates that there is much room for improvement in collection performance. As a consequence the following was proposed to the European Commission as options for revising the legal texts:

- *Alternative definition for the generic 4 kg target per inhabitant*. This can, for instance, be based on figures for the amount of EEE put on the market in the previous year. In terms of setting an overall collection target, it is clear that the current 4 kg/head target is difficult for some member states and not challenging at all for others. An alternative definition based on percentage of amounts put on the market in the previous year offers a fair way of applying a target which can be responsive to the dynamics of the EEE/WEEE market in each member state. From a simplification point of view, obviously unambiguous registrations of the exact historic amounts put on market are needed which were lacking in 2005 (and are found to be still very incomplete in 2011).
- *Higher or specific collection targets for more hazardous WEEE*. Although the Restriction on Hazardous Substances (ROHS) Directive aims to reduce the hazardousness of WEEE in the longer term, it has been shown in the environmental impact assessment (to be illustrated



6.1 Breakdown of WEEE arising 2005.

Table 6.1 2005 collections amount as percentage of WEEE generated

No.	Treatment category	2005 WEEE collection rates (%)
1A	Large household appliances	16
1B	Cooling and freezing	27
1C	Large household appliances (smaller items)	40
2,5A,8	Small household appliances, luminaires and household medical devices	27
3A	IT and Telecom excluding cathod ray tubes (CRT)	28
3B	CRT monitors	35
3C	Liquid crystal display (LCD) monitors	41
4A	Consumer electronics excluding CRTs	40
4B	CRT TVs	30
4C	Flat panel TVs	41
5B	Lighting equipment – lamps	28
6	Electrical and electronic tools	21
7	Toys, leisure and sports equipment	24
8	Medical devices	50
9	Monitoring and control instruments	65
10	Automatic dispensers	59

in the next section) that more (toxic) control is highly environmentally beneficial. Thus it is relevant to set specific collection targets for items where certain substances cannot be replaced due to functionality or more important environmental benefits like energy reduction, such as mercury-containing gas discharge lamps and LCD backlights in TV sets and monitors. In addition, the ozone-layer depletion and global warming potential of CFC fridges also make minimising leakage from controlled collection and recycling systems a very first priority. In the case of CFC fridges, the potential CO_2 savings of more collection and better treatment were found to be higher than 30 Mt per year when old CFC fridges are returned.

- *More enforcement on waste shipments*. There is mounting evidence that illegal shipments of WEEE under the guise of equipment for reuse occurs widely. There is evidence that increased monitoring and enforcement can help to eliminate this practice (see Sander and Schilling, 2010),
- *Mandatory consumer education*. Evidence from recent surveys show there remains a lack of consumer awareness of the WEEE Directive in general and where to dispose of WEEE products. Although the quantification of the likely benefits of consumer awareness raising initiatives is difficult, currently it is clear that these do have a positive effect on consumer behaviour.

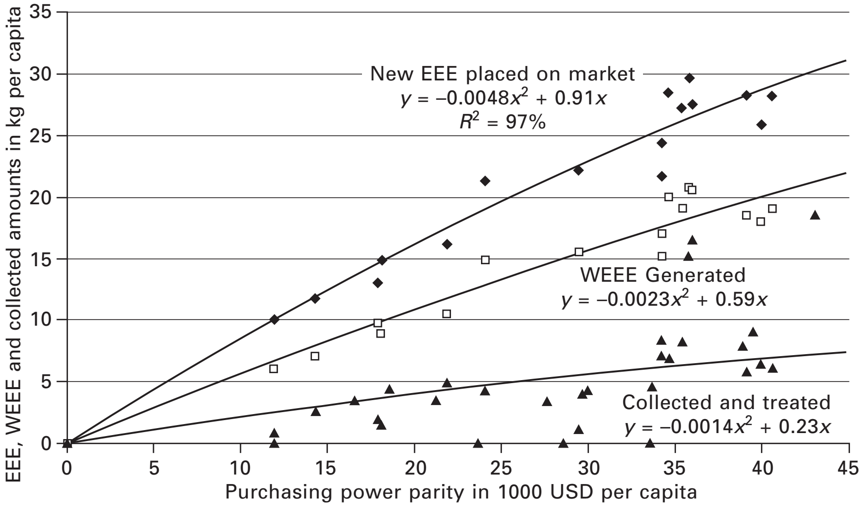
From these recommended options provided in 2008 and debated among many stakeholders, the first and third ones are taken up in the subsequent drafts of the WEEE recast and the following political debate between various stakeholders and European Parliament and Council (European Parliament, 2011). In addition, although not directly making an environmental impact, the second option to focus more on the most relevant environmental impacts has been taken into account by the European Parliament by redefining the scope towards the actual collection and treatment categories. This enables indirectly a better focus per collection category on their dedicated environmental concerns. This positive development is accompanied by more focus on the development of (hopefully more dynamic) treatment standards per collection category which was another main recommendation in the UNU WEEE review study.

6.2.3 The 2010 WEEE recast collection target discussion

In 2010 and 2011, the WEEE recast debate is still ongoing in Europe, focusing on, among a few other key items, the definition of the proposed collection target. This will either be based on 65% of EEE placed on market (PoM) to be collected based on two or three preceding years of sales and/or as a target of 85% based on amounts of WEEE generated (GEN). In both cases the new target will have the advantage that the old 'flat rate' of 4 kg for each country is replaced with one that is more directly related to actual quantities of EEE becoming WEEE and thus better representing the variety in different economic status of the EU member states.

However, what these targets mean in practical compliance terms is still highly uncertain. For the 65% of PoM option, although being a clear legal starting point, it does not necessarily represent the amounts becoming waste, as for some categories the average lifetime is much longer than for others. For the 85% WEEE generated target, although being in principle directly related to the waste amounts, it will be very hard to determine those quantities per country over time. Regardless of the choice made, both targets will be complicated to use in practice because the total amounts to be collected do not work as a simple statistical average that can be applied to all individual products, product categories or collection categories. Therefore, an update of the quantities of EEE and WEEE known and unknown over time is needed. Moreover, a translation of the proposed targets in kilograms per inhabitant per EU member state to be collected would prove important guidance. This counts specifically for determining amounts per individual collection categories or product categories.

In Fig. 6.2, the result of a renewed set of calculations is given. This result is coming from correlating known EEE amounts from various registers



6.2 WEEE amounts versus 'disposable income' EU27 in 2009, as of 30 January 2011.

and countries versus purchasing power parity (PPP) (IMF, 2010). PPP is a measure for the actual purchasing power of consumers based on a fixed basket of goods/services and levels out currency and inflation effects compared to using gross domestic product (GDP) as a parameter. Economic data is derived from the IMF World Economic Outlook 2010 (IMF, 2010). For the amounts placed on market (in kg/capita) versus PPP (in 1000 USD per capita), there is a high correlation found. This means that correlating well known PoM data in relation to spendable income forms a good estimate of e-waste newly entering the market. Note that there are, of course, quite some differences in the e-waste breakdown in various products and products categories. Therefore, the correlation works for the sum of e-waste bought, not necessarily for individual products. As a second line, the amount of WEEE generated is predicted assuming saturated markets and based on a few well-known countries, the delay of new products becoming waste relative to a growing market of new equipment is found to be a rather stable constant of around 70–75% (Eijsbouts, 2008). The uncertainty in this second line as derived from multiplying this factor to other country data as displayed in Fig. 6.2 is much higher.

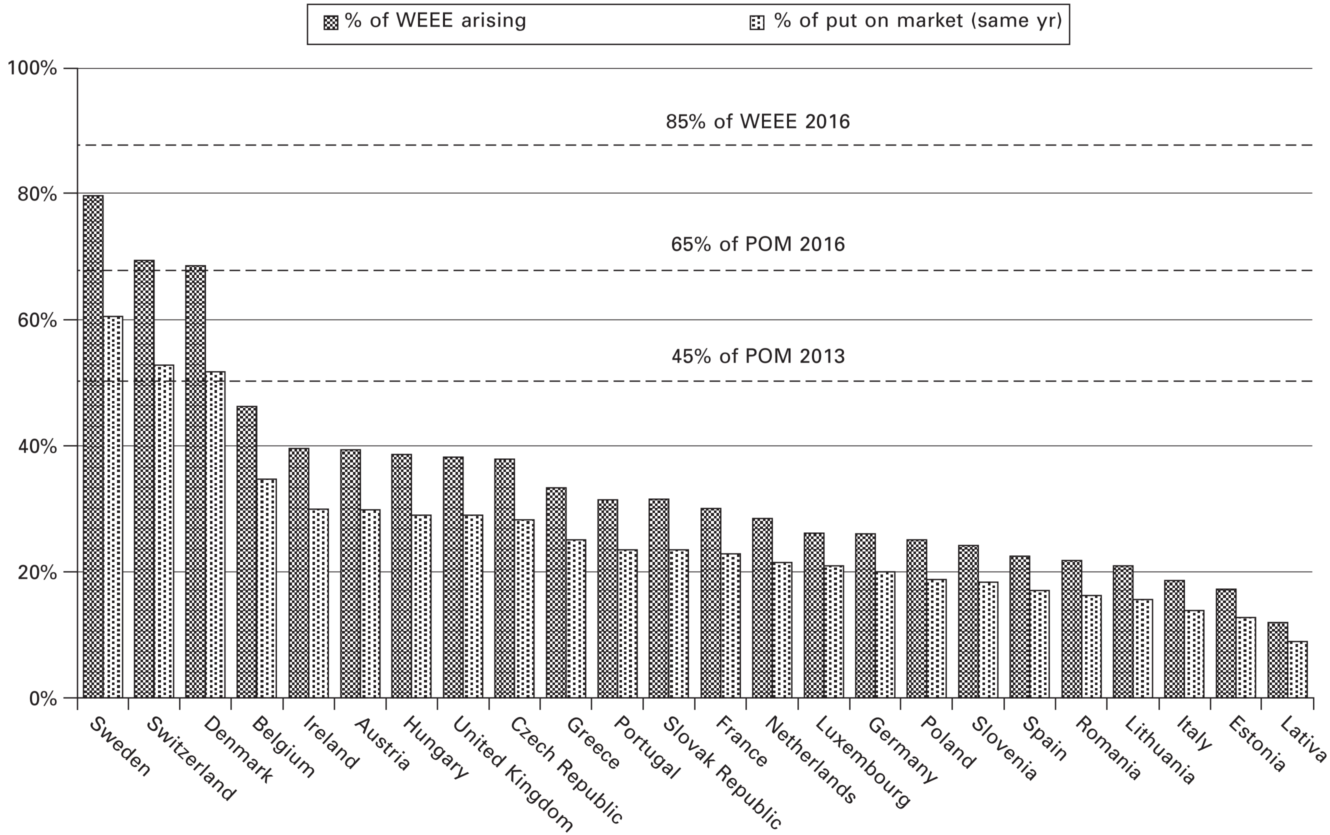
The correlations of Fig. 6.2 are valid under the following assumptions and restrictions:

- The IMF PPP basket of goods is used. It is not known whether electronic goods follow the same trend per year as the average basket.
- Predicting future growth, especially after the 2008/2009 economic crises, is highly uncertain.

- Not all EEE PoM is officially reported. Therefore, the actual amounts of EEE PoM coming from several registers has been corrected for missing product groups and missing business to business (B2B) amounts. Thus the EEE amounts for some countries used for the above correlation are higher than the official numbers for those countries known to have an 'incomplete register'.
- Figure 6.2 is applicable only between PPP $0 and $45 000 per inhabitant. For example Luxembourg (PPP 2008: $88 000) is too far to the right on the *x*-axis and does not fall within the parameters tested.
- The actual WEEE amounts estimated per country can be around 2 or 3 kg higher or lower per capita in practice (for higher PPP per capita values). The correlation is based on the average behaviour for the entire EU. For instance for flat panel displays it is known that in some countries (such as Switzerland) already significant numbers of LCD TVs and monitors are becoming visible in the collection streams, whereas in others, they do not appear yet (Böni and Widmer, 2011).
- The amounts 'officially collected and treated' are gathered from various sources. Key source of information is the WEEE Forum Annual Report 2009 (WEEE Forum, 2010).

6.2.4 Where are WEEE now per EU member state?

'Official' collection numbers obtained are related to the correlation numbers derived from Fig. 6.2 and displayed in Fig. 6.3. This shows for 2009, that none of the EU member states is actually capable of achieving either the proposed 65% PoM target (here based on the same year PoM, not on basis of previous 2 or 3 years' sales) or the 85% of WEEE generated target. It also illustrates that there is hardly any correlation between the collected amounts and income per head, which is understandable knowing that the EU member states are all 'rather unique' in their take-back system configuration, division of responsibilities, experiences, consumer awareness and cultural settings. For simplicity, the amounts are plotted against the same year placed on market amounts, thus also removing potential fluctuations due to economic decline in case multiple years before 2009 are taken as a reference. It has to be noted that there is still a high level of uncertainty related to these below amounts. In Eurostat (2011) official data for amounts placed on the market in 2009 as well as amounts collected and treated are published. However, there are many mismatches with data published elsewhere for European markets by collection schemes and national registers (WEEE Forum, 2010). Moreover, the current reports on amounts 'collected and treated' do not necessarily mean these are also 'properly' treated due to lack of supervision on possible downstream trading outside the EU. The relatively high collection numbers in Sweden, Denmark, Norway and Switzerland are caused by relatively



6.3 EU collection amounts as a percentage of same year placed on market in 2009.

little trading (geographic position) and good monitoring practices in these countries.

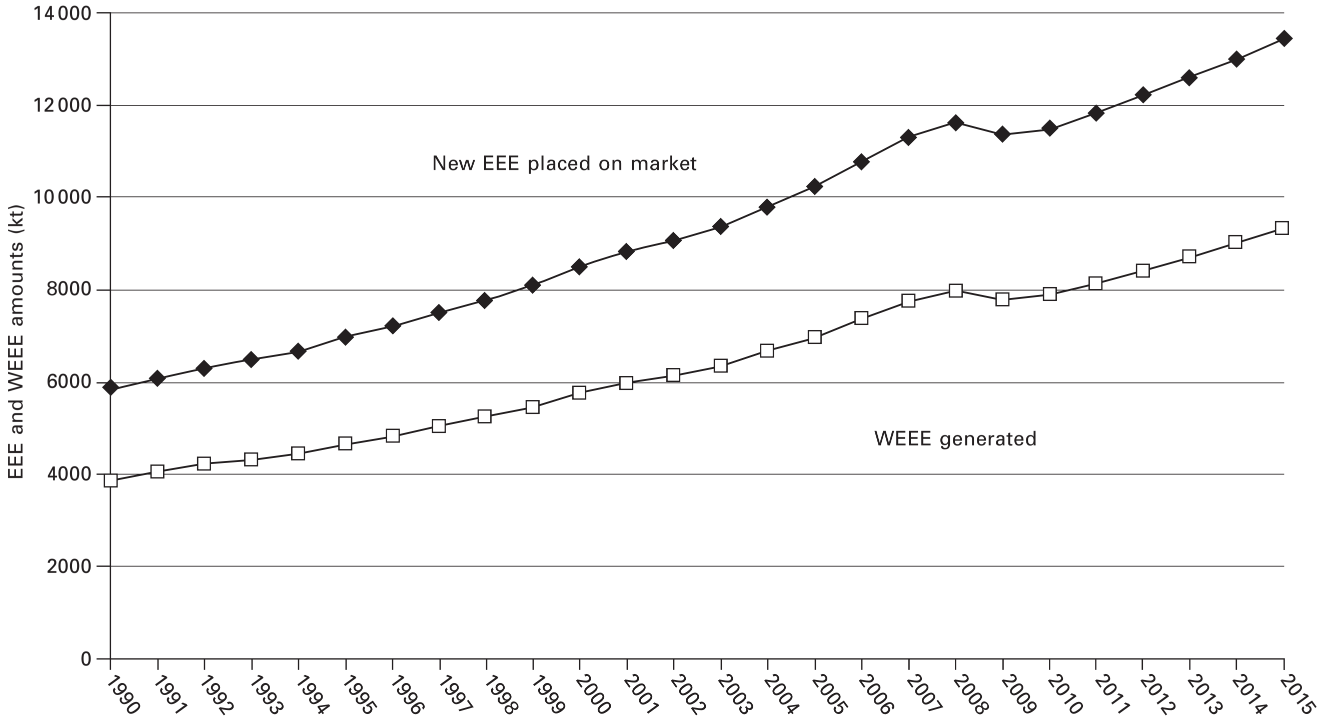
With the ongoing quantifications, the UNU calculations for 2005 are more and more refined due to more information and studies getting available and processed as part of the StEP ADDRESS project. Based on the previous assessment the UNU assessment for the total EU27+2 WEEE quantities are updated to 2009 numbers. The peak in 2008 is due to years of continuous economic growth ending in 2009 with the global financial crisis. Figure 6.4 shows the quantities of WEEE generated from 2005 to 2015.

From this analysis, for 2010 it means 11.5 Mt EEE PoM, WEEE generated (WA) is approximately 7.9 Mt, whereas officially collected and treated (C&T) are around 3.1 Mt. This means the collection percentage is still only one-third compared to the same year EEE values. It also shows that by 2016 with a 65% target, roughly 8.7 Mt which is +180% of WEEE, needs to be collected over the 2010 status.

In any case, the new percentage-based collection target needs proper definition as any legal target in principle should be based on easily measurable data in order to unambiguously assign collection requirements and to minimise room for avoiding responsibilities. A complication will come from the gradual change in composition of EEE and WEEE over time as displayed in Table 6.2. For products such as lamps and large household appliances which often stay on the market for longer than 15 years, the proposed 2 or 3 year PoM target improperly reflects actual waste amounts originating from historic sales. Likewise, changes like picture tubes (CRTs) being replaced by relatively lighter flat panels (light-emitting diode, LED, and LCD) influence the breakdown of total WEEE per category. With the additional variety in market saturation, economic ups and downs plus specific consumer behaviour in different countries, the composition of WEEE will fluctuate significantly, making the translation of the 65% to specific WEEE categories, collection categories or product types rather difficult. Furthermore, another complicating issue is the large intra- and extra-communitarian trade amounts of WEEE and 'reusable' EEE. This happens mainly from the more saturated rich markets to the less saturated markets in Eastern Europe. The consequence is that the translation of the both proposed definitions towards the various collection categories will be troublesome and require specific research studies per market.

6.2.5 Global amounts of EEE and WEEE

So far, there is very little insight on the worldwide development of EEE and WEEE amounts. Therefore, as an initial estimation for global amounts, in Fig. 6.5, the quantities of EEE placed on the global market are presented for 1990, 2000, 2010 and 2015. This estimate is based on the previous



6.4 EU27 EEE and WEEE amounts 1990–2015.

Table 6.2 Change in EEE PoM generated versus WEEE composition

Treatment category	WEEE 2008 (% of total)	POM 2008 (% of total)	Difference (%)
Large household appliances	28	31	10
Cooling and freezing	18	17	–4
Small domestic appliances	31	38	23
Screens	22	13	–42
Gas discharge lamps	2	2	–6

correlations derived from European data which extrapolated to all markets. Despite a number of assumptions and uncertainties, clear trends can be derived from these assessments. In particular, the economies in transition, China, India, Brazil, Russia but also countries like Mexico, Turkey and several Asian countries, are and will increasingly be contributing to future WEEE generation. The consumption of EEE is growing at a very rapid pace and from 1990 onwards (19 Mt) roughly doubled in 2000, tripled in 2010 and will likely have quadrupled in 2015 towards a staggering amount of 76 Mt of new equipment. In essence, the simple and straightforward extrapolation based on EU correlations between PPP and EEE amounts visualises the observed trend of substantial population and economic growth in Asia and South America and the rise of a new middle class in these countries also having the budgets to buy much more electronic products.

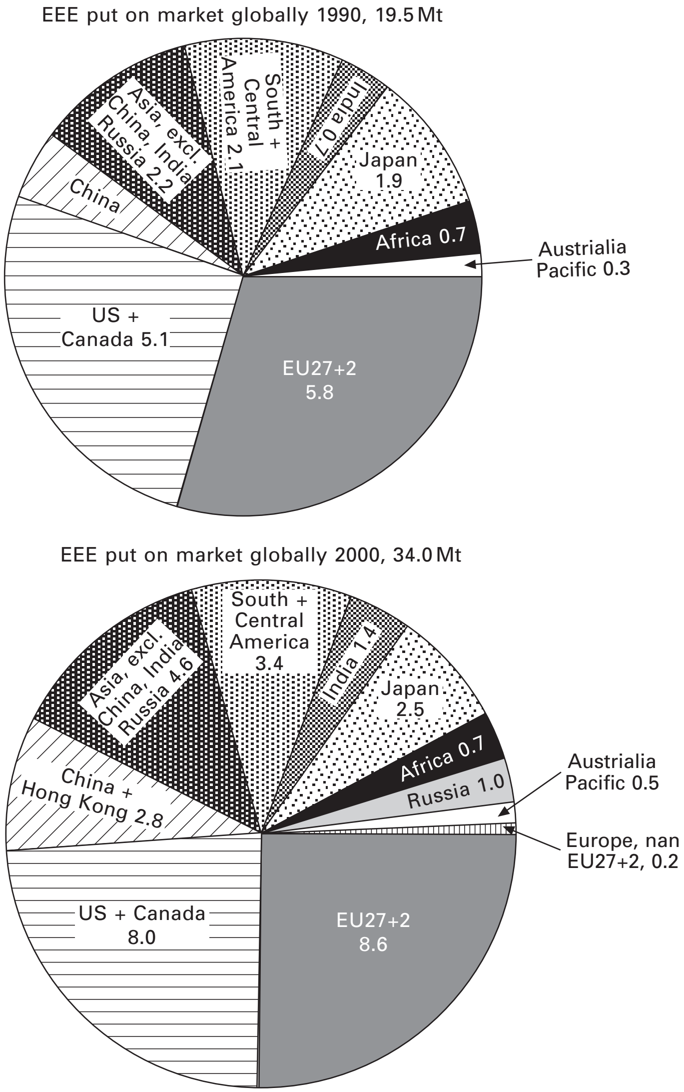
The estimates are expected to be accurate for all EEE sold and display the global trends quite well. However, they do not necessarily apply to individual products or collection categories. Estimating (specific) WEEE amounts from these numbers is still regarded as too uncertain due to very different consumer behaviour in emerging and developing markets as well as to international flows and non-saturated markets. In particular, for countries with a PPP lower than 10 000 USD per head, the estimates are uncertain. As part of the StEP ADDRESS work, these quantifications will be further refined over time in terms of prognoses of WEEE generated amounts per country per product type.

6.3 How do WEEE quantify and prioritise environmental impacts?

6.3.1 The QWERTY concept

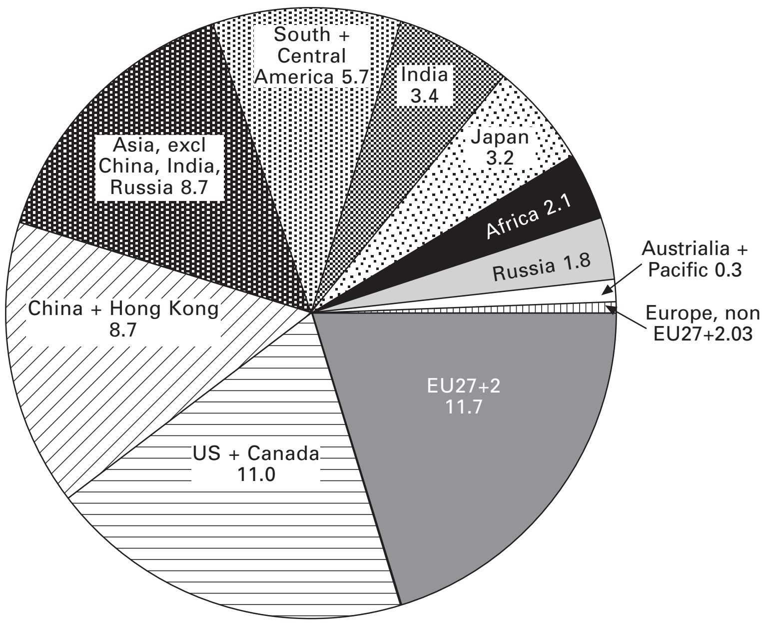
The QWERTY/EE tool is a software tool developed at TU Delft, which evaluates the environmental and economic impacts of electronic products in the entire end-of-life chain (Huisman, 2003). QWERTY stands for Quotes for environmentally Weighted RecyclabilitY. The EE stands for Eco-Efficiency. The general idea is based on environmental and economic quantification of three values as displayed in Fig. 6.6 below and subsequent calculation of the distances between these three outcomes.

The minimum values (environmental and economic) correspond with the theoretical scenario of 'all materials being recovered completely without any environmental impact or economic costs of end-of-life treatment steps'. As such, they represent the environmental and economic substitution values of primary materials that are the values for newly extracted and produced

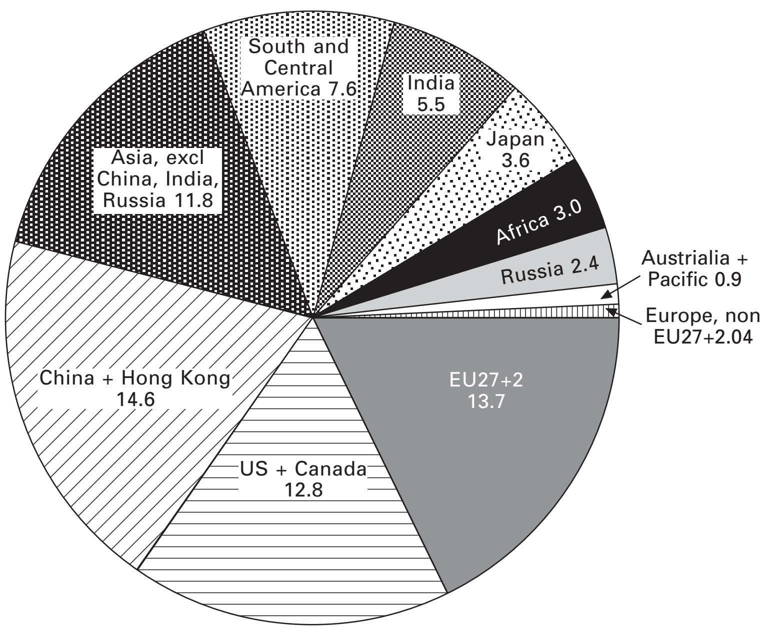


6.5 Prognosis of 1990–2015 EEE amounts globally.

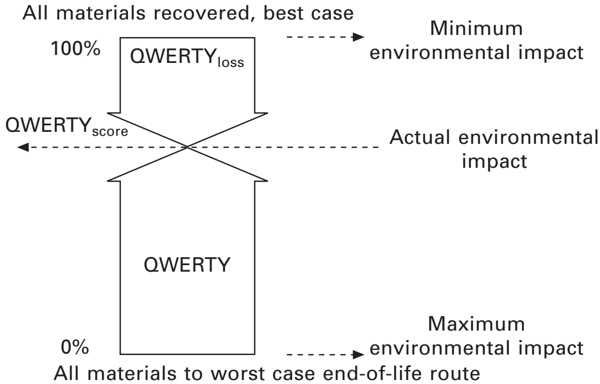
EEE put on market globally 2010, 57.4 Mt



EEE put on market globally 2015, 76.1 Mt



6.5 Continued

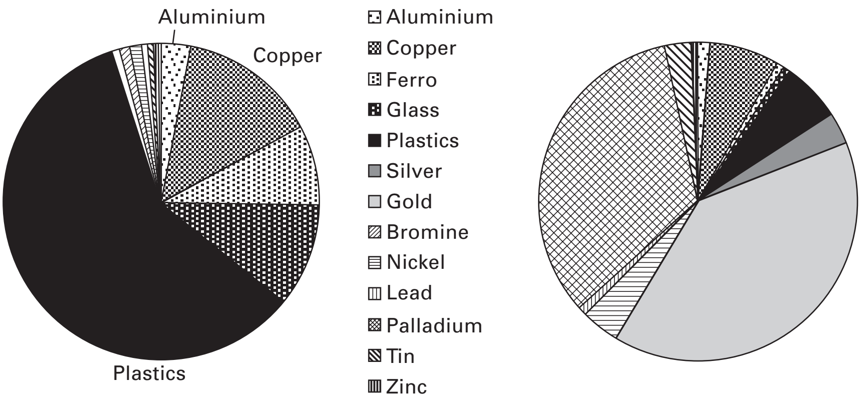


6.6 The QWERTY concept.

materials for 100%. Usually both are negative (avoided environmental impacts of new extraction and processing and revenues being negative costs). The values are strictly theoretical: in practice there will always be (environmental) costs connected to separation of materials, energy consumption and transport in order to realize recovery of materials.

The maximum values are defined as the theoretical scenario of 'every material ending up in the worst possible (realistic) end-of-life route', including the environmental burden plus (environmental) costs of pre-treatment: collection, transport, disassembly and shredding and separation into fractions. The 'realistic' end-of-life scenarios under consideration are controlled and uncontrolled landfill, incineration with or without energy recovery and all subsequent treatment steps for material fractions, like copper, ferrous and aluminium smelting, glass ovens and plastic recyclers. In addition this theoretical value cannot easily be exceeded except under extreme disposal conditions, which are normally forbidden by law.

The actual recycling scenario values are based on the environmental and economic performance of the end-of-life scenario under consideration and are compared with the two boundary conditions above and finally expressed as percentages or in absolute numbers. These actual values are obtained by tracking the behaviour of all materials over all end-of-life routes and by taking into account all costs and environmental effects connected to this. It includes all environmental impacts including recycling, fate of hazardous substances, additional environmental burden of processing, transport and energy use, as well as all prevented environmental impacts (including toxicity) for recovered materials. An example outcome for a cellular phone is displayed in Fig. 6.7. It effectively illustrates the priorities of different materials such as trace amounts of precious metals not just according to their physical weight, but rather as their environmental weight to the total product. In addition, the calculations will describe the main causes of environmental



6.7 Example, weight versus environmental weight of a mobile phone.

losses and recoveries related to the materials present and thus form the basis of prioritisation in the case of material substitutions.

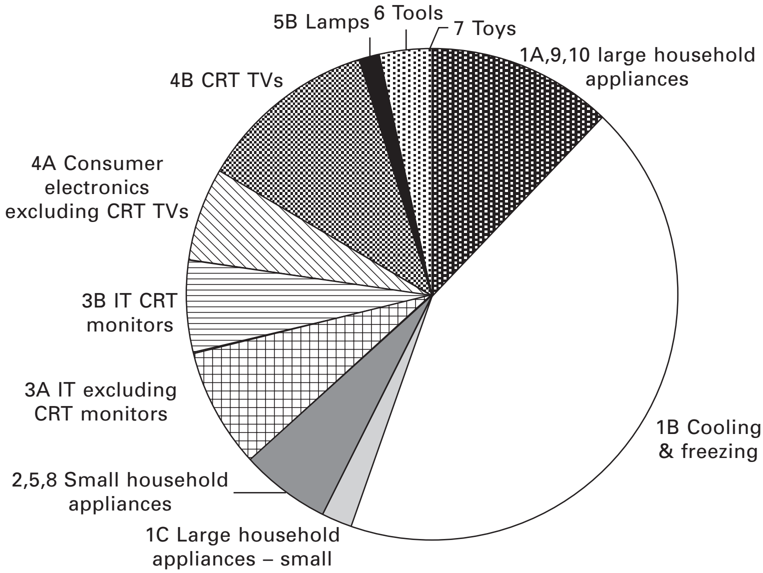
6.3.2 Application for the EU WEEE revision

The model is based on large-scale modelling of the e-waste collection, logistics, pre-processing and end-processing chain. It is built on over 350 literature sources, many direct evaluations of various WEEE processing technologies. It tracks the fate of 64 WEEE relevant substances present in either products or product streams flowing through take-back and recycling systems. The environmental and economic parts of the model are constructed as a streamlined environmental life-cycle analysis and life-cycle costing coming together in eco-efficiency graphs showing preferable and less preferable scenarios.

Figure 6.8 shows the contribution of each WEEE category to the total impacts of diverting WEEE from landfill and incineration to average European treatment. Figure 6.9 demonstrates the avoided environmental impact when product are diverted from MSW to collection and treatment, based on assuming a 65% collection rate instead of the 2005 measured collection levels per category (Huisman *et al.*, 2008a). Under the Eco-Indicator'99 single indicators, the most relevant products to divert from disposal are the CFC containing fridges, due to their very high global warming potential (± 2 tonnes of CO_2 equivalent per appliance). From the total WEEE treatment there were 36 Mt of avoided CO_2 emissions, 34 Mt resulted from removing CFC-based cooling agents.

Besides this, there is a considerable variety in environmental themes per treatment category due to different substances of environmental concern:

- toxicity effects in various environmental impact categories are dominant



6.8 Contribution of categories to environmental impacts of WEEE total (EI99 H/A).

for Category 3C LCD Monitors and Category 5B Lamps (especially in terrestrial eco-toxicity and ecosystem quality);

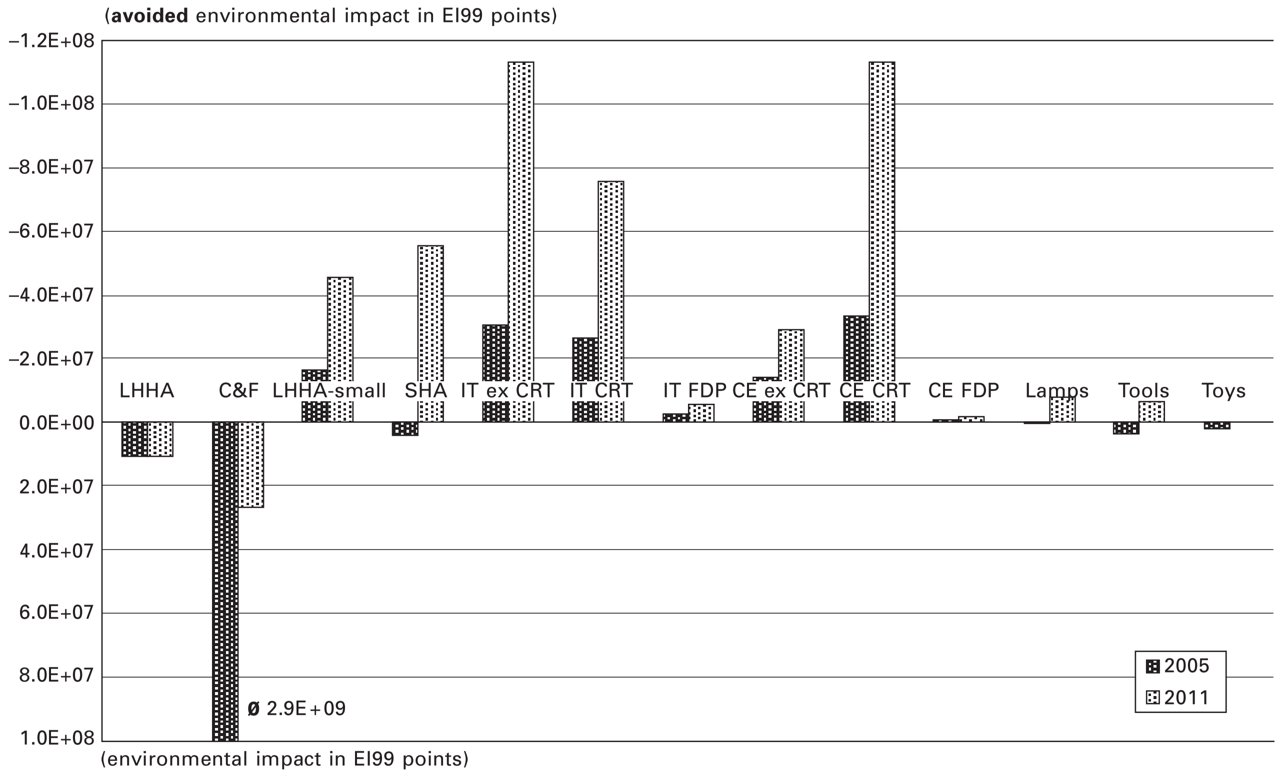
- avoiding ozone-layer depletion and global warming potential for Category 1B Cooling and freezing;
- cumulative energy demand and resource depletion for Category 1B Cooling and freezing, 3B and 4B CRT screens; and
- acidification for Category 3A IT excluding CRT and 3C LCD Monitors and Eutrophication for Category 3C LCD monitors and Category 6 Tools.

Again, please note a few important assumptions behind these calculations. A key one is the changing waste stream composition over time which is not taken into account here. There is not enough information available yet to assess the influence of the future decline in CFC appliances returning.

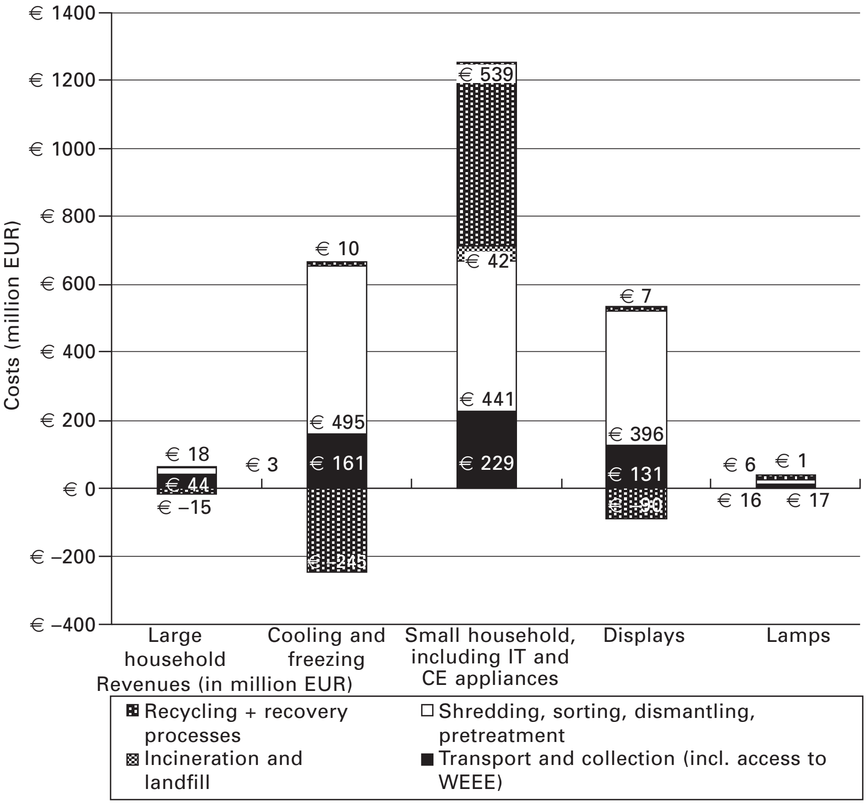
6.4 How much do WEEE have to pay?

6.4.1 WEEE economic impacts for the EU27

Figure 6.10 demonstrates the total WEEE technical costs breakdown in million euros per main collection category assuming full implementation of the WEEE Directive, being the maximum collection per category of around 65% for large appliances and 45% for small appliances. It shows the highest



6.9 Eco-indicator '99 results by increased WEEE collection 2005–2011.



6.10 Breakdown of total EU technical costs for the five main collection categories (2005 long running systems).

contributions to the total costs are from cooling and freezing appliances and small household appliances. Per collection category, the cost breakdown also varies: for Category 1A, 10 Large household appliances, the main part is the transport costs. After these transport steps, the revenues are almost equal to the further processing costs. For Category 1B, Cooling and freezing appliances, the treatment costs (CFC removal) are obviously a major portion of the total. This is also the case for the CRT-containing appliances. Although generated in small tonnages, relatively high costs per tonne occur for lamps. After transport and pre-treatment, for the small appliances there is no net revenue from the remaining fractions at 2005 price levels.

These economic impacts of WEEE take-back and treatment are influenced by:

- Prices for secondary materials. Sensitivity analysis showed that current 2011 market prices increase the revenues of the above categories by

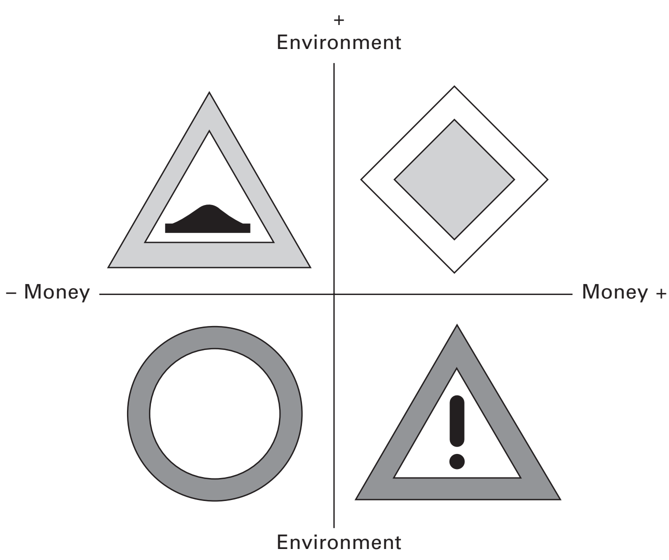
100–250 EUR/tonne compared with 2005 levels. This means a net revenue after collection and transport for most categories now.

- Developments and availability of markets for downstream fractions and high-level re-application/valorisation of secondary raw materials.
- Future developments of treatment technologies, as well as different treatment/dismantling requirements for particular product streams, which means that costs for CFC-containing appliances are likely to decrease and flat panels are expected to cause an significant increase in total costs due to costly mercury removal steps.

6.4.2 Eco-efficiency

By combining the environmental values and costs in one eco-efficiency approach it is possible to link environmental effectiveness with cost efficiency. This helps answer a central question from a societal point of view: what environmental improvements can be achieved for the money invested?

Figure 6.11 shows the basic idea behind the eco-efficiency calculations of the QWERTY/EE approach. The *x*-axis represents an economic indicator (in this case €) for the total costs along the recycling chain. The *y*-axis represents the environmental indicator (LCA scores in points from for instance the Eco-Indicator'99 or from individual environmental indicators like CO_2 equivalent or cumulative energy demand values. Different end-of-life scenarios for one and the same product, relative to a certain starting



6.11 Eco-efficiency of WEEE scenarios.

point (the origin in the figure) can be displayed as vectors. Such scenarios or options describe certain changes in end-of-life treatment or the application of certain technological improvements such as redesigned products, other pre-processing options, or separate or increased collection and treatment. In order to achieve higher eco-efficiencies, improvement options should lead to a change from the reference or starting point into the direction of the upper right part. However, options with a direction towards the bottom-left part should be avoided (higher costs and higher environmental impacts), because from the point of reference a lower eco-efficiency is realized. From this, clear lessons and priority setting can be derived as illustrated for many scenarios in Huisman (2003). Although not further substantiated here, the application of such eco-efficiency evaluations should be regarded as a crucial activity in the development and implementation of e-waste policies as it quantifies where in the end taxpayers' money could be spent best and where a low return on investment can be expected.

6.5 How do WEEE benefit from impact assessment in policy development?

6.5.1 Lessons from determining EEE and WEEE amounts in Europe

In the example of the EU27 EEE and WEEE amounts, the following practical difficulties and uncertainties influencing the collection target setting and definition are identified, based on researching in detail about these quantities:

- Most registers are far from complete and thus not a good source for historic data needed for future WEEE generated quantifications.
- None of the EU member states knows sufficiently in detail about its 'complementary streams'.
- A general percentage based EEE PoM or WEEE generated target can work as a statistical total, but it needs to be translated into specific and dynamic targets for the individual collection or product categories.
- The average product life time and market saturation conditions vary significantly per collection category and per country.
- Further country assessments/complementary stream studies are needed in order to be able to set the precise collection targets and definition criteria that are required from a legal perspective.

From these difficulties, it can be concluded that, owing to the lack of data, a precise decision on the collection target definition per country/collection category simply cannot be made yet. Positively said, the quantities assessment does pinpoint what needs to be investigated in detail per country and region to be able to set meaningful targets. The steps needed for the EU27 and WEEE recast collection target definition are described below.

6.5.2 Future work and WEEE country assessments

The following methodologies are potentially available to quantify EU EEE and WEEE amounts:

- The various National Bureaux of Statistics could provide (historic) data on EEE amounts placed on market corrected for imports and exports, provided the underlying international good codes (PRODCOM and CN) data is reliable and equipment is properly classified. The problem will be that good codes (± 300–400 codes are EEE products related) will not straighforwardly represent the various WEEE (sub)categories (International Telecommunication Union, 2009). When this data is cross-checked with data from the official registers, then by means of different correlations with, for instance, MSW amounts (Johnstone and Labone, 2004), or PPP values per capita, estimates for WEEE generated can be obtained. Importantly, these statistical bureau can be an independent data provider. Based on all quantification experiences, in early 2012 a StEP/UNU 'compatibility list' for linking any WEEE classification system is expected.
- By means of economic correlations between 'disposable income' and EEE/WEEE amounts per head as illustrated in Fig. 6.3, another cross-check can be made whether the amounts found from the previous method are reasonable. See (Huisman, 2010) and (Huisman *et al.*, 2011).
- Country studies on the size and destination of the complementary streams should be performed (WEEE Forum, 2010), preferably linked to inspection and enforcement work on 'origins' and 'destinations'. From this a country matrix per collection category could be derived which can be the basis of later updating of specific collection targets per collection category.
- For the longer term, one can develop 'lifetime – weight' distribution models (Nordic Council, 2009; Oguchi *et al.*, 2010). But this requires complete registers, plotting PoM versus disposal, including possessions studies, and sampling of (all key) return stream on weight and lifetime distribution which is only feasible for larger items and not for every type of product. Also to be included are B2B EEE/WEEE amounts in SMEs and large enterprises, which are generally overlooked.

When the above methods are applied and more information sources become available, then the following calculation steps can be followed in order to pin-point specific collection targets:

- *Step 1: Translate the 65% or 85% target into a total number of kilograms to be collected next year per country*. The chosen generic collection target as a percentage should be converted into a number of kilograms per collection category per country as a guideline for the coming 'collection year'. The guideline should make sure that the most environmentally relevant products (lamps, CFC fridges, LCD panels) do not disappear in the totals and also the deviations per member state should be taken into account. Furthermore, an extra requirement regarding the level and format of the quantities to be collected can be mandated in order to determine the annual division of the 65% target back to kilograms per EU member state per collection category.
- *Step 2: Determine the current contribution of the 5 or 6 collection categories to the total WEEE amounts*. After a certain collection and reporting period, the actual collection amount and percentage should be checked again versus the reality of the collection achievement. The resulting numbers and new POM data can then be used to repeat step 1. The gradual change indicated in Table 6.2 and the anticipated shift in age of products and country-specific consumers' discarding behaviour can be quantified by sampling the return stream and then be taken into account in the new collection targets for the next year.
- *Step 3: Correct for the expected gradual change in total composition based on sampling the return stream and past sales data and then divide the total kilograms into individual percentages per collection category. Adjust next year's division of the total collection target and redo Step 1*. The division into collection categories and compliance schemes covering such collection categories can vary per country. For instance, there are dedicated compliance schemes (often covering multiple countries) for the product categories 8 (medical), 9 (monitoring) and 10 (dispensers). In particular for large, dedicated medical appliances already EU wide (not country specific!) mature existing collection and refurbishing channels exist. It is recommended to either exclude this subcategory from any national collection targets and/or to allow separate reporting of compliance efforts to the European Commission directly.

Obviously, the above steps need to be defined mathematically in more detail and result in common European terms of reference for determining specific legal collection obligations, in which also criteria regarding data uncertainty, chosen formats, chosen statistical methods and sampling are laid down. The StEP ADDRESS work will partly facilitate such necessary fact finding. For the Netherlands, a specific study including a complementary streams assessment and prediction model for EEE/WEEE amounts took place in 2011, from which valuable lessons can be learned for later precise collection target definition. There is a great deal of feedback that also directly and practically provides a starting point for financial planning and anticipated collection amounts, registration of EEE placed on market and identification of 'free-riders' as well insights into where to intervene or enforce in the end-of-life chain for electronics. This work will be extended to other European markets in 2012.

6.5.3 Lessons from determining environmental impacts

Key lessons from applying the QWERTY methodology for the impact assessment in the EU WEEE review study (Huisman *et al.*, 2008a) are illustrated in the recommendations for shaping the collection and recycling targets and treatment requirements in the WEEE Directive recast preparation. The environmental findings and priority setting lead to the conclusion that differentiating in environmental priorities over the various treatment categories leads to the most preferable options. The above is summarised in Table 6.3 for each treatment category.

6.6 Conclusions

In general, the debates between various actors and stakeholders in many regions in the world on e-waste/WEEE responsibilities, principles, policies and management, can be regarded as highly politicised. An independent search for key environmental and economic facts and figures and research on potentially successful and unsuccessful policy options, technical developments and performance, plus reviewing other take-back system settings, can support

Table 6.3 Differentiated targets for collection, recycling and treatment

Category	Collection target	Recycling target	Specific treatment requirement
Large household (1A,10)	No	No	No
Cooling and freezing (1B)	Yes	Maybe	Yes: CFCs, in standards
Small household: 2A,3A,4A,6,7 (plastic-dominated part)	Yes	Yes: For plastic recycling	Yes: NiCd from Cat. 6, in standards
Small household: (1C, 3A) (metal-dominated part)	No	No	No
CRT containing (3B, 4B)	Yes	Yes: For CRT glass	Yes: Control over PbO, in standards
Flat panels (3C, 4C)	Yes	Maybe	Yes: For LCD Hg removal, in standards
Gas discharge lamps	Yes	Maybe for high-quality glass and fluorescent powders	Yes: Hg removal, in standards

and streamline the development of e-waste management significantly. Science-based communications with those actors can push for more data availability and transparency as well as more targeted intervening where needed from a societal point of view. In the case of the EU WEEE recast, the majority of the headlines in the UNU study listing of options for improvement are positively followed up in the various Commission and Council/Parliament proposals. In the latest document (European Parliament, 2011), the draft recommendation for the second reading by the Parliament of early August 2011, more focus is laid on: standards for collection and treatment (Art. 8 and 12), percentage-based collection targets (from 4 kg to 85%) based on the actual amount of WEEE generated, consumer education (Art. 14), other actors besides producers having responsibilities in the chain (Recital 19 and Art. 1, 14), less administrative burden by one European Union producer definition (Recital 27 and Art. 3, 16), more focus on enforcement including waste shipments (Art. 10, Annex VI), inspection of reported EEE quantities placed on the market (Art. 23 and Annex X). Also importantly: a re-categorisation into six collection categories instead of ten product-oriented categories (Annex III) is applied, by which the primary legal objective is finally where it should be from an environmental point of view: aiming to minimise environmental impacts and maximising material recovery at the end-of-life stage of electronics.

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7
The materials of WEEE

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Abstract: The chapter focuses on the materials found in, and the composition of, waste electrical and electronic equipment (WEEE). This is discussed in the context of historical, current and future WEEE, taking into account the impact new technologies have on material composition. The materials composition of WEEE is also reviewed from the perspective of the available recycling and recovery technologies used by recyclers. The recent change in the technology used for TV and computer displays is highlighted as a specific example of changing materials requirements and how they have an impact on recovery and reuse. The potential loss of valuable materials and elements in the context of the growing list of endangered elements and the need to ensure a strategic supply of such materials is also presented. Examples of novel approaches to materials recovery using ionic liquids and embedded intelligence are used to highlight the importance of new technologies in enhancing materials recovery rates from WEEE. There then follows a section that discusses some of the new materials that are beginning to find use in electrical and electronic applications and that will have an impact on the composition of WEEE in the future, e.g. nanomaterials and organic/printed electronics. The chapter concludes with sources of further information.

Key words: WEEE, waste electrical and electronic materials, scarce elements, LCDs, repurposing, recovery, recycling.

7.1 The material content of WEEE

The modern electronics industry has developed in parallel with the transistor, which was invented by William Shockley at Bell Laboratories in 1948. More recently, the evolution of the integrated circuit has enabled electronics to pervade all walks of life and to provide functionality that was unimaginable when the first transistors were produced. The widespread use of electronics has undoubtedly brought huge benefits to both individuals and society, particularly as the producers of electrical and electronic equipment have typically managed to improve performance and functionality in each new generation of products, while also reducing costs. This has also led to the commoditisation of electronics, especially in consumer devices and, for the last 20 years or so, there has been increasing concern about the fate of the materials used in appliances as products reach end of life and become waste electrical and electronic equipment (WEEE). These concerns have led to the introduction of legislation that has forced producers to take responsibility for their products, not just during their service lives but at end of life as well. Legislation such as the WEEE and Restriction on Hazardous Substances (RoHS) Directives have thus had a major impact on the choices of materials that can be used in products, since some important materials have been proscribed, while others offer benefits from an end of life recycling and recovery perspective. In addition, the economics of materials supply and their management across the whole product life cycle are key factors that will inform the choices of materials used in future products and define those which need to be developed to replace unacceptable or scarce materials.

One of the key factors that will determine the choice of the most appropriate technology for recycling is the material composition of WEEE. However, the term WEEE covers a very wide range of products from small consumer devices, such as MP3 players, to large white goods including washing machines and tumble driers. There are not only clearly significant differences in the types of equipment that constitute the various categories of WEEE but even with individual types of products. The rapidly accelerating transition from CRT-based televisions to those employing liquid crystal displays (LCDs) is a very apposite example. Also, even in terms of the materials that are common to many electrical and electronic devices, there are changes being driven by legislation such as the RoHS Directive.

Perhaps the best-known example has been the transition from lead-based to lead-free solder that has been mandated for most products put on the market in Europe since July 2006 and which now impacts manufacturers globally. Whilst for some long lifetime products such as TVs this will not have an impact for many years, the entry into the waste stream of short lifetime products, e.g. mobile phones, will mean that the metals make-up of related materials found in such devices will vary and there are likely to be a wider range of metals encountered than the tin, lead and copper associated with traditional lead-based solders and the related components and circuit boards. Similarly, the proscription of cadmium, mercury and hexavalent chromium, as well as certain brominated flame retardants, has led to compositional changes that will herald the introduction into the waste stream of a wider range of materials. This in turn will have ramifications for any new recycling technologies that are developed to address individual waste streams. In particular, it will also mean that the recyclate intended for reuse in new electronics applications will not be able to contain any materials that are proscribed by the legislation. For example, there may be a need to ensure that recycled plastic materials do not contain any proscribed brominated flame retardants if they are to be recovered for reuse rather than incinerated for energy recovery.

Most types of electrical and electronic products contain varying quantities and types of plastics. It has been understood for some time that there is a need to minimise the range of plastics used in electrical and electronic products in order to facilitate more effective recycling. The situation can be further complicated by the fact that there are compatibility issues, not only between individual classes of polymers, but also between the many different products that are produced for each class. Examples of some of the plastics commonly encountered in EEE are listed below,

- acrylonitrile butadiene styrene (ABS);
- polycarbonate (PC);
- PC/ABS blends;
- high impact polystyrene (HIPS);
- polyphenylene oxide blends (PPO)
- polyethylene and polypropylene (PE and PP).

However, it should be noted that it is quite common to find many more types of materials used in specialist applications. The ability to find uses for recycled plastics largely depends on the type of polymer, the cost compared to virgin material and the work needed to produce recovered material with the required purity and quality. For example, the separation of materials and the removal of potential contaminants such as labels, screws and fixings can significantly increase the cost of recycled materials. It is also important to consider the implications of recycling plastics that contain brominated flame retardants, due to the increasing proscription and unpopularity of these materials. Interestingly, in Japan, recycled plastics containing such flame retardants have found use as cable conduits at the side of railway lines.

Data on the specific material composition of WEEE is both limited and disparate in nature. However, information based on Japanese experiences reported in a Department of Trade and Industry (DTI) report published in September 2005 (Waste electrical and electronics equipment (WEEE): innovating novel recovery and recycling technologies in Japan), gives material compositions for the four products covered by the Japanese Home Appliance Recycling Laws (HARL). See Table 7.1.

One major difficulty from a materials recycling perspective is that it is still often uncertain how end-of-life electronics will actually be segregated during the journey from the end user to the recycler. In the case of consumer electronics deposited at civic amenity sites, a wide range of products are

Table 7.1 Materials composition (% by weight) of the four products covered by HARL in 2005

Material	Television	Washing Machine	Air conditioner	Refrigerator
Glass	57	–	–	–
Plastic	23	36	11	40
Iron	10	53	55	50
Copper	3	4	17	4
Aluminium	2	3	7	3
Other	5	4	10	3

mixed together and they can often suffer contamination and exposure to the elements, which has a negative impact on the ease of recycling and the cost of producing reusable materials. A far better approach is to segregate products by type as early as possible and to avoid subsequent contamination etc., see for example the Guidance on Best Available Treatment, Recovery and Recycling Techniques (BATRRT) and Treatment of Waste Electrical and Electronic Equipment (WEEE) (UK Department of the Environment, 2006). This would enable recyclers to implement successful category-specific focused recycling technologies, where each recycling process will have an optimum efficiency in terms of the raw material supply to be processed. Information about the materials make up required to achieve this maximum efficiency would thus enable those collecting and aggregating the specific groups of products to effectively control the product mix of WEEE in order to enable enhanced efficiencies.

7.2 Materials and their recovery and recycling technologies

Traditional materials recycling approaches for end-of-life electrical and electronic products have often been focused on the basic separation of metals from non-metals using various proprietary high volume processes based on mechanical shredding, comminution and separation technologies that produce ferrous and non-ferrous metal fractions, along with plastic and other fractions. Hammer mills and shredders are the most common comminution devices that are used to reduce WEEE to smaller sized fractions from which it is possible to isolate individual material streams. The standard approaches employed to separate these liberated materials can then include various combinations of other techniques such as manual sorting, magnetic separation, eddy current separation and air table sorting etc. Examples of the different materials recovery and recycling approaches used for large and small domestic appliances are detailed below. For larger domestic appliances, which contain significant quantities of metal, the schemes used are relatively straightforward, e.g.:

- pre-shredding decontamination i.e. removal of cables and other easily removable components and metal and plastic items;
- shredding;
- magnetic removal of the ferrous metal component;
- eddy current removal of non-ferrous metal fraction;
- remaining polymeric component, possibly for subsequent sorting.

However, for small domestic appliances, where there is a greater variety of both products and material types, the process may be more complex, e.g.:

- manual pre-treatment, e.g. for removal of individual components e.g. ink cartridges, batteries and cables etc.;
- removal and separation of individual components;
- mechanical separation to give coarse ferrous and non-ferrous fractions as well as a fine material fraction;
- use of a picking station to remove remaining items such as batteries capacitors, electric motors, printed circuit boards and any identified hazardous materials;
- granulation to give further non-ferrous and ferrous fractions;
- separation of non-ferrous from polymeric fractions.

In the past, the metals have typically been consigned to a refining process, while the plastics were either incinerated to recover the embodied energy or sent to the Far East for manual sorting, recovery and reuse in secondary applications. However, because of the disparate nature of the materials used in electrical and electronic products, complete separation and recovery of all of the materials is not possible within the typical economic constraints that normally apply. For example, the plastics waste stream generated by the established primary WEEE treatment processors in the UK and Europe is typically not a simple mixture of a few polymer types and there is a need for new high efficiency separation processes that can generate discrete high purity polymer recyclate streams. Such a process must be highly efficient and able to handle and remove a wide range of contaminants such as dirt, glass, stones, rubber, wood, card, paper and cables etc.

Although contamination is often present, the mechanical processes used by recyclers do usually manage to separate out at least four basic different material fractions, which are ferrous metal, non-ferrous metal, plastics and printed circuit board (PCB) fragments. The metal and PCB fractions are normally consigned to pyrolysis-based metal refining treatments (Goosey and Kellner, 2002). The manufacturers of electrical and electronic products use a wide range of different polymers and formulations within their products, which leads to the recyclate produced by these mechanical processes being complex in composition. Polystyrene-based polymers and polypropylene account for a large percentage by weight of all plastics used in the manufacture of these products. In large household appliances, the most commonly used polymer types are polypropylene, polyurethanes and the styrene-based materials (Goosey and Stevens, 2009). Unfortunately, the additional use of many other small polymer parts produces a complex waste stream that has many implications for the subsequent separation of a fraction for recovery and recycling. This is a situation that can be further complicated by the presence of PVC which, while being recyclable, causes problems because of its halogen content.

One novel polymer separation process developed by the Argonne National Laboratory (Pomykala *et al.*, 2007) uses a technique known as froth flotation to separate the different types of polymers. In this process, gas bubbles attach to the surface of the polymers, thereby modifying their effective density and enhancing the separation of lighter fractions from denser ones. A pilot plant with a 2 tonne per hour capacity was built and this consisted of a mechanical separation facility and a six-stage wet density/froth flotation plant. In the mechanical part of the plant, the shredder waste was separated into five primary components: a polymer fraction (about 45% by weight), a residual metals concentrate (about 10% by weight), a polyurethane foam portion (about 5% by weight), an organic-rich fraction (about 25% by weight) and a metal oxides fraction (about 15% by weight). The polymer fraction was then separated further in the wet density/froth flotation system to recover individual plastic types or compatible families of polymers.

As reported above, many of the plastics used in electrical and electronic product applications are flame retardant grades and this property has traditionally been imparted via the use of brominated flame retardants (BFRs) such as the polybrominated diphenyl ethers (PBDEs). Given that some of these materials are now proscribed by legislation, there are widespread concerns about both the use and impacts of these materials. Many manufacturers have made commitments not to use them in their products, but there is still a need to segregate polymers containing BFRs from those without them when recycling at end of life. Rapidly identifying flame retardant grades of polymer in a mixed waste stream is not an easy task and methods for their detection tend to be based on the use of a range of advanced spectroscopic techniques, as detailed in the Combident report (Fh-ICT, 2001). Examples of these spectroscopic methods include;

- near infra-red (NIR);
- mid infra-red (MIR) reflection;
- MIR pyrolysis;
- Raman scattering;
- mass pyrolysis;
- sliding spark (spark ablation);
- X-ray fluorescence;
- MIR acousto-optic tunable filter (MIR AOTF);
- laser-induced plasma spectroscopy (LIPS).

In 2005, over 300 million tonnes of PVC were estimated to be in existence around the world and there is a real need to develop new recycling processes for this polymer. PVC recycling is difficult because of the relatively high separation and collection costs, the potential for loss of material quality after recycling, the low market price of PVC recyclate compared with virgin PVC and, therefore, the limited potential for reuse. Several routes are available for recycling PVC materials including simple size reduction (fragmentation, regrinding and pulverisation), mechanical contaminant removal (via melt filtration, tribo-electric separation, air classification etc.), dissolution methods (such as the Solvay Vinyloop process) and feedstock recycling. Feedstock recycling of PVC is not realistically feasible at the moment from an economic or an environmental perspective and it is doubtful whether it will ever play a significant role in PVC waste management. There are clearly significant opportunities to develop new materials recovery and recycling processes for PVC (Braun, 2002; Sadat-Shojai and Bakhshandeh, 2011).

In Japan, recycling of domestic electrical appliances such as TVs, washing machines, refrigerators and air conditioners is carried out in a much more controlled way than it is in Europe and this enables different approaches to be adopted that can produce a better quality recyclate which is more likely to find reuse (UK Department of Trade and Industry, 2006). Such end of life appliances are transported to recycling centres that employ what are effectively production lines operating in reverse. In this way, there is an opportunity to remove plastic equipment casings manually and these can then be more easily segregated according to polymer type. This makes subsequent processing much easier and enables clean, good quality polymer streams to be produced via mechanical processing and reformulation. These output polymers are then typically used in lower grade applications in new products. It is interesting to note that the Japanese large electrical and electronics manufacturers are heavily involved in the end-of-life and recycling operations via ownership of recycling facilities. This not only enables them to be involved in the whole life cycle of their products but it also gives them an internal outlet for recycled materials.

7.3 The transition from cathode ray tube (CRT) to liquid crystal display (LCD) display screens and its implications for materials recycling

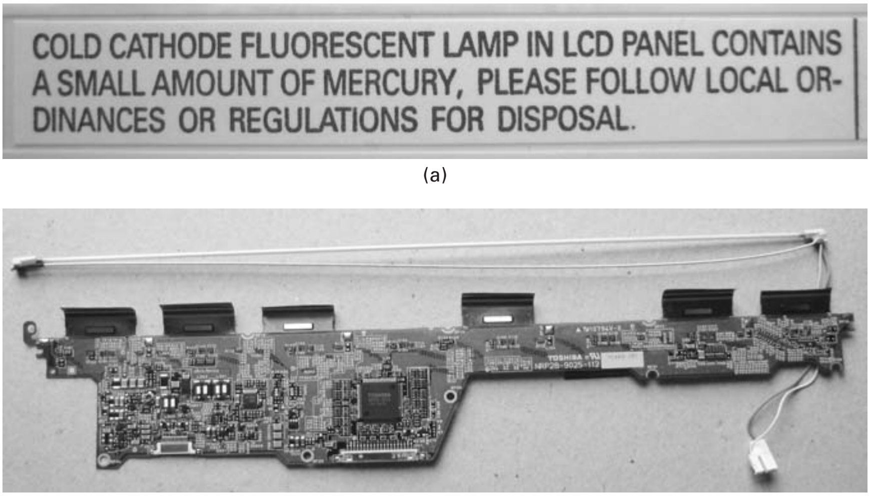
Since the introduction of television broadcasting over 80 years ago, the cathode ray tube (CRT) has been the predominant device used for displaying images. However, over the last ten years or so, the ability of liquid crystal-based devices to provide large area, full colour displays (LCDs) has led to their widespread use in TVs, computer monitors and related applications. Such has been the degree of change, that it is now effectively impossible to purchase a CRT television or computer monitor. From a materials end-of-life and recycling perspective, there have been a number of major impacts of this move to LCD technology. Firstly, the materials used in each type of display are totally different and it is interesting to note that this change in technology effectively represents the same type of change as that from the use of thermionic valves to discrete transistors. The older CRT technology was based on the use of glass vacuum tubes and metals, whereas the new flat panel LCDs utilise solid state switching technology which in turn has required the use of a wider range of disparate and often higher value materials.

With the emergence of large area LCD display-based televisions, there has been a purging of CRT-type TVs from the system, which has led to large numbers of CRT TVs appearing at recycling sites. Fortunately, there are established treatment routes for CRTs and, although these will undoubtedly continue to appear in the waste stream for a number of years, their numbers will eventually decline. LCDs have also been appearing in the waste stream in growing volumes for a number of years and these now also need to be processed in an efficient manner that enables as much of their materials as possible to be recovered for reuse. LCDs contain a number of valuable materials, such as the liquid crystals themselves, indium, tin, gold and other metals and there is clearly some additional value via the various other materials and components they contain (Matharu and Wu, 2009). This has generated considerable interest from recyclers, who are interested in recovering the maximum value from recycling such displays.

However, LCDs can also contain hazardous materials and one such material that is commonly encountered is the heavy metal, mercury. Unlike CRTs, LCDs need a back light source to make the display effective and this has typically been achieved by the use of miniature strip lights placed behind, or at the edges of the display to produce a uniform white illumination that is transmitted through the liquid crystals to the viewer. These so-called cold cathode fluorescent lamps (CCFLs) typically contain small amounts of mercury, which is highly toxic. An example of a CCFL, its associated driver circuitry and warning label from a laptop computer are shown in Fig. 7.1.

Mercury presents a major problem for recyclers, since these tubes are very delicate and are easily broken, leading to the potential for mercury contamination and exposure in recycling facilities. This includes exposure to workers involved in the manual disassembly of such devices or contamination of materials and the local environment when mechanical techniques, i.e. comminution and shredding, are used as part of the materials separation and recycling process.

The issues around the presence of mercury in LCDs are therefore significant and present a currently unresolved challenge for recyclers who have to handle end-of-life LCD TVs and monitors. More recently, LCD manufacturers have started to use light emitting diodes (LEDs) as backlights instead of the mercury-containing fluorescent tubes, and it seems likely that these may soon be the dominant backlight technology (Jamieson, 2006; Gagnon and Torii, 2011). However, there are huge numbers of displays that contain mercury backlights and these will be appearing in the waste stream for many years to come. There is thus a real need to understand the scale of the problem and to provide safe and economically viable solutions for those engaged in the treatment of end of life displays.



7.1 Compact fluorescent tube, driver circuitry and warning label removed from a laptop computer.

Standard hand-dismantling of LCDs is a very labour-intensive process requiring a large number of manual operators if significant quantities of units are to be processed. In a study undertaken by a large electronics recycling company (author's unpublished data), trials were conducted with between six and eight operators per shift who were each able to take apart the components at a rate of 10 units per hour. It requires patience and concentration to dismantle the displays and to remove the fluorescent tubes without breaking them during this process. In trials using a mechanical shredder, 5.4 tonnes of material was processed in one hour without any prior manual disassembly. The trial was completed on an existing WEEE scrap processing line that included all the downstream metals recovery equipment but which, for the purposes of the trial, did not have any dust extraction etc. The capital costs of such a line would be around £1 million and this would be able to shred approximately 10 000 tonnes of LCD units per annum. In terms of labour costs, the savings from not having to operate a disassembly line would mean that the capital costs of such a process line could be recovered within one year. The overall running costs of a standard shredder line are obviously dependent on the volumes being processed: the higher the volume, the cheaper the process (usually) but, overall, the costs for mechanical recycling are far lower than for hand dismantling. Such a processing plant will produce the following output from the shredded LCDs: steel, non-ferrous metals, circuit boards, plastics, glass and a remaining waste fraction depending on the level of sophistication of the plant.

Currently, in a typical shredding plant only the steel and non-ferrous metals are likely to be recovered because of the increased capital cost needed to separate out all the other materials. Since there was no removal of the backlights from the displays, there was the issue of mercury contamination in the various materials recovered after the shredding operation. In order to make an assessment of the real levels of mercury contamination actually occurring in the shredding process, the separated fractions were analysed using a hand-held X ray fluorescence (XRF) spectrometer and the results compared to the contamination found in a low grade shredded e-scrap material. The results are shown in Table 7.2 below. (It should be noted that these are single point inspections (snap-shots) and may not be fully representative of the contamination levels of a full scale process.)

As can be seen from Table 7.2, most of the contamination appears to remain in the steel fraction, with little or no effect on the quality of the aluminium or waste fractions. As previously mentioned, there was no air extraction on the shredder and this may be the reason for the apparently high level of mercury found in the steel. While the high levels of mercury found in the steel fraction suggest that less than anticipated amounts of mercury may enter the atmosphere, workers involved in this type of recycling operation should be provided with suitable protective equipment and the operation should be undertaken in an area where there is good extraction capable of capturing volatilised mercury.

7.4 The loss of scarce elements

Significant growth in the production of electronic devices has put huge demands on the supply of materials needed to manufacture these products. In some cases, there is no immediate problem in supplying the requisite materials but, for some of the other rarer materials that are often needed, there are increasing concerns about their continuing supply, as the known accessible reserves are either finite or they may be restricted by their producer countries. Over the last 20 years or so, there has been a significant migration of electronics manufacturing capability from the West i.e. Europe and the USA to the Far East and particularly to China. The result has been that most of the consumer

Table 7.2 Post-treatment heavy metal contamination in standard e-scrap and LCD displays (author's unpublished data)

Material	Mercury (ppm)	Cadmium (ppm)	Lead (ppm)
Low grade steel	1000	112	510
LCD steel	3000	401	1800
Low grade aluminium	153	145	25
LCD aluminium	25	160	19
Low grade waste	46	182	59
LCD waste	66	111	22

electrical and electronic appliances used in the West are actually produced in China. This has led to the scenario that, while the materials needed to make these products are required in China, at end of life they are typically often a long way from where they could be reused. Access to these materials also has strategic implications and ensuring security of supply may become an issue if developing countries such as China control the supply chains of key elements and minerals through the use of export tariffs and restrictions in order to protect their own internal demands that arise from fast technological growth. In addition, some of the more important elements required for current electronics production are largely extracted from mineral deposits in China. According to the British Geological Survey, China supplies about 96% of the world's rare earth elements and it has recently started to cut its exports of these important materials (Davies, 2011). This is partly because there is a large demand for the materials within China itself, e.g. for neodymium, dysprosium and terbium.

There are thus growing concerns in the West about the continued supply of these strategically important metals and new approaches to their sourcing are beginning to be adopted. One route would be to establish new primary sources by opening mines where there are reserves, but consideration is also being given to potential secondary sources, i.e. by recovering the materials from waste electrical and electronic products. One such example is neodymium, which is used in the magnets found in computer hard drives and which can thus be found in relatively high concentrations in end-of-life computers etc.

7.5 Novel materials recovery approaches

Companies undertaking materials recovery from WEEE typically try to keep the number and complexity of any treatment stages to a minimum for the simple reason that each stage used adds additional costs that cannot be recovered, thus reducing the overall return obtained from the recovered materials. For example, the plastics fraction from the treatment of WEEE is typically in the form of a mixture of flakes of all the common types of polymers that are a few centimetres in size. Current options for their subsequent treatment, recycling and/or disposal include some further types of sorting and grading or incineration for energy recovery. While it is possible to use the mixed polymer waste for energy recovery via incineration, the process is often compromised by the presence of PVC, which is commonly found in this type of product. When incinerated, PVC decomposes to give a range of persistent organic pollutants that are highly toxic and which require the incinerator facility to be equipped with scrubbers etc. If the PVC could be selectively removed it would enable the remaining materials to be more safely incinerated. Ideally, however, it would be preferable to separate the individual polymer types and, at the moment, if such sorting is required, it is undertaken manually, often by low-paid workers in China. These workers are apparently able, with the minimum of equipment, to identify individual types of plastics and when these have been sorted they are recompounded into recycled materials that are used by moulders in China to make new products.

While it is preferable to recycle these materials, the shipping of mixed polymer waste to China to have it sorted by hand is much less desirable from an environmental perspective. A technique for identifying polymers in a mixed polymer waste stream has been developed by workers at the University of Surrey and this uses a multi-wavelength spectroscopic analytical technique in combination with sophisticated statistical analysis methods to rapidly identify individual polymer types, thereby allowing them to be sorted (Stevens *et al.*, n.d.). Although this method is only at the feasibility stage, it does offer the potential to enable recyclers of WEEE to carry out polymer identification and separation in house rather than having to consign it to hand sorting in the Far East.

Research has recently been carried out in the UK to develop a new method for the separation of individual polymers found in the mixed recyclate from WEEE which is based on the use of ionic liquids (UK Technology Strategy Board, 2008–2011). (In this case, ionic liquids are defined as salts that are liquids at room temperature and which posses a range of novel properties, including the ability to selectively dissolve thermoplastic materials; Freemantle, 2009.) This novel approach seeks to use a range of newly developed ionic liquids to selectively isolate specific polymers and to enable their recovery in a highly pure form separate from other polymers and their fillers and additives. Once a polymer fraction has been separated from the other WEEE materials, i.e. metal and PCB fractions, and possibly itself sorted into different types of polymers, tailored ionic liquids can be used in a closed loop process to dissolve an individual polymer type that can subsequently be reused in new formulations.

If this, or any similar process, is to be successful in producing high quality polymers from WEEE, it is likely that the incoming materials may actually need to be pre-sorted into individual polymer types prior to treatment. However, there is also interest from recyclers in being able to selectively remove PVC from mixed polymer streams and the aim here could be to dissolve it using a specific type of ionic liquid. Recovery of the pure PVC would enable it to be used elsewhere, while it would be possible to consign the remaining material to incineration for energy recovery.

There are various mechanical methods that can be used to reduce the size of the plastics arising from WEEE and each recycler tends to use their own proprietary variations on a basic theme. For example, shredders are used to carry out initial size-reduction on large pieces of WEEE-derived plastics. Shredders utilise a rotary and slow speed chopping, ripping and tearing action to reduce the size of the plastic pieces and the actual final material size is determined by forcing material through a fixed aperture screen. Shredders can function even if there is a degree of metallic contamination such as from clips, screws or inserts that may be present with the plastic and thus there may need to be a subsequent metal removal stage. Typically, a shredder would be used to produce materials with at least one dimension in the size range of 20 to 50 mm.

Where it is necessary to reduce the particle size further, polymer flakes can be introduced into a granulator or grinder which is designed to produce fine granules of plastic. These machines typically use the scissor or guillotine cutting action of close tolerance sharp blades spinning at high speed. The ultimate output particle size is determined by a rigid mesh screen that is often positioned close to the cutting zone and is usually less than 10 mm in size. Granulators typically have a low tolerance for metal contamination in the feed materials as it can blunt or damage the edges of the cutting blades. Depending on the source of the material to be treated, it may be necessary to undertake demetallisation prior to the granulation stage in order to avoid damage to the equipment. In conventional mechanical WEEE treatment processes, there can be three stages where metal is removed, e.g.;

- Removal of large pieces of metal prior to shredding.
- Removal of screws, inserts and other smaller pieces prior to granulation.
- Removal of fine metal residues after granulation.

There are a number of established techniques available for the removal of metal and examples of these and their equipment are given below;

- Permanent or over-band magnets – for removal of large ferrous pieces.
- Magnetic head rollers – for ferrous and some stainless steel removal.
- Eddy-current separators – for removal of non-ferrous metals.
- Inductive metal removal methods – for all types of metal.
- Vibrating tables and air-classifiers – for fine particle removal.

New materials recovery technologies are also needed for some of the more specialised materials that are increasingly found in electronics applications. One such example is the metal indium, which is widely used to manufacture the indium tin oxide transparent conductive electrodes that are found in most displays. Indium is only used in relatively small quantities in individual displays but since supplies of this valuable metal may be exhausted by as soon as 2020, there is a clear need to find efficient and economical ways of recovering this valuable metal from the large number of displays reaching end of life. Technically, the recovery of indium from end-of-life LCD displays is not particularly difficult, but it will probably require a multistage approach (Hsieh *et al.*, 2009). One such approach was proposed during a recently completed multi-partner research project into liquid crystal recycling that was supported by the UK's Technology Strategy Board. This approach involves the removal of the actual displays themselves from the display assembly, followed by comminution and subsequent dissolution of the indium tin oxide. Following some further treatment stages the indium could be recovered by electrochemical recovery, after which is was further purified.

It should also be noted that other electronics-related applications are being proposed for indium and these could actually lead to increased demand for the metal. For example, there is growing interest in the use of compound semiconductor materials as alternatives for silicon in photovoltaic (PV) applications (Anwar, 2008). One such material is copper indium gallium diselenide (CIGS). This thin film semiconductor material can give efficiencies of 20% and thus it is a very promising material that will achieve growing use in PV applications. It is predicted that, in less than ten years, CIGS production may require around 10% of the known available indium. Clearly, with a finite primary supply of the metal, there is a growing need to implement efficient indium recovery processes. However, also because of the finite supply of indium and the current limited ability to recover it economically, there is research underway to develop alternatives to indium tin oxide that can utilise more abundant materials. Examples of these are discussed later in this chapter.

Although the introduction of new materials may necessitate the development of complementary materials recovery and recycling technologies, there are also measures that can be utilised to enable recycling to be undertaken more efficiently. For example, if information can be provided to recyclers about the specific materials and components used in a particular product, it would enable more informed decisions to be made about their recovery and recycling. One such approach to the provision of this type of information involves the incorporation of intelligence into a product via the use, for example, of an embedded wireless component that can provide data to recyclers. One such proposed approach involves embedding wireless components known as RFIX tags into the multilayer circuit boards used in many electronic products (Murata, 2009). These devices enable product-specific life-cycle information to be available to recyclers so that they can make more informed decisions about the value of a product and thus the best way to undertake recycling. The information can include a use profile, a bill of materials, details of the product's manufacturer, disassembly guides, location of valuable components and specific materials content, e.g. hazardous materials or materials of high value. At end of life the RFIX devices can be remotely interrogated via a wireless reader which provides real time information to enable recyclers to make decisions about the best reuse, recovery and recycling strategies to implement on an individual product basis. As they are radio-based devices, no line of sight is needed to interrogate these devices and one reader can be used to interrogate multiple tags over a range of up to approximately 10 metres (depending on reader power and operation frequency). At the time of writing, this concept was being developed by a UK-based multi-partner research consortium in a project known as InBoard. Further information on this project can be found in the paper by Bindel *et al*. (2010).

7.6 New materials and their implications

The continuing introduction of new and better performing electrical and electronic products has often been made possible through the development and application of innovative new materials. Sometimes, the use of these materials enables incremental improvements in existing products, but they may also lead to the introduction of completely new technologies that offer a paradigm shift away from the established approaches. The shift from CRT-based televisions to those employing LCDs discussed above is perhaps the best known example and the use of LCDs has also diffused into a wide range of complementary products such as computer displays, mobile phones and other portable devices. There are many materials innovations that are likely to emerge in the future and while these will undoubtedly enable new and improved products to be manufactured, they will also have specific treatment requirements at end of life in terms of recycling, recovery and potential environmental impact etc. It is beyond the scope of this short chapter to cover these in detail, but a few examples are now cited in order to give an overview of some of the implications of new materials development.

The issues regarding the use of mercury-containing compact fluorescent tubes to provide the backlighting mentioned above have meant that the use of conventional mercury-containing backlights is declining and there has already been considerable progress made in the development and implementation of new types of backlight technology based on the use of LEDs. LEDs are effectively solid state equivalents of miniature light bulbs that are available in a range of colours and which have extremely good reliability with long service lives. These LEDs come in several forms and are employed in different ways, depending on the preference of the manufacturer and the specific product. From an environmental perspective, an LED-backlit LCD TV is considered to be more sustainable, as it will have a longer life and better energy efficiency than both plasma and conventionally backlit LCD TVs. Also, LEDs do not contain mercury. However, LEDs do contain other elements with questionable environmental credentials, examples here being gallium and arsenic. This means that there may still be issues to be addressed regarding these materials when undertaking recycling operations at end of life and it is not yet clear if they offer a significantly better long term solution to the current problems encountered when treating end of life TVs (Lim and Schoenung, 2009; Lim *et al.*, 2011).

For the future there are moves to develop alternative materials that could ultimately displace LCDs in a similar manner to how LCDs replaced CRTs. Two key examples that are currently in development are displays based on either organic light emitting diodes (OLEDs) or quantum dots. However, there are also other new display technologies that are likely to emerge and it has been predicted that, by 2020, the use of OLED displays for TVs will be greater than that of LCDs.

OLEDs are a type of LED in which the emissive electroluminescent layer is formed from a film of organic compounds, as opposed to conventional LEDs, which utilise compound inorganic semiconductor materials. Their key advantage is that, because the OLED structure emits light, there is no need for a backlight in typical display applications. There are two types of OLEDs from a materials perspective; those based on small organic molecules and those that use polymers. OLEDs offer a number of other advantages for displays, but they also currently exhibit a number of disadvantages, such as sensitivity to moisture and a reduced light output capability, both of which still need to be addressed. It seems likely that OLEDs will enable display technology to move to very thin lightweight displays, which may also be operated using organic thin film transistors. This could ultimately lead to far fewer materials being required for a given display area than is currently the case.

Another display technology, which is perhaps a little further away from commercial exploitation, but which is receiving much attention, is based on the use of quantum dots. A quantum dot is a type of semiconductor material with electronic properties somewhere between those of bulk semiconductors and discrete molecules. There has been a lot of recent interest in using quantum dots as LEDs to make displays (QD-LEDs) and other light sources. The first proof-of-concept quantum dot display was produced several years ago (Nanowerk News, 2006) and quantum dots are increasingly being considered important materials for future displays. Quantum dots can also be made to emit white light and these could also be used as an alternative light source for LCDs. The materials originally used to produce quantum dots often included materials such as cadmium, e.g. cadmium selenide and cadmium sulphide, which are now effectively proscribed in many applications including consumer electronics. Consequently, alternative materials will be needed before they can be widely used in displays and there are reports of a range of quantum dots having been produced that are free of restricted and hazardous materials; see for example the web site of the company Nanoco (Nanoco, n.d.), which claims to have developed a range of restricted metal-free quantum dots that show bright emission in the visible and near infra-red.

At a perhaps more prosaic level, there have been moves to develop new polymers for electrical and electronics applications that are not derived from petrochemical-based precursors. A relatively new biodegradable polymer that has received a lot of attention in recent years is polylactic acid (PLA). This is a thermoplastic aliphatic polyester that is derived from renewable resources including corn starch, wheat and sugar cane. There have already been some moves to replace the conventional plastics used in mobile phone and laptop cases with more sustainable materials, such as PLA (Dorgan *et al.*, 2001). Examples from Japanese manufacturers include composite polymers made using the natural fibre kenaf to reinforce the PLA (Serizawa *et al.*, 2006). Also, NEC Corporation has developed a flame resistant biodegradable PLA resin that avoids the use of halogen or phosphorus-based flame retardants and, instead, uses a proprietary metal hydroxide. However, if new materials such as PLA do find increasing use in electrical and electronic applications, there are likely to be issues around how they are best treated at end of life. Concerns have already been voiced that PLA has not yet been properly tested for recyclability and that it could be detrimental to the established recycling systems currently in use for the more traditional range of polymers.

There are concerns about the finite supply of a number of key materials used in electronics applications and, in addition to the development of new recovery methods, there is also research work underway to develop alternative materials, see for example the US Department of Energy's Report (2010). A detailed review of the research is beyond the scope of this chapter but an example worth citing is that of indium, which has a number of key applications in electronics, as described above. Indium is used in indium tin oxide which is the transparent conductive film used in many displays and, to give an indication of the scale of the demand for this metal, the total transparent conductor market has been valued at over US$3 billion for 2011 and is predicted to reach US$10 billion by 2018. Because of potential future supply problems with indium, researchers have been working to develop alternative materials and it is estimated that the market for materials to replace indium tin oxide will be worth almost US$1.9 billion by 2018. In addition to providing direct replacements for indium, it is hoped that some of the new materials will have enhanced properties, e.g. there is a need for more flexible transparent conductors that can be used in plastic electronics applications. The key properties that are important with these types of film are transparency, conductivity, flexibility/resiliency and cost. One approach is to produce alternative oxide materials such as antimony tin oxide, but these tend to exhibit the same issues as indium tin oxide and so intrinsically conductive polymers and nanomaterials such as graphene are also being developed. Some examples of potential replacements for indium tin oxide are as follows:

- Antimony tin oxide – a lower cost, indium-free oxide material, but which still exhibits the same problems, e.g. lack of flexibility.

- PEDOT/PSS – a conducting polymer made from polyethylene dioxythiophene and polystyrene sulphonic acid which is highly transparent but which needs conductivity enhancements to equal the performance of indium tin oxide.
- Carbon nanotubes – these nanomaterials are solution based and are thus easier and cheaper than ITO to deposit on glass and plastic surfaces. A transparent tangled mat only a few nanometres thick can provide similar conductivity to indium tin oxide.

If, as predicted, there is continuing use of these types of new material to replace indium tin oxide, there could be new issues to be addressed as products containing them reach end of life. Although the use of conducting polymers may not present a major problem, the presence of antimony may require more attention and there are also concerns about the potential health and safety impacts of carbon nanotubes (Lam *et al.*, 2006).

7.7 Summary and conclusions

The development and implementation of new materials technology have been key factors enabling the wide proliferation of electrical and electronic products in all walks of life. However, the large volumes produced have also resulted in the emergence of huge quantities of waste materials being generated when they reach end of life. This has major environmental and sustainability implications and there has been growing pressure to apply new materials management approaches to end-of-life waste electrical and electronic products. The implementation of producer responsibility legislation such as the WEEE and RoHS Directives has required electronics producers to consider end-of-life implications at the design stage of their products. This has resulted both in a change in the types and quantities of materials used in electrical and electronic products and in the approaches required at end of life to enable better recycling rates to be achieved. New materials are continuing to emerge which enable improved product performance, as well as reduced environmental impact from a life-cycle perspective and this trend is likely to continue as consumers demand new products and as legislation proscribes the use of conventional materials. It will be important to ensure that viable end of life treatment and recovery technologies are available to handle both these new materials and to enable the recovery of valuable materials that are in finite supply from primary sources.

7.8 Sources of further information and advice

There are numerous sources of further information relating to the specific materials related contents of this chapter. For example, the Royal Society of

Chemistry recently produced a book entitled *Electronic Waste Management* in its series on Issues in Environmental Science. The details of this book are as follows;

Electronic Waste Management: Design Analysis and Application. Edited by Hester R F and Harrison R M. 2009. The Royal Society of Chemistry, Cambridge. ISBN: 978-0-85404-112-1.

Other useful sources of information and advice are as follows: In the UK, the Environment Agency is public body whose principal aims are to protect and improve the environment, and to promote sustainable development. It plays a central role in delivering the environmental priorities of government. The Environment Agency provides information and advice on complying with the WEEE Regulations to producers of Electrical or Electronic Equipment (EEE) and the waste management industry. There is a large amount of information on its website, see for example: http://www.environment-agency.gov.uk/business/regulation/31975.aspx.

Also in the UK, the Waste Resources Action Programme (WRAP) has supported work into the recycling of materials from electronics waste and more details, including downloadable versions of reports, can be obtained by visiting their website at www.wrap.org.uk and especially at: http://www.wrap.org.uk/recycling_industry/information_by_material/electrical_and_electronic_products

Another key organisation involved with end of life electronics and materials recycling is ICER, the Industry Council for Electronic Equipment Recycling. ICER is a cross-industry association focusing on WEEE and it is a source of knowledge and expertise, as well as being the key forum for industry. ICER members include equipment producers, retailers, waste management companies, WEEE treatment facilities (recyclers) and producer compliance schemes. More information can be found at the ICER website: www.icer.org.uk.

A UK company that has been actively involved in the recycling of plastics from WEEE is Axion Polymers Ltd, Langley Road South, Salford, Manchester M6 6HQ. Visit http://www.axionrecycling.com/polymers.cfm for more details.

Information on the REACH Regulations is available from the European Chemicals Agency (ECHA) which is based at Annankatu 18, 00120 Helsinki, Finland. Information is also available at the ECHA website: http://www.echa.europa.eu.

In Ireland, the Environmental Protection Agency (EPA) provides information and advice on environmental legislation such as the WEEE and RoHS Directives. The EPA is headquartered at PO Box 3000, Johnstown Castle Estate, County Wexford, Ireland and further information is also available at the EPA website; http://www.epa.ie.

Another good source of information on all aspects of electronics waste and related materials can be found in the proceedings of the biannual Joint International Congress and Exhibition known as 'Electronics Goes Green'. The proceedings are published by Fraunhofer IRB Verlag, Stuttgart, Germany. An example is the proceedings of the *Electronics Goes Green 2008 Joint International Congress and Exhibition – Merging Technology and Sustainable Development* edited by Herbert Reichl, Nils Nissen, Jutta Müller and Otmar Deubzer, ISBN 978-3-8167-7668-0, and available from Fraunhofer Institut Zuverlässigkeit und Mikrointegration (IZM), Gustav-Meyer-Allee 25, 13355 Berlin, Germany. (See http://egg2008.izm.fraunhofer.de for more details.)

Greenpeace International has been very active in highlighting the global issues associated with end-of-life electronics and in promoting best practice in recovery and recycling of materials. It provides a wide range of useful information on greener electronics on its website. See for, example, http://www.greenpeace.org/international/en/campaigns/toxics/electronics/.

In the United States, the Environmental Protection Agency (EPA), is working to educate consumers and others about the reuse and recycling of electronics. See for example: http://www.epa.gov/osw/conserve/materials/ecycling/.

The Japanese electronics company Panasonic (Matsushita) has taken a proactive approach to the recovery and recycling of materials from end of life electronics and, in Japan, it operates the PETEC facility (Panasonic Eco Technology Centre). See http://panasonic.net/eco/petec/ for more information.

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8
Refurbishment and reuse of WEEE

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Abstract: This chapter gives an overview of waste electrical and electronic equipment (WEEE) refurbishment and reuse. It begins by stating why the management of end-of-life (EoL) electrical and electronic equipment deserves more focus than most other categories of solid waste. It describes and differentiates the reuse processes available for WEEE management, and based on this gives an industry sector specific example by describing the refurbishment of computers. It also outlines the key issues and future trends in that area.

Key words: sustainable manufacturing, reuse processes, design, business models.

8.1 Need for WEEE refurbishment and reuse

Key manufacturing challenges include pollution, natural resource depletion, waste management and landfill space, thus increasingly severe legislation now demands a reduction in the environmental impacts of products and manufacturing processes. The accelerating pace of technology effectively renders sectors of products obsolete almost as soon as they are purchased. This is especially true for electronic and electrical equipment where ever-improving gadgets provide many benefits but unfortunately also now contribute towards these products becoming our most rapidly growing waste stream.

The quantities of waste generated each year from electrical and electronic products will continue to rise (Ijomah and Chiodo 2010). However, product life cycle analysis (LCA) demonstrates that the disposal phase contributes substantially to the environmental impacts of Waste Electrical and Electronic Equipment (WEEE), (Hawken, 1993; EEC Council Directive on Hazardous Waste, 1991; EEC Council Directive on Hazardous Waste, 1994), particularly in products containing toxic materials, scarce or valuable materials, or materials with a high energy content. Within WEEE there is the combination of all these situations, including for example, batteries, quality plastics, precious metals and toxic solder. Reuse and refurbishment of WEEE are therefore critical because of the significant environmental impacts of WEEE.

8.2 Reuse processes and their role in sustainable manufacturing

8.2.1 Component versus material reuse

The general reuse strategies include recycling, repair, reconditioning and remanufacturing, all are important sustainable manufacture strategies because they help to limit landfill and the need for virgin material use in production. Since they typically involve some degree of disassembly, they are also called disassembly processes. However they are not all equal. Repair, reconditioning and remanufacturing (also known as component reuse, product recovery or secondary market processes) are the various production processes that use components from used products and are preferable to recycling (material reclaim/recovery or material reuse). Recycling describes the series of activities by which discarded materials are collected, sorted, processed and used to produce new products (NRC, 1999). The advantages of product recovery over recycling include (Ijomah, 2010):

- Product recovery is an 'addition' process while recycling is a 'reduction' process because product recovery *adds value* to waste products by bringing them back to working order; recycling, on the other hand *reduces* the product to its raw materials.
- Less of the energy and resources used in the product's original manufacture are lost via product recovery. The reason here is that product recovery keeps the product as whole as possible, thus retaining the energy and resource input into them at their first manufacture. Recycling by reducing the product to raw material loses the bulk of this energy and resource. This loss is even greater if factors such as the resource and energy used in raw material extraction and transportation are included.
- Energy and resource expenditure to obtain a useful product again from the waste product is greater via the recycling approach. This is because with recycling, energy is expended twice; firstly, in 'reducing' the product to raw material (e.g. by smelting), and, secondly, to turn the reclaimed materials into useful products.
- Designers may be unwilling to use recycled material because they are unsure of the quality (Chick and Micklethwaite, 2002). The highest form of product recovery, remanufacture, is typically much more profitable than recycling, especially for large complex, mechanical and electromechanical products.

The decision to use product recovery should be carefully considered as under certain circumstances it can be counterproductive to sustainable development, for example, by assisting inefficient products to stay in circulation longer than may be desirable. This is the case for products where the newer generation products tend to be more environmentally friendly and cost effective in operation, for example, new version washing machines typically require less water, detergent and electricity. Ideally product recovery should be used when it would be both profitable and environmentally beneficial to do so. Other issues to consider include the establishment of new business models that include an effective reverse logistics system to ensure adequate quantities of used products (cores) to support the product recovery processes. The reason here is that used products are the primary ‘raw material’ source in product recovery: firstly, they cannot begin without used products to rebuild, and, secondly components to assist product rebuilding should ideally be obtained from other failed similar products since using virgin components would raise production costs and hence product price. This is particularly important as consumers will purchase recovered products only if they are significantly less expensive than new alternatives (Ijomah, 2002; Ijomah and Childe, 2007). Ensuring adequate core supply is especially difficult in the case of domestic products because it is impossible to have a definition or statement of lifetime for such products. The reason here is that it cannot be determined when the products will come to the end of their lives. This depends entirely on the consumer; some consumers may use their products only until a new version comes into the market while others would use them as long as they operate, no matter the level of inefficiency.

Product recovery processes should also ideally be relatively localized to avoid large carbon footprints from transportation if parts of the process were undertaken in different locations or, worse, used products were exported for processing and then imported back into the country of origin for sale. Within the product recovery processes there is a hierarchy based primarily on quality. Remanufacturing is at the top of this hierarchy because it is the only product recovery process that can bring used products to a standard equal to that of the new alternative in terms of quality, performance and warranty. The following section outlines the key differences between remanufacture and the other product recovery processes and describes the major advantages of remanufacturing.

8.2.2 A comparison of options in component reuse

The three major component reuse options are not equal but rather exist on a hierarchy with remanufacture at the top, followed by reconditioning and then repair. Remanufacturing is a process of returning a used product to at least original performance specification from the customers’ perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent (Ijomah, 2002; Ijomah *et al.*, 2004). Currently, remanufacturing is profitable typically for large complex mechanical and electromechanical products with highly stable product and process technology (Ijomah, 2002; Ijomah *et al.*, 2007a), materials and components that are costly to manufacture or may become costly in the future. The value of reusing these products' components relative to the cost of disassembly makes manual disassembly worthwhile, which enables profitable remanufacture of these products.

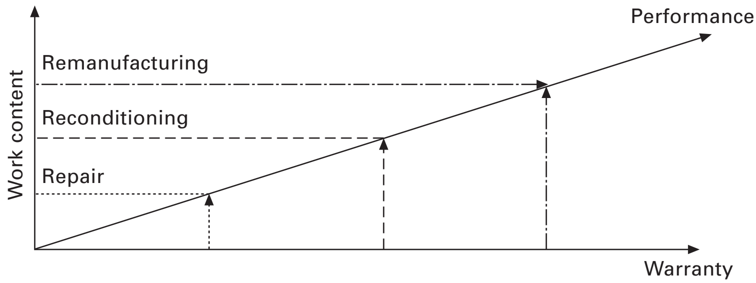
Remanufacturing can be differentiated from repair and reconditioning in four key ways (Ijomah, 2002):

- Remanufactured products have warranties equal to that of new alternatives whilst repaired and reconditioned ones have inferior guarantees. Typically, with reconditioning the warranty applies to all major wearing parts, while for repair it applies only to the component that has been repaired.
- Remanufacturing generally involves greater work content than the other two processes and as a result its products tend to have superior quality and performance.
- Remanufactured products lose their identity while repaired and reconditioned products retain theirs – because in remanufacturing all product components are assessed, and those that cannot be brought back at least to original performance specification are replaced with new components.
- Remanufacture may involve an upgrade of a used product beyond the original specification, which does not occur with repair and reconditioning.

Table 8.1 defines and differentiates repair, reconditioning and remanufacturing. Figure 8.1 shows the three processes on a hierarchy based on the work content that they typically require, the performance that should

Table 8.1 Definitions of secondary market processes (Ijomah, 2002; BSI, 2010)

Remanufacturing	The process of returning a used product to at least original equipment manufacturer's (OEM) original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent.
Reconditioning	The process of returning a used product to a satisfactory working condition that may be inferior to the original specification. Generally, the resultant product has a warranty that is less than that of a newly manufactured equivalent. The warranty applies to all major wearing parts.
Repair	Repairing is simply the correction of specified faults in a product. Generally, the quality of a repaired product is inferior to that of the remanufactured and reconditioned alternative. When repaired products have warranties, they are less than those of newly manufactured equivalents. Also, the warranty may not cover the whole product but only the component that has been repaired.



8.1 A hierarchy of product recovery processes (Ijomah, 2002).

be obtained from them, and the value of the warranty that they normally carry.

The key advantage of remanufacturing over reconditioning and repair is that it permits an organisation to combine the key order winners of low price and product quality, especially as remanufacturing also includes increasing the performance and quality of the used product beyond that of its original standards when new. This ability of remanufacturing to deliver high quality is especially important to 'A' class manufacturers and 'customers' who value the reputation of their service and brand name above low product cost. Xerox is a key example of successful remanufacture because its copiers typically undergo seven life cycles. This means that seven revenue streams are generated from the manufacture of a single product, and materials are diverted from landfill or recycling at least six times (Gray and Charter, 2006).

The disadvantage of remanufacture to the lesser product recovery processes is that it is generally more expensive because of the greater resource and work content involved. Thus there are many products where remanufacturing would be cost prohibitive given current remanufacturing technology and knowledge base. Domestic appliances remanufacturing for example, would not be viable as a profitable business. This is because the cost of processing items such as fridges and cookers for recycling continues to decrease and according to AMDEA (2008) would be less than £5.00 in 2009, whilst the value obtained at the treatment plant continues to increase. Also, the value of steel doubled between 2002 and 2006 (AMDEA, 2008), thus increasing the profitability of recycling relatively low price goods with good metallic content. Interviews by the authors of major domestic appliance manufacturers such as Lec Refrigeration and Merloni indicate that remanufacturing of domestic appliances is cost prohibitive – at least within the EU. The main reason here is the cost of manual labour involved in remanufacturing as well as additional costs such as that for testing to safety standards. Such tests are expensive to run and their costs in new manufacture can be limited by running in batches; however, with remanufacturing the test must be undertaken individually.

8.3 Industry sector specific example: refurbishment of computers

The refurbishment of computers and other office products such as printers has been occurring for more than 20 years, and was led not by the original manufacturers but by independent specialists who identified a commercial opportunity. Most manufacturers still do not address this as a priority in serving their customers or the market, and so the naturally occurring demand is still mainly satisfied by independent providers. The rework of computers and printing products can be broadly grouped into three categories; repaired, refurbished and remanufactured. There is now a growing number of manufacturers who have implemented processes to provide used equipment to their customers, with some utilising their in-house capabilities and others engaging independent specialists as service providers.

In the absence of legislation and standards, the accepted practices will vary between all used equipment providers (be they manufacturer or specialist), but the following descriptions provide a guide as to the product expectations within the three categories within the IT market sector as observed by the authors.

8.3.1 Repair

The act of fixing or correcting a fault, defect or damage is called a repair. An electrical or mechanical repair brings a product back to a functional, working state, while a cosmetic repair restores minor exterior surface damage and or blemishes (such as a scratch, dent, crack or chip). A product can be repaired in the field by a service technician or at a dedicated service or repair facility at the manufacturer or specialist. Testing is performed only to ensure that the repair did in fact eliminate or fix the specific identified defect. Repairs are inherent activities in either of the more extensive processes of refurbishment or remanufacturing.

8.3.2 Refurbishment

One of the two processes most associated with reused product, Refurbishment provides a cleaned and repaired product in full working order with minimal or no visual flaws. Unlike a field repair or upgrade (see discussion below), refurbishment is performed in a factory setting with operational specifications, where a more expanded tool set, cleaning solutions, solvents, paints and other surface treatment capabilities are involved. Upgrade here describes the returning of a used product to a performance or quality standard greater than it had when new. While the refurbishment process does not seek to increase the product's original manufactured capability, higher capacity components may be added if original parts are no longer available, or if later higher capacity parts are of a comparable cost. A refurbished product generally carries a limited warranty, dependent upon the supplier (original manufacturer or independent specialist), age of product and price charged.

8.3.3 Remanufacture

Remanufacturing is more complex than refurbishment, and is a detailed and comprehensive disassembly and reassembly process that brings a used product back to at least its original equipment specified state. Dependent upon the processes of the remanufacturer (whether original manufacturer or independent specialist), the disassembly process can either preserve the identity of the original product (via its serial number), or a completely new system identity can be created (supported by a new serial number).

Remanufacture includes the thorough cleaning, testing and diagnosis of all the disassembled parts. Dependent upon the commercial viability, worn, failing or obsolete components are either repaired or replaced. Repairs to components or sub-assemblies may be carried out by the remanufacturer or be sent to a product specialist. Upgrades to hardware parts are also provided where commercially viable, and any other software or firmware engineering changes developed since the product was introduced will also be included in the remanufacturing process.

Remanufacturing is performed in a factory setting with supporting tool and test sets that are equivalent to those used in current production, with instructions contained in floor controlled process documentation. As products are completely disassembled, original factory settings can be reset or readjusted. New features and upgrades can be added so that products share the latest technology available on current production models. Remanufactured products can thus have capability equivalent to current production models, are tested to the same levels, and are generally sold on an 'as new' basis with a comprehensive or as new warranty.

It should be noted that the accepted industry term of remanufacturing in IT is more akin to rebuild, as very little is actually remanufactured in the same way that a component is originally manufactured. Most computer and printer suppliers will use specialist manufacturers for the fabrication of key components and sub-assemblies (such as CPUs, memory chips, optical and hard disc drives), and the cost of replacement with a current production part is generally less than trying to repair the older failed product.

The labour cost to determine a fault and then repair and test it generally outweighs the cost to quickly replace with a new (and often upgraded) component. Most manufacturers will also not invest in a specific element of a production process to handle such repaired products, as the economies of scale are inferior compared with the high throughput of new manufactured parts. Thus the most common solution is that of replacement for a part or sub-assembly.

8.3.4 Upgrade

A repair can be a part of a refurbishment or remanufacturing process, as too can an upgrade. Upgrades can be developed to fix customer satisfaction issues, or be planned events in the product life cycle, especially where that product is complex and designed for an extended life. An upgrade generally enhances or improves the performance of a product by increasing its function or capacity, and involves the substitution, replacement or addition of components (hardware) or applications (software) to increase a product's original capability. As with a repair, testing is limited, and just to ensure that the upgrade was installed correctly and is working properly.

Some upgrades may increase the product capability beyond the original manufactured technology level, but others can bring a product up to that of the latest production performance. This is based on the forward compatibility of a product, which is dependent upon the functional flexibility in the design and manufacture to the ability to enhance a product throughout its lifecycle.

Upgrades can also result from the lack of availability of the original component, and thus both repairs and refurbishment can contain upgrades through lack of choice.

8.4 Role of the third sector

Although secondary market processing, particularly remanufacturing of domestic appliances, may not be justifiable on environmental or profitability grounds, it may be justifiable in terms of its societal benefits, for example, addressing poverty, unemployment and lack of skills. The great decision to be made in considering secondary market processing of certain product types such as domestic appliances is whether their environmental and profitability disadvantages can be offset by their immense societal benefits plus the environmental benefits of reworking products from other sectors. Additionally, it could be that the positive societal impacts outweigh the environmental disadvantages. The societal benefits of secondary market processes include, employment creation, creation of a living for local community and for people selling second-hand goods, provision of goods for poor people who would otherwise not be able to afford them and provision of training for low skilled and unskilled labour. The societal benefits of secondary market processes can be illustrated through the work of EMMAUS, a Catholic charity for the homeless (www.emmaus.org.uk). EMMAUS takes donated products requiring rework and helps homeless people rework the products under supervision. The key benefits of this arrangement include:

- The homeless benefit by having a roof over their heads, paid employment, confidence and new skills to help them start again.
- EMMAUS benefits by using the excess profits to continue their various charitable causes.
- Employment is created for the technician supervising the ex-homeless.
- Poor people benefit because they can afford to purchase the goods.
- Employment is created.

8.5 Issues in WEEE refurbishment and reuse

8.5.1 Variability in standards and quality of refurbishment and reused products

The authors' observations and work within industry indicates that in contrast to the handling of products once they have reached the end of their usable life, there is currently no legislation in the EU or in other developed economies or regions that directs the reuse of computer equipment through refurbishment or remanufacturing. Existing WEEE legislation covers the responsibilities and requirements for the effective treatment of products once they are defined as waste, but as yet there is nothing to guide users or manufacturers on reuse or extended use.

Without legislation there is little framework for industry standards, and with the majority of the refurbishment in the hands of independent specialists there are variations in the levels of rework and the quality of output. Being commercially driven, the independent providers will generally seek the most cost-effective options to return a system to a working order such that it may benefit from a second productive life, and so the market offering becomes variable and complex. Some industry associations that represent both manufacturers and independent providers have attempted to clarify equipment rework processes through the creation of definitions, but as yet these have not been developed into recognised national or international standards that can be independently audited to provide recognised levels of accreditation.

8.5.2 Quality criteria for reuse and accreditation for reuse centres

As previously stated, there is little regulation in the area of reused IT, and thus the standards and quality levels across the providers to the used IT market vary widely. The clearest current control is legislation over the sale of goods, in that a product may not be misrepresented, and must be fit for purpose and as described. Thus most products offered for sale are merely described as 'used', but without any further clarification. Some manufacturers may further differentiate their offerings by describing their products as ex-demonstration, ex-fair, ex-loan, ex-rental, etc. This typically applies to newer used equipment that is less than 12 months old. Occasionally some manufacturers will sell off excess new product inventory or overstock through their used product channels, and at lower prices even if unopened and in new condition.

Most manufacturers and the larger independent providers will identify their product rework processes with other business accreditations held, such as international ISO or CEN standards, or standards from national bodies such as BSI or DIN. In the UK the BSI has provided a standard that in part covers the definitions and procedures in the reuse and resale of used IT equipment, in BS 8887 (BSI, 2009). This Standard has the acronym MADE (Manufacture for Assembly, Disassembly and End of life). Within some of the sub-parts in Part 2 of BS 8887 there are process descriptions for levels of rework and the re-offering of such equipment back to the market. At present this Standard serves as a voluntary guide to the industry, with no certification or accreditation process yet in place to confirm correct practice by a provider (be they manufacturer or independent).

Many of the providers of used equipment also have a waste treatment licence for their rework facilities, to ensure compliance with legislation for the correct disposal of any waste created in the rework processes. As with some repair work, some used equipment providers may subcontract this recycling work to third party specialists.

8.5.3 The design issues in remanufacturing

Optimizing reuse and refurbishment would require changes in design methods because design is the stage of the product life cycle that has the strongest influence on environmental impacts (Graedel and Allenby, 1995) and also sets the product's capabilities. This would initially raise product price and thus would initially be costly, but would lead to long-term profitability especially given the increase in waste disposal costs and other environmental legislation. A key problem here is designers' lack of expertise in designing products for reuse (see, for example, Ijomah *et al*., 2007a). As extensively discussed in Ijomah *et al*. (2007b), a key issue in designing products for reuse is avoiding features that prevent the product or component from being brought back to at least like-new functionality. These include:

- non-durable material that may lead to breakage during refurbishment (manufacturing, repair or reconditioning) or to deterioration during use to the extent that product is beyond 'refurbishment';
- joining technologies that prevent separation of components or that are likely to lead to damage of components during separation: for instance

epoxy resin adhesive bonding may be used to facilitate rapid assembly, but this would hinder disassembly without damage that is an even greater refurbishment and reuse requirement;

- features that require banned substances or processing methods or that may make returning to functionality cost prohibitive.

However, many of the key determinants of potential for refurbishment and reuse fall outside the designer's control. The major ones of these include legislation, demand, fashion and manufacturers' prohibitive practices. Legislation can have a positive impact because it requires organizations to undertake added value recovery of their products and is making waste disposal increasingly expensive. This may thus encourage manufacturers to design refurbishable products. However, when legislation bans the use of a substance, products containing it cannot be reintroduced into the market and hence would not be reused. Refurbishment and reuse are appropriate only where there is a market for the reworked product. Thus fashion-affected products are inappropriate because users may prefer the newer product no matter the quality and cost of the refurbished alternative. Some customers demand newness as a lifestyle choice, thus products – especially those requiring relatively low initial financial outlay or that are in prominent locations in homes – are generally less amenable to profitable refurbishment and reuse. Manufacturers' prohibitive practices such as patents, intellectual property rights and anti-competitive manufacturing also hinder refurbishment and reuse. For example, some printer manufacturers have designed their inkjet cartridges so that they self-destruct when empty thus preventing their remanufacturing. However, if there are no old products to cannibalise or good parts cannot be obtained from existing used products and the technology for producing new parts becomes obsolete then refurbishment of the product would be impossible.

8.5.4 Paradigm shifts affecting the use of refurbishment and reuse

Traditionally, safety, performance and cost were the key considerations in manufacturing decisions. However, changing global and business circumstances are forcing organisations to reanalyse their strategic decisions so additional factors such as raw material costs and environmental legislation are also considered design and manufacture decisions. This is leading to paradigm shifts that affect reuse and refurbishment. Two key ones here are the move from product sale to sale of capability (the move to 'product-service' systems; Ijomah *et al*., 2007b; Ijomah, 2009; Sundin *et al*., 2009) and the move by some companies away from manufacturing to assembly or bought-out parts. Regarding the first, traditionally, manufacturers sold products to their customers so there is transfer of ownership from the manufacturer to the customer. Today some manufacturers are opting to keep ownership of their product and to instead sell the product's capability to the customer – an example being 'power-by-the-hour' in the aerospace industry. The manufacturer acts as a service provider and takes any risks associated with the product's failure. As the customer purchases only the guarantee of provision of capability the focus changes to the customer's satisfaction with the capability provided and the issue of the product's newness (number of life cycles) becomes less important. Refurbishment and reuse reduce the costs to the organisation of adopting the service business model, for example maintenance costs are reduced through the use of refurbished and reused components and remanufactured or refurbished whole engines can be used in place of more expensive all new engines. In the case of the latter, to save costs some producers now purchase components from countries with lower labour costs and simply assemble these parts. This is leading to a loss of the practical engineering skills required to remanufacture.

8.5.5 Availability of information on components, materials and method of repair of products

There is a clear difference here between the position of the original manufacturer and the independent specialist refurbishment provider. The original manufacturer will have access to all the original manufacturing information as well as subsequent engineering changes throughout the product's production run (covering hardware, firmware and software). Most manufacturers provide a dedicated production line or bench areas for rework, to maintain a single focus for the production of new products, but some companies (such as Ricoh Printers) run their reworked products for reassembly down the same production lines as the new products.

Necessary comprehensive information is generally provided by the manufacturer should they outsource the rework to a contracted service provider, who may operate on-site at the manufacturer's location(s) or at their own off-site location(s). The manufacturer will also have access to spare parts holdings and the original components suppliers, as well as the supply of newer or current parts to upgrade products that are reworked.

Independent specialist refurbishers have greater challenges in rework as they operate without the authority of the original manufacturer. They do not have such access to data on the processes or to the component suppliers, and thus achieve their comparative operational capabilities in other ways. Required components are purchased from the open market in either new or used condition, and sometimes direct from authorised and independent maintenance providers, or the manufacturer's own distribution or channel partners. In some instances complete systems will be purchased for spare parts harvesting, to enable component replacement in products that are being reworked. Knowledge and expertise on products will be acquired through the hiring of staff formerly the employees of the original manufacturer or its authorised sales and service partners.

Owing to the range in size of independent specialists, the rework capabilities vary in scale and depth of process, but even the larger independents cannot invest to completely replicate the original manufacturer's production or rework environments. The methods of repair and rework will be broadly similar between the manufacturer, authorised agent or independent specialist – to test product, rework to the required level, and make ready for reuse. Independent specialists will generally take the most cost-effective route to bringing a used product back to a repaired or refurbished working condition, whereas the manufacturer may choose to invest more in rework time and cost to provide a premium standard used product with a commensurate warranty.

All parties employ decision processes that assess the product to be reworked at various stages, to ensure that a viable level of rework is chosen that enables the resale at a profit and not a loss. Some manufacturers will not target a high profit in the resale of used equipment, as they are keen to make the offering as competitive as possible against the independent suppliers, and support their customer as more of a service in this area.

8.6 Future trends

It is likely that the interest in used equipment will increase as demand for sustainability and responsibility in product manufacturing continues to grow. Manufacturers are focused on continual improvement for their new products, principally to ensure commercial success and survival, and they continue to develop greener products that have lower carbon impacts in use, and higher raw materials recovery when recycled at end of life.

Additional focus is now being placed on design-for-disassembly, originally intended to reduce costs as products were dismantled into their major materials groups for recycling (plastics, metals, precious metals, etc.). The design-for-disassembly approach also facilitates rework activities, by making component or sub-assembly exchange quicker and easier, for example through the use of plastic clips as opposed to parts that are screwed in place with metal screws.

For those manufacturers actively engaged in providing used equipment, such activities continue to be a small single digit percentage of their overall hardware sales revenues, and sometimes only a fraction of a single per cent. Niche activities that do not offer economies of scale are therefore not a priority. Thus focus and attention remain in the competitive area of designing and manufacturing ever better new products, and future attention to reworked product is only likely to be driven by four main factors.

8.6.1 Legislation

As with the WEEE legislation in the EU, manufacturers will only act (and incur costs) if they have to, to maintain compliance with legislation. At present the WEEE legislation only covers the responsibilities for electrical and electronic equipment at the point that it is declared and treated as waste, but future extensions to this legislation could move into the part of the product life cycle immediately preceding this point, when equipment is used or reused. Reused electrical and electronic equipment (REEE) legislation could provide targets for manufacturers to ensure a contribution towards raw materials sustainability, through the reuse or extended use of previously manufactured product.

8.6.2 Customer demand

Existing demand for reused IT equipment is driven by three main factors, some of which may develop further into stronger reasons to deploy such product.

- Used equipment offers an attractive proposition for customers limited to a lower pricepoint than new equipment. Similar to buying a used car, a larger or better equipped product can be acquired for the same investment as an inferior standard new product. In challenging and competitive economic times this option can become more attractive.
- Support and maintenance costs are an important factor in the total cost of ownership of IT equipment, and these can be contained by maintaining a homogeneous environment, where all the products are the same. Supporting a common platform reduces the need for staff training, repair tools, and spare parts inventories, and also provides a stable platform for applications that are deployed, making the role of the software support engineers more straightforward. Thus the choice to purchase used equipment is based on the need to consume more of what the customer already has, and provide the additional required capacity by acquiring previous generation technology that matches the existing infrastructure.
- Hardware life cycles and innovations are now deployed faster than software developments, and thus applications may continue to run just as effectively on previous generation technology, and display no benefit when run on the latest systems. Thus a perception of ‘good enough computing’ is developing, where a more cost-effective solution can be applied to a business need without impacting on business performance or efficiency.

Combining these three existing elements delivers compelling solutions for some customers, and all potentially could become of greater interest to the market in future.

As well as seeking to lead the market through product improvement and innovation, most manufacturers will also respond to qualified and substantive customer demand, especially if a trend is identified. Should the market continue to develop an interest in 'green' or sustainable products, then greater attention may be given to reworked product offerings.

Many companies are seeking to demonstrate their own green credentials to their own customers and stakeholders, through efficient practices and responsible procurement; thus the purchase of recycled products such as pens, paper, or furniture could be extended into electronic products as well, as a demonstration of a green contribution towards materials sustainability. Should this area of demand establish a long-term niche in the market then many manufacturers may respond and devote more attention and resources into this area.

8.6.3 Cost savings

The competitiveness in the marketplace drives all suppliers to seek cost savings in all aspects of their business, and if the market demand for reused equipment were to develop, and achieve greater economies of scale, then manufacturers may perceive that an economic advantage can be realised in the area of providing reworked products. Being able to sell the same product twice, with a smaller investment through rework compared to the costs of new manufacture, may become a more interesting business case that manufacturers will respond to in future.

8.6.4 Competition

There are not many manufacturers that will lead as strongly or independently as Apple, but most will tend to deliver evolution more than innovation in IT product offerings. After an innovator, one or two first movers will lead the market, after which the rest will be drawn to follow, to ensure that they do not suffer a comparative or competitive disadvantage against the competition. Thus if a number of manufacturers drive more focus and attention into the reused equipment market, based on any of the other factors above, then others will be prompted into following suit.

Another factor that may attract more interest in reused IT equipment in the future is the diminishing returns from energy efficiency. The market offerings now include products that draw zero watts of electricity in standby mode, which cannot be improved upon. Products are also drawing less energy when in operation, but the comparative savings are reducing over time. Thus in the near future, products returning to the market as reused will not be as inefficient as those in the past, and as the greater carbon impact is in the use of a system (compared to manufacture), the differential between new and used systems in this respect is narrowing.

8.6.5 New technologies

The remanufacture of small-sized WEEE products at end of life (EoL) is not typically profitable as their volatile technological pace and size makes their disassembly by conventional means overly expensive. The high cost of manual disassembly (potentially worsened by design that unintentionally or sometimes intentionally makes it more difficult) can result in a low return on investment (RoI) for remanufacturing the product. This stops businesses engaging in remanufacturing and so prevents business and the environment benefitting from this more sustainable production technique. 'Active disassembly' (AD) is an alternative to conventional dismantling techniques that enables the non-destructive, self-disassembly of a wide variety of consumer electronics on the same generic dismantling line, thus reducing disassembly cost (Chiodo and Boks, 2002). AD is an alternative to conventional dismantling that can remove the barrier of expensive manual disassembly. AD enables cost-effective, non-destructive, self-disassembly for a wide variety of WEEE and is particularly suited to high-value consumer electronics. Furthermore, AD can be carried out for different products on the same dismantling line and thereby exponentially reduce disassembly costs. The AD technique has been applied to a variety of electronic products since the 1990s (for example, Chiodo *et al.*, 1997; Masui *et al.*, 1999; Nishiwaki *et al.*, 2000; Li *et al.*, 2001; Braunschweig, 2004; Jones *et al.*, 2004; Klett and Blessing, 2004; Duflou *et al.*, 2007), but to benefit recycling. Originally AD was designed with the intension of reducing disassembly costs in recycling. However, work is now being undertaken to use AD to extend profitable remanufacturing to small sized WEEE, an area where disassembly cost has traditionally made remanufacturing economically unviable (see for example Ijomah and Chiodo, 2010).

8.7 Summary of WEEE reuse and refurbishment

Within manufacturing, the need for sustainable development is being addressed by promoting the reuse processes (recycling, repair, reconditioning and remanufacturing). There is an urgent need to advance reuse and refurbishment of EoL WEEE more than most other solid waste categories because of their greater adverse environmental impacts plus rapidly increasing quantities. Currently legislation regarding WEEE is inadequate, leading to disparity in the standards and quality of reworked products as well as poor customer perception and snobbery against them. For example, refurbished computer and printing equipment is generally presented back to the market as 'used', but there is rarely any description regards the extent of rework carried out to present the product in full working order for its next life cycle. In the absence of any legislative requirements, neither manufacturer nor independent specialist will reveal the history of a product, and any faults or failings previously experienced. The focus is on the provision of a working system at a competitive price compared to a new product, underpinned by a limited level of warranty that is generally related to the level of rework and the price. Other issues in WEEE reuse and refurbishment include OEM's actions to prevent refurbishment (e.g. individual producer responsibility, IPR), legislation and poor expertise in design-for-reuse. Reuse and refurbishment are being affected by paradigm shifts in industry. The key ones are manufacturers moving from product sale to service sale business model and from manufacturing and assembly to assembly only. The former favours refurbishment and reuse by reducing customer demand for newness in the products they use. The latter hinders refurbishment and reuse due to loss of the practical engineering skills required.

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9
Shredding, sorting and recovery of metals from WEEE: linking design to resource efficiency

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Abstract: Metals and other materials play a pivotal role in electrical and electronic equipment (EEE) as their properties impart unique functionality to consumer products. Metals are theoretically infinitely recyclable; however, the functionality and design of EEE complicate recycling due to their ever more complex structures producing un-liberated low grade and complex WEEE recyclates. Metallurgical smelting ingenuity helps very much to 'close' the loop of WEEE. This chapter will elaborate on the various issues that affect the recyclability of WEEE such as product design, physical separation and extractive metallurgy. It will also discuss the limits of recycling and what has to be done to increase resource efficiency of the various metals contained in WEEE.

Key words: design, particulate recycling properties, liberation, material connections, critical materials, closing resource loops, recycling, physical sorting, metallurgy, thermodynamics, design for recycling, design for sustainability.

9.1 Introduction

Natural resources underpin the functioning of the global economy and the material quality of life. The flagship initiative for a 'Resource-efficient Europe' under the Europe 2020 strategy (COM, 2008) supports the shift towards a resource-efficient, low-carbon economy to achieve sustainable growth. Increasing resource efficiency has been pinpointed as key to this sustainable development. Securing reliable and undistorted access to (critical) non-energy raw materials has become a critical challenge to many resource-dependent countries all over the world and is imperative to ensure that for the enabling of sustainable technology there remains a secured supply of metals for products in the renewable energy and other sustainability sectors.

The EU produced a document discussing scarce materials (Critical Raw Materials for the EU, 2010) (Table 9.1). Rare earths (REs) were highlighted, specifically neodymium for magnets. RE elements have an important role in modern sustainable society as they enable the creation of sustainable

Table 9.1 Critical raw materials in the EU (Critical Raw Materials for the EU, 2010)

Antimony	Indium
Beryllium	Magnesium
Cobalt	Niobium
Fluorspar	Platinum group metals[1] (PGMs)
Gallium	Rare earths[2]
Germanium	Tantalum
Graphite	Tungsten

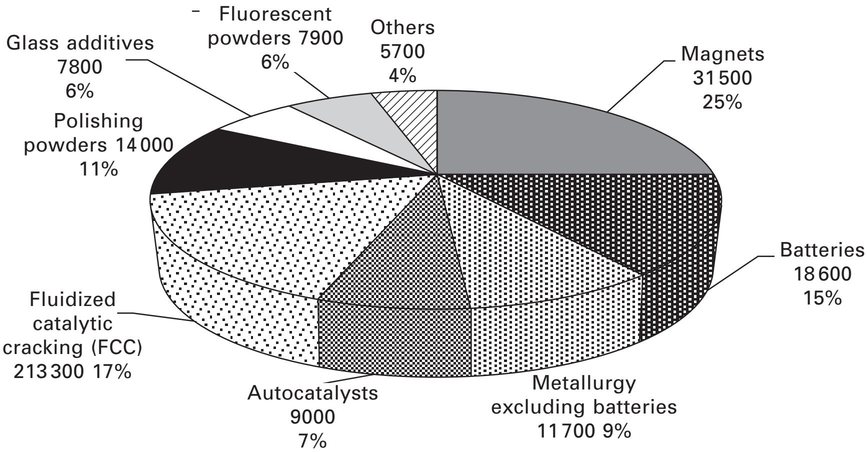
[1] The PGMs regroup platinum, palladium, iridium, rhodium, ruthenium and osmium.
[2] Rare earths include yttrium, scandium, and the so-called lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium).

Table 9.2 The main driving emerging technologies for the critical raw materials (Critical Raw Materials for the EU, 2010)

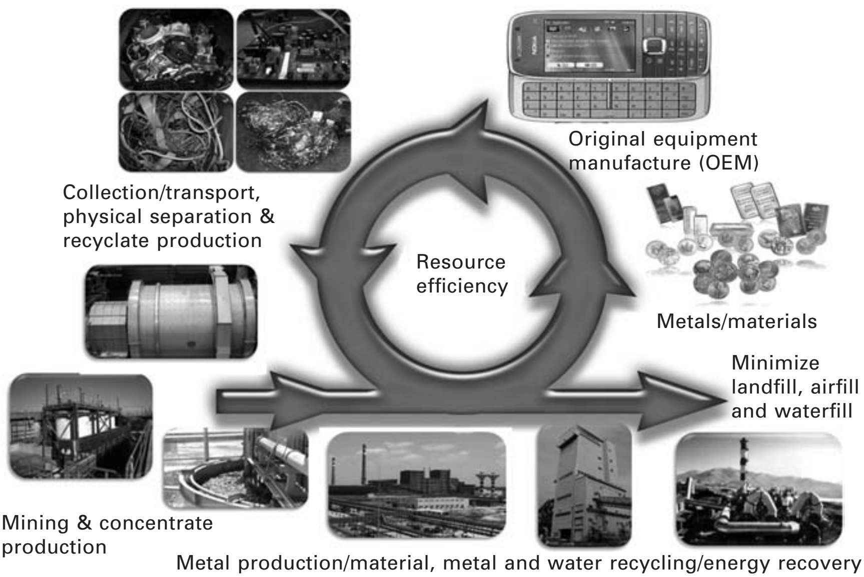
Raw material	Emerging technologies (selected)
Gallium	Thin layer photovoltaics, integrated circuits (IC), white light emitting diode (WLED)
Neodymium	Permanent magnets, laser technology
Indium	Displays, thin layer photovoltaics
Germanium	Fibre optic cable, IR optical technologies
Platinum	Fuel cells, catalysts
Tantalum	Micro-capacitors, medical technology
Silver	Radio-frequency identification (RFID), lead-free soft solder
Cobalt	Lithium-ion batteries, synthetic fuels
Palladium	Catalysts, seawater desalination
Titanium	Seawater desalination, implants
Copper	Efficient electric motors, RFID
Niobium	Micro-capacitors, ferroalloys
Antimony	ATO, micro-capacitors
Chromium	Seawater desalination, marine technologies

products for modern transport, wind power energy and for energy efficient lighting (Table 9.2). Not only have REs to be sourced from minerals but also from the various (end-of-life) consumer products, such as e-waste, cars and other applications that use these (see Fig. 9.1). Prudent use of resources and safeguarding the supply of critical materials can among others be achieved through the closure of material cycles and minimization of waste creation (see Fig. 9.2). Therefore recycling has been identified as one of the pillars on which to build a resource-efficient Europe (COM, 2011).

Since e-waste or waste electrical and electronic equipment (WEEE) involves a wide spectrum of products and materials, ranging from commodity



9.1 Application of REs in 2010: total = 127 500 t versus production of 114 800 t (Lynas, 2011).



9.2 Resource efficiency and closing material loops in industry (www.outotec.com).

metals and different plastic types (e.g. containing flame retardants or not), to precious metals and a range of critical materials (see Table 9.3) as well as potentially harmful minor elements, recycling of e-waste/WEEE plays an important role in closing resource cycles for a variety of (critical and commodity) materials. The so-called critical materials are often present in the products in minor quantities (scarce/minor elements) and are complexly linked to other materials in order to fulfil functional and aesthetic product and component performance specifications.

Table 9.3 Critical materials in different e-waste products (van Schaik, 2011)

Quantities (gram/tonne product)	PMs		PGMs		Rare earths (oxides)			Others					
	Ag	Au	Pd	Pt	Y	Eu	Other REs	Sb	Co	In	Ga	W	Ta
Washing machines	0.59–0.64	0.14–0.15	0.07–0.08										
Large household appliances (excluding fridges)	0.00–0.54	0.00–0.13	0.00–0.07										
Video recorder	67–94	3.1–4.3	1.0–1.4				*	*					*
DVD player	70–113	10–16	2.1–3.4				*	*					*
Hifi unit	54–71	2.5–3.3	0.8–1.1				*	*					*
Radio set	104–107	13.6–13.9	1.6–1.7				*	*					*
CRT TV	8.4–155	0.51–11	0.3–4.0		16–19	1.3–2.0	*	216	8			*	*
Mobile telephone	786–2440	81–800	63–610	1.5–36		*		*	19 289–45 509	*			*
Fluorescent lamps						1514–16 245						*	*
LED						*				*	*	*	
Liquid crystal display (LCD) screens	*	*	*			*				+			
Batteries (NiMH)						~80 000			~30 000				

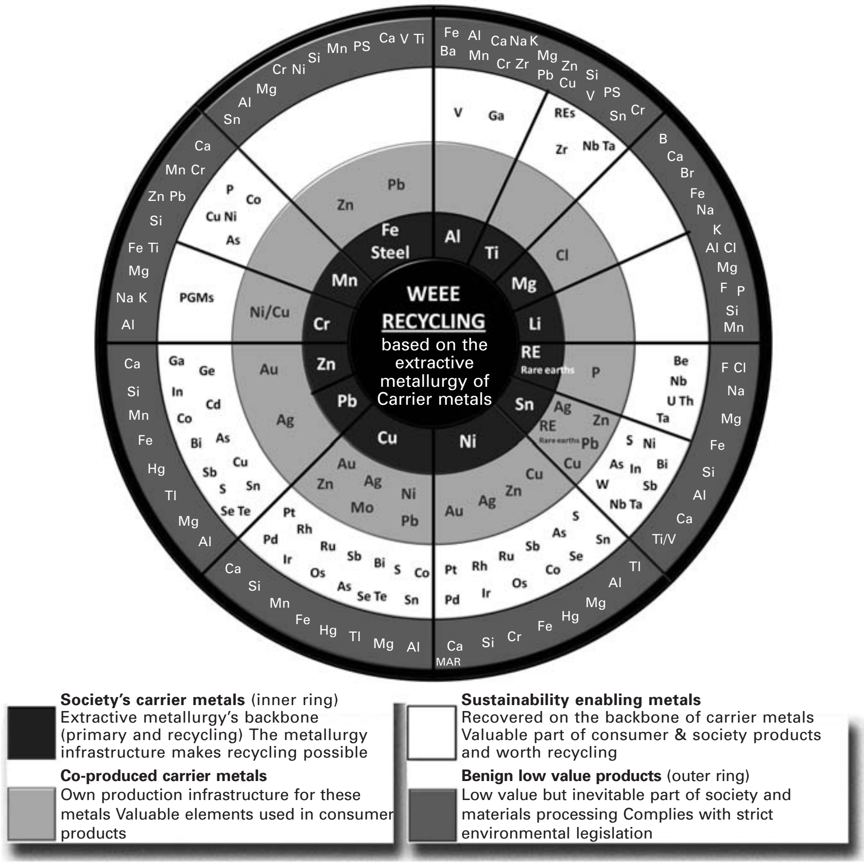
*Possibly present, not (enough) quantitative data available.
+ 0.06–5.6 gram In/m^2.

This implies that closing of material cycles of complex, interconnected material resources requires a first-principles understanding (implying physics of processing, physics of design/joining/strength, etc., chemistry, engineering and thermodynamics) of the principles that maximize the recovery of materials, such as metals and energy from end-of-life (EoL) consumer goods including WEEE and e-waste, materials, waste, residues and sludges from waste water among others and the economics thereof. Metallurgy plays a crucial role in enabling sustainability, being the source of these elements and derived materials as well as the ultimate 'organism' or unit operation that closes the material cycle as one has to reduce and/or re-melt metals to refine these to new high quality products. The recovery in metallurgical operation is to a large end dictated by the second law of thermodynamics. Thermodynamics of furnace technology dictate the combinations of materials which can or cannot be recovered together from recyclates arising from shredding, dismantling and physical sorting of consumer goods, hence dictating the compatibility of applied and connected materials in design to optimize resource efficiency and closure of material cycles for both commodity and critical/minor elements.

Critical resources are applied in WEEE/e-waste in the following products/components (overview is not exhaustive, but gives the most important applications(s) based on data availability from literature and/or analyses) (van Schaik, 2011):

- Printed wire boards (PWB): PGMs (platinum group metals), PMs (precious metals), Sb, Ta, REs (La, Nd), Fe, Al, Cu, Pb, Ni, Sn, As, Ba, Br, Bi;
- liquid crystal display (LCD) screens: indium (In) as indium tin oxide (ITO);
- light emitting diode (LED): Ga, In and REs (Gd, Ce, Tb, Eu, Y, La, Sm, Lu, Tm, Dy);
- getters (lighting and cathode ray tube (CRT) TVs): W, Ta;
- fluorescent powders (lighting and CRT TVs): REs (La, Tb, Eu, Y, Ce);
- hard disks: PGMs;
- flame retardants: antimony (Sb);
- CRT glass: antimony (Sb);
- batteries: cobalt (Co) and REs (Ce, La, Nd, Pr).

The WEEE wheel of Fig. 9.3, as developed based on the metal wheel developed by Reuter (Critical Raw Materials for the EU, 2010; Reuter *et al.*, 2005), illustrates that geology and the fundamental properties of the elements have created various mineral deposits around which extraction technologies have been developed and perfected as far as possible. Modern products contain a combination of metals that are not linked in the natural resource systems as depicted by this WEEE wheel. In general, an increased complexity of



9.3 WEEE Wheel: linkages of metals as found in natural resources related to WEEE products – map to sustainable recycling of metals (legend top to bottom equivalent to rings from the inside to the outside).

recycling pyrometallurgy has arisen through the development and design of these modern consumer products (such as WEEE and passenger vehicles). As a consequence, these material combinations as present in recyclates (due to imperfection in liberation and separation) to be processed by metallurgical furnace technology are not always compatible with the current processes in the metals production network, which was developed for the processing of primary natural resources and, therefore, optimized for the processing of the primary metal and all mineralogically associated valuable and harmful minor elements. Only when the physics of recyclate quality and metallurgical process technology, including process thermodynamics, are included in the evaluation of product recycling efficiency, can the formation of complex residue streams (undesired harmful emissions that cannot be handled in the current system) and material losses be minimized from the processing and recycling of those products at their end-of-life to maximize material recovery and safeguard the supply of resources from these products.

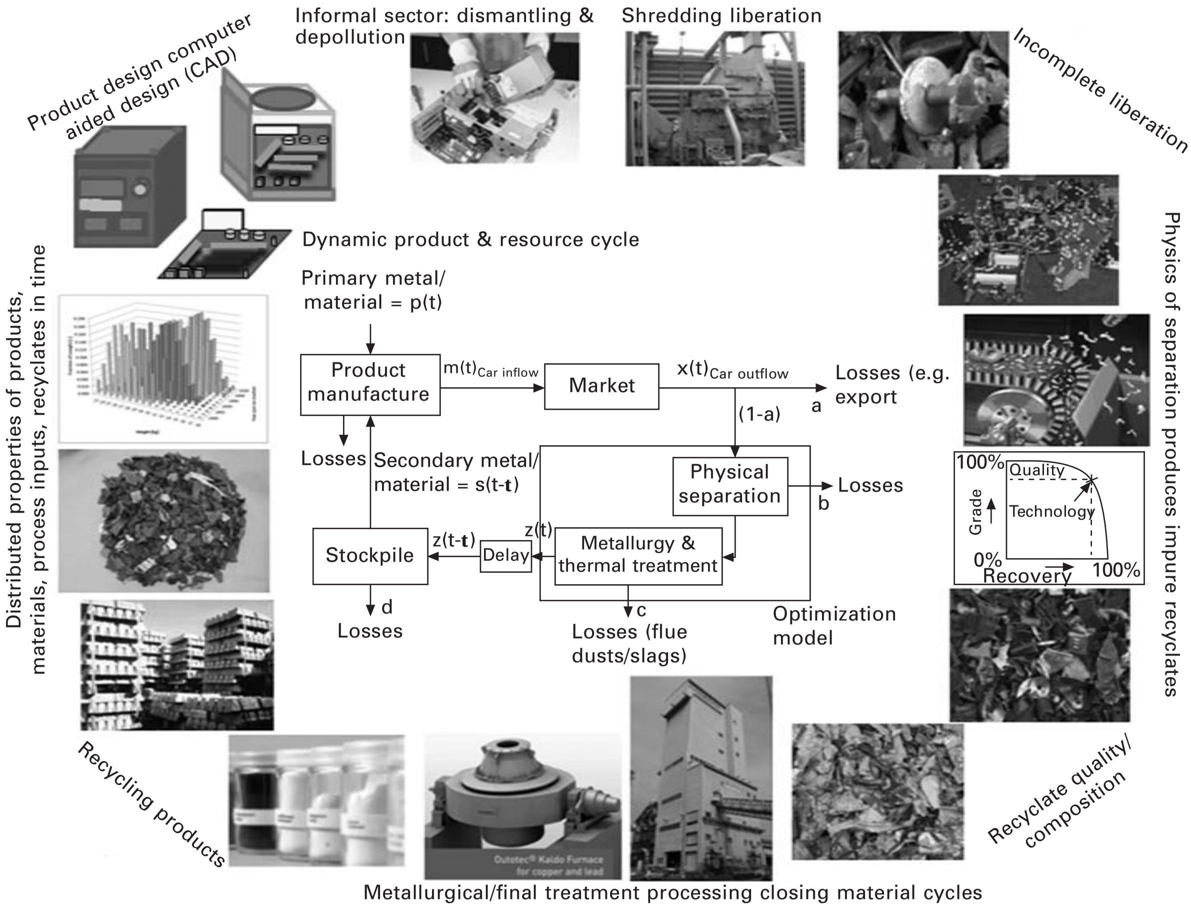
9.2 Theory of recycling

Reuter (2011) reviewed a large body of literature on this topic (147 references) discussing what has been accomplished to achieve a first-principles (i.e. physics based) link between product design and resource efficiency through design for recycling (DfR). Readers are encouraged to consult this review for an extensive overview of existing methods and tools in this area. The review concludes that although material flow analysis (MFA) and life cycle assessment (LCA) methodologies are generally accepted tools, they have not generally been adapted to the depth required to link computer aided design (CAD) techniques (with this is meant inclusive of the physics of design/joining/strength, etc.) for consumer product design and process technology. Various simpler recycling models as reviewed cannot be applied to support sustainable product designs and closure of material cycles, since the particulate nature of recyclates and hence recyclate quality is not captured; something which is crucial in predicting and improving recycling system performance, hence engineering the opportunities. To address the gaps and deficiencies in the modelling of recycling systems the authors have developed simulation models for, among others, car and e-waste recycling based on the authors' experience in simulating classical mineral and metallurgical processing systems.

This chapter describes the first principles of recycling by discussing the various stages of the recycling system as depicted by Fig. 9.4, from product design to metallurgical processing, being the ultimate closure of the resource cycle. Resource efficiency, closing of material cycles and metrics of recycling/resource efficiency as a function of design, shredding, sorting (automatic and hand) and metallurgical processing will be topics of this chapter.

9.2.1 Product design, liberation and recyclate quality

The various materials applied in multi-material products such as consumer electronic products are selected, combined and complexly connected as a function of the functional, safety, durability, sustainability and aesthetic specifications of a product to name a few. The extent to which the different connected materials are liberated (disconnected) during shredding, cutting and/or dismantling and the composition of the particulates is determined by design considerations and by the efficiency and intensity of shredding (or dismantling). The quality of recycling streams is determined by the liberation process, through creation of mono (pure) or multi-material (impure) particles, of which the latter cannot be further separated by physical sorting technology.



9.4 Dynamic product and resource cycle of (recycling) modern consumer goods.

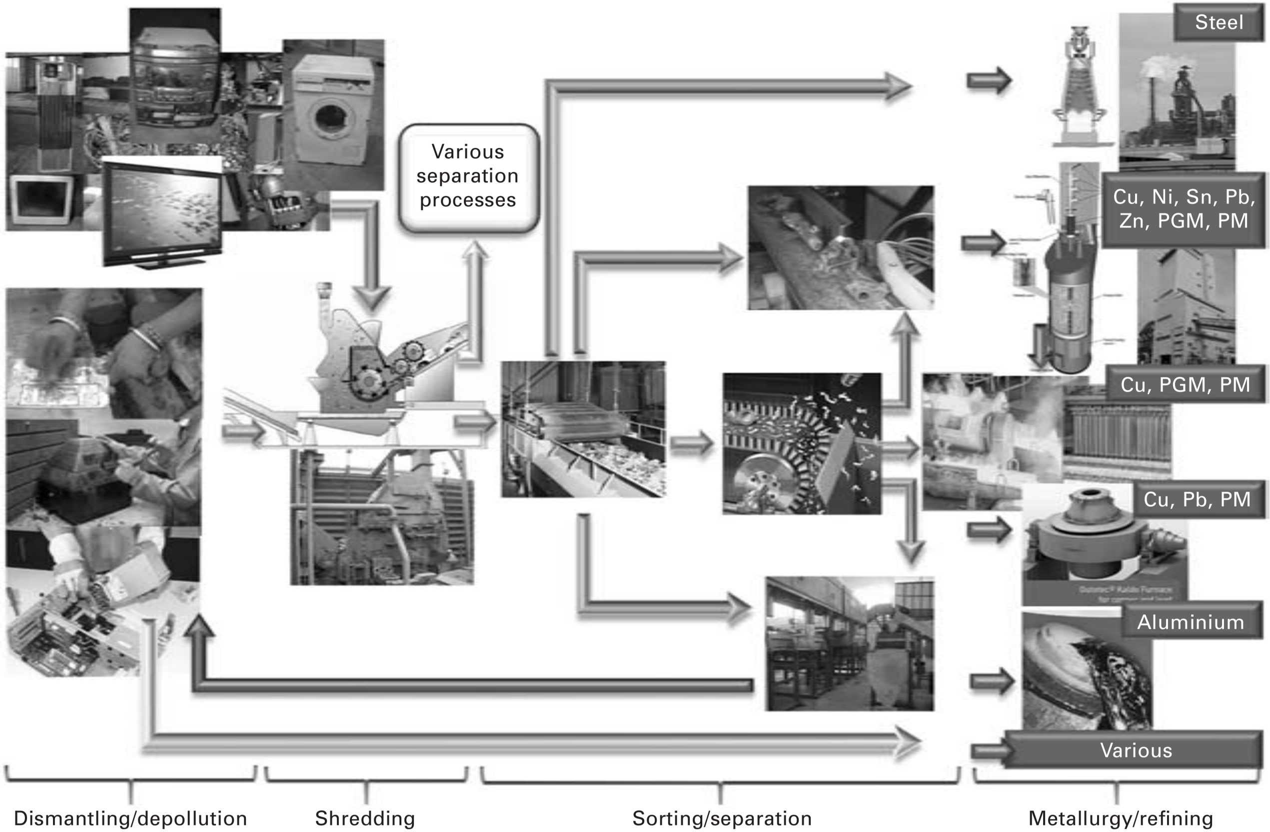
These all affect the physical separation efficiency, metallurgical and energy recovery, which all in turn determine the quality and economic value of the recycling (intermediate) products in the recycling system, and the closure of material cycles. Hence understanding and predicting the particulate nature of recycling streams plays an indispensable role in prediction and calculation of recycling performance and is prerequisite in driving changes to improve recycling system performance and close material loops. The prediction and modelling of liberation as a function of product design will be discussed in Section 9.3.

9.2.2 Recycling flow sheet (recycling scenarios)

Recycling of complex, multi-material consumer products demands an extended network of different types of processes in order to recover the wide range of materials present, ranging from manual sorting/depollution, shredding, physical sorting and plastic and inorganic treatment processes, energy recovery and metallurgical (furnace) technology, being the ultimate closure of the material cycle as metal recyclates have to be reduced and/or re-melted to refine these to new high quality materials to be applied in new products. The selection and arrangement of processes determines the ultimate quality of intermediates and recyclates and hence material/energy recovery from it. This chapter discusses how these flow sheets, representing the entire recycling system based on the network of processes and material flows, dictate the limits and possibilities of resource recovery. Also discussed is the development of recycling optimization simulation as well as dynamic models for different consumer products (cars, fridges, CRT TVs, washing/drying machines, small household appliances such as vacuum cleaners, toasters, mixers, coffee makers, etc.) by van Schaik and Reuter (Reuter *et al.*, 2006; van Schaik and Reuter, 2010, 2007, 2004) to investigate existing and alternative processing routes for these products and/or product mixtures. Multi-dimensional flow sheets (as simply depicted by Fig. 9.5) provide a graphical and technological blueprint of these recycling system models as developed to predict and calculate the possibilities and limits of recycling.

9.2.3 Physical separation

The sorting efficiencies of physical separation processes are governed by physics of separation, the physical properties of the different materials present in the shredded product and the composition of intermediate recycling streams (recyclates), hence being a function of the particulate nature and actual composition the individual mono- and multi-material particles created by design and liberation processes. Section 9.4 describes how separation efficiency has been accounted for as a function of particle composition, i.e.



9.5 E-waste recycling – a complex network of processes and interconnected material flows.

the separation efficiencies of the multi-material (un-liberated) particles are calculated in the recycling models as developed by Reuter and van Schaik (Reuter *et al.*, 2006; Van Schaik and Reuter, 2010, 2007, 2004) based on the pure elements in a process and relate the imperfection of separation to recyclate quality and hence recycling performance (decreased separation efficiency as a function of poor liberation as shown by Fig. 9.6).

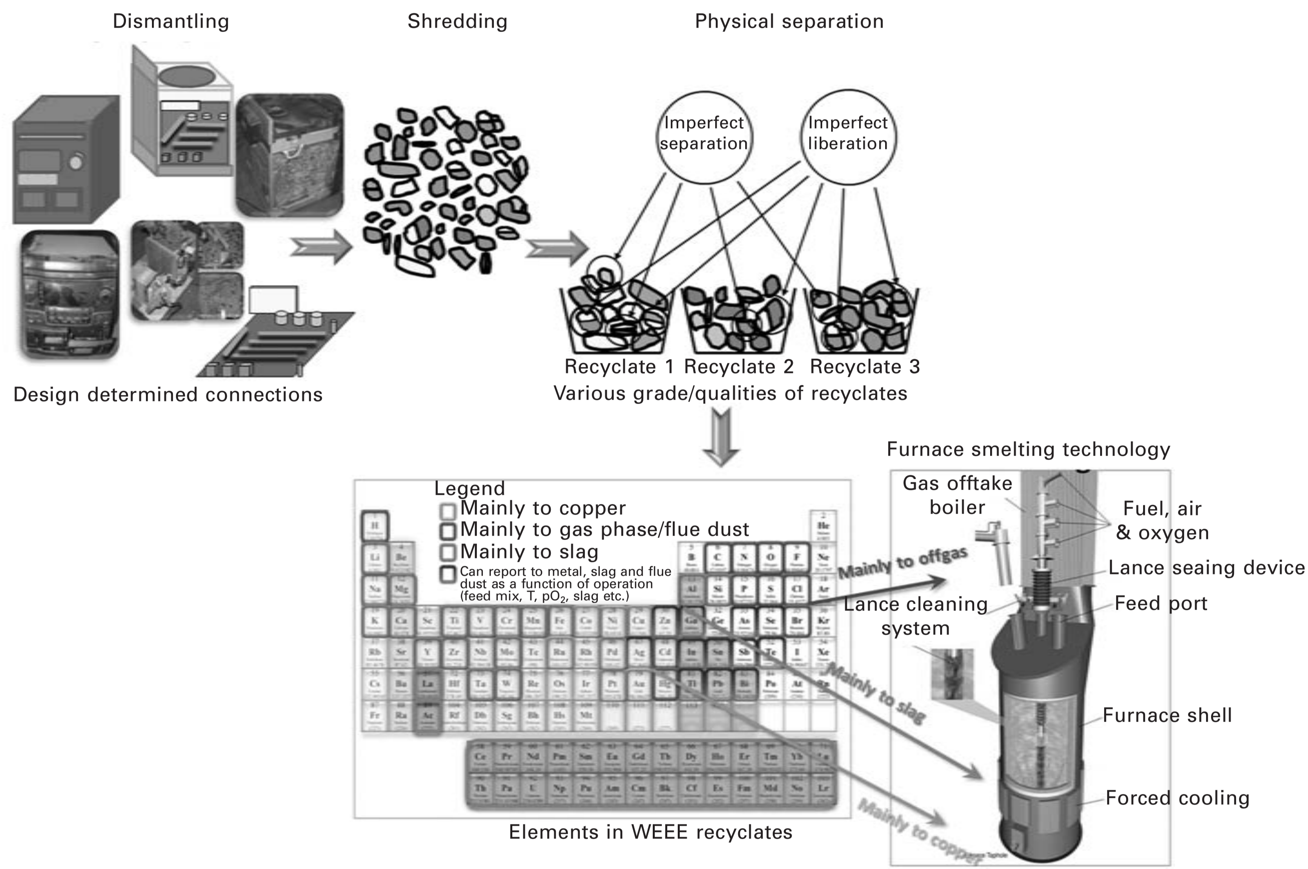
9.2.4 Metallurgical, thermal and (in-)organics processing

The 'cradle-to-cradle (C2C)' (McDonough and Braungart, 2002) philosophy for the material and/or energy cycle of products is limited by the second law of thermodynamics and economics, which to a large extent determines the recovery in the final treatment processes such as metallurgical and thermal processing (see Fig. 9.6). The separation and recovery in these types of processes into different phases (metal, matte, speiss, slag, flue dust, off gas) are based on process thermodynamics and the chemical content and interaction between different elements/phases present in the recyclates obtained from dismantling, shredding and/or physical separation. Section 9.5 discusses the models capturing this knowledge based on a physics understanding as well as industrial knowledge of thermodynamics and associated process technology in an appropriate economic environment (Reuter *et al.*, 2006; Van Schaik and Reuter, 2010, 2007, 2004). The limits and opportunities of recycling of critical metals from WEEE/e-waste based on thermodynamic process principles will be discussed, hence providing feedback on the actual recoverability of (critical) materials from e-waste and providing suggestions for DfR and sorting of materials to optimise resource recovery. Hydrometallurgical processing is included in Section 9.5 in view of the recovery of REs from, for example, batteries and fluorescent powders from lamps.

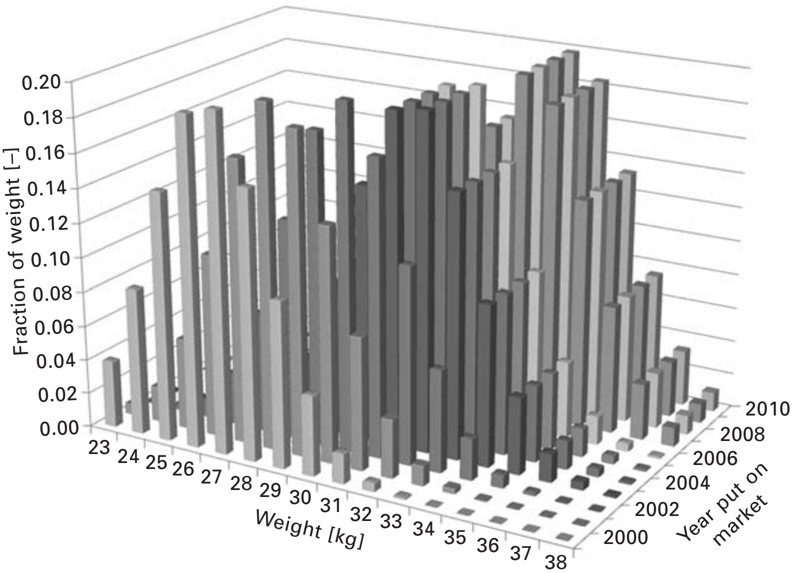
9.2.5 Dynamic feedback control loop

The input to the recycling system and hence the recovery of materials from it, i.e. the WEEE arising and their weight and composition for different products, change over time as a function of, for example (van Schaik and Reuter, 2004):

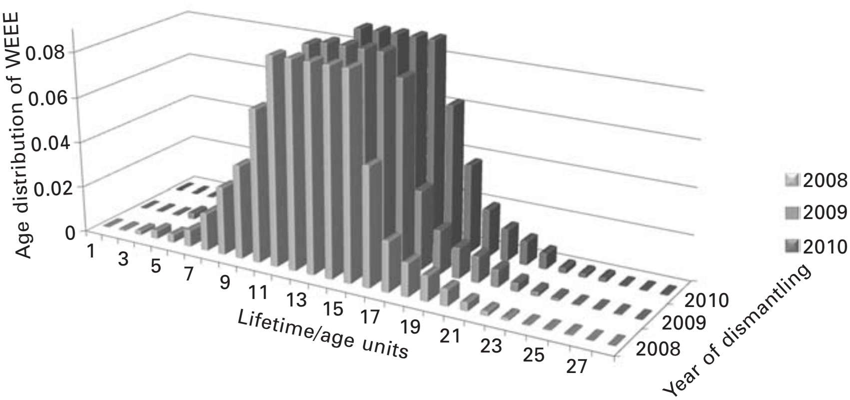
- changing product design and product weight (see Fig. 9.7);
- product composition (e.g. as a function of legislative restrictions such as the ban on the use of CFC coolants in refrigerators, lead-free soldering, changing technology, consumer demands, etc.);
- life time (usage) distributions of products (determining the distribution of WEEE arisings over time) (see Fig. 9.8);
- consumer behaviour; and
- disposal behaviour and stocks.



9.6 A schematic overview of the link between product design, liberation, separation efficiency, recyclate quality and quality (and hence toxicity) of final output streams.



9.7 Weight distribution of electronic consumer product as a function of year put on market.



9.8 Age distribution of WEEE fitted as Weibull function.

All these aspects have been included in a dynamic modelling approach. This is imperative in order to drive changes. Section 9.6 describes how the models can predict the recycling performance for different EoL systems and mixtures of products, recovery of (precious/scarce) materials and leakage for minor elements for different (changing) plant configurations (including dismantling), shredder settings, as well changing designs and recycling trends into the future (see Fig. 9.4).

9.2.6 Design for recycling (DfR)

By capturing the effect of design on liberation behaviour, recyclate quality, separation and metallurgical process efficiency and hence recyclability, a physics basis is provided for DfR for modern complex consumer goods such as EEE and cars. The authors have developed and applied fuzzy recycling models (Krinke *et al.*, 2009; van Schaik and Reuter, 2007), which capture the detail of the developed rigorous recycling optimization models in a semi-empirical way. These have been linked to CAD and LCA software for the automotive industry in an EU 6th framework project SuperLightCar (Krinke *et al.*, 2009; SLC, 2009) and have been applied to calculate recycling rates of this light-weight multi-material design (including various design concepts). Applying physics based knowledge on material combinations in design linked to compatibility and hence recovery and losses of materials in metallurgical processing is critical in ensuring the supply and recovery of commodity and in particular critical resources from WEEE/e-waste. A compatibility matrix for DfR for various materials (including critical/minor elements) will be discussed in Section 9.5.3 providing an overview of recycling increasing and limiting factors for various combined materials in EEE (electric and electronic equipment) on the bases of liberation, sorting and the second law of thermodynamics.

9.2.7 (First principles) metrics of resource efficiency: physics: exergy/entropy/thermodynamics

Exergy analysis is introduced as an additional constraint in the first-principle recycling system optimization models (Ignatenko *et al.*, 2007). This allows evaluation and optimization of the recycling systems environmental performance by capturing the effect of recyclate quality, related to physical, metallurgical and thermal processing and waste/losses in the system (Reuter, 2011; Reuter *et al.*, 2005).

9.3 Product design, shredding and liberation of waste products

This section will discuss the link between product design and the effect of shredding and liberation on the particulate nature of recyclate quality and hence overall recycling performance. At the same time, this section will reveal the first principles of technology driven DfR. This refers back to Section 9.2.1.

The design of the product determines the selection of materials (materials implying metals, compounds, composites, etc. as per their functionality) which are applied in products as well as the complexity of the material combinations and interactions within this product and its components. The liberation (disconnection) of the different materials, which have been complexly integrated and connected in the product design, determines the quality and materials combined in the particles after shredding/cutting/dismantling and hence in the different recycling streams (van Schaik and Reuter, 2007). The particulate nature and composition of recyclates (both for physical materials as well as chemical compounds, phases and connections) affects the separation efficiency and recovery of subsequent physical and metallurgical processing as is graphically illustrated by Fig. 9.6. Hence, prediction and understanding of the liberation behaviour as a function of design and the modelling thereof are crucial in the prediction and control of recyclates and output streams qualities (composition), as well as the dispersion of critical, minor and/or toxic elements over the various recycling (output) streams as a function of imperfect liberation, separation and design choices.

9.3.1 Theory on liberation behaviour

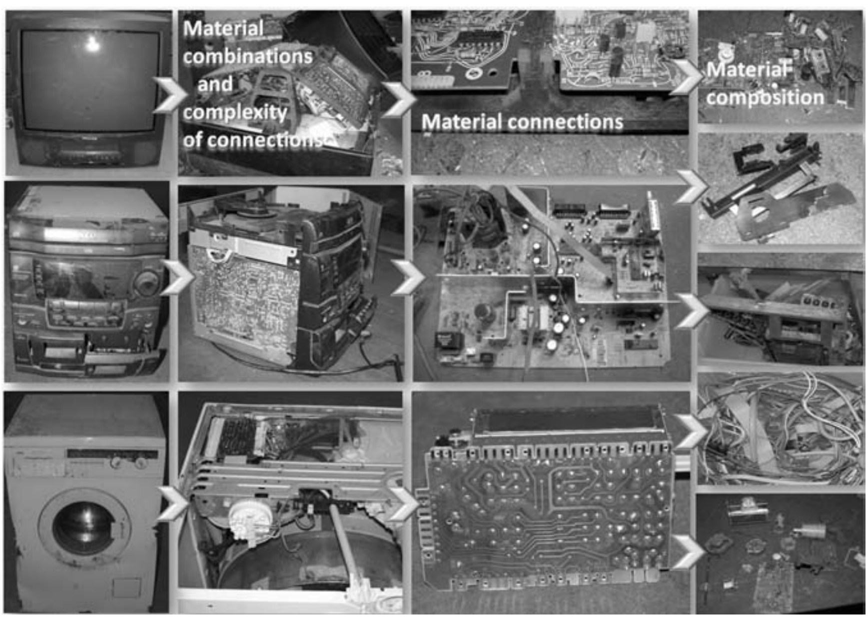
The fundamental modelling of liberation and comminution not only applies to the recycling of consumer goods, but dates back to classical minerals processing. The modelling of liberation behaviour of mineral ores has been discussed by, for example, Andrews and Mika (1976), Heiskanen (1993), King (2001) and Gay (2004). These references indicate that even in the field of classical minerals processing difficulties still exist to model the liberation of multi-component materials (which is the case for WEEE products), despite the long period in which theory has been developed in this field. From the extensive comparison of the modelling of liberation of ores with that of consumer products (Richard *et al.*, 2005) it was learned that the breakage and liberation behaviour of consumer products differs fundamentally from that of mineral ores, indicating that a different approach is required to predict the liberation behaviour and hence the recyclate quality of consumer products.

9.3.2 Data collection on liberation behaviour

In order to understand and predict the effect of design and shredding on liberation behaviour, van Schaik and Reuter (2010, 2007) have gathered a large body of data on shredding and recycling plants, trials done in industry (e.g. the authors managed and reported on a dedicated trial for recycling of 1153 cars in Belgium) as well as by detailed and careful dismantling, destruction tests and analysis of a wide range of different WEEE products (with different joints, connected materials, complexities etc.). This data considers particle characteristics after shredding as well as product and component composition, connected and non-connected materials, connected and liberated materials after careful dismantling, connection types, connection properties (surface of connections, amount of connected materials per joint, heterogeneity/ homogeneity and complexity of design). This information is gathered by manual dismantling and destruction procedures and/or from product design data as derived from the CAD software. These aspects have been collated in Fig. 9.9, which the following discussion will reference.

The various joint types, connection properties and connected materials were investigated and reported on, and recognized the breakage laws of the particles. Characteristic design properties and related liberation behaviour (degree of liberation) have been identified for different connection types, connected materials and connection complexities and heterogeneity/ homogeneity thereof, being the basis for defining models for liberation. It was learned that the degree to which the different connected materials are liberated into mono- and multi-material particles during shredding and/or mono- and multi-material particles or components during dismantling is determined by the following design properties:

- applied and combined materials (brittle, ductile etc.) in connection/ product/component;
- type of the material joints/connections (inclusive of chemically connected



9.9 Example of detailed and careful dismantling, analyses and destruction tests for data collection to derive heuristics for the modelling of liberation behaviour of complex multi-material consumer goods.

materials/phases in compounds) such as bolted, rivet, shape, glue, surface coating, foaming connections, etc.;

- characteristics of connection/joint, e.g. size of the connections in relation to the particle size distribution after shredding, connected surface, the type of connections (joint types) applied and the combined materials (brittle, ductile, etc.);
- complexity and homo-/heterogeneity of the product/component/connection (e.g. spatial distribution of the connections in the product, number of materials connected per connection, etc.).

9.3.3 Modelling design characteristics and shredding (liberation and particle composition)

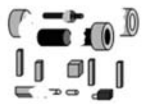
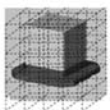
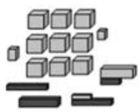
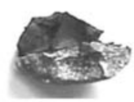
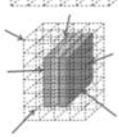
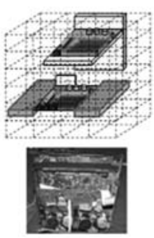
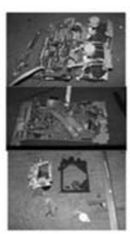
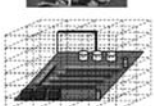
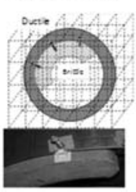
Since design characteristics and liberation behaviour are extremely complex, they cannot be approximated by classical crushing and milling models used in the mining industry. These laws, rules and properties have been the basis for defining heuristic rules for liberation. The very complex liberation behaviour of materials during shredding has been modelled as a function of product design characteristics, defined by material combinations and material connections. The unusual mix of material properties requires some heuristic rules in support of the modelling of liberation behaviour and predicting the particle and recyclate composition after shredding. Therefore, on the basis of the derived observed heuristics van Schaik and Reuter (2010, 2007) have trained fuzzy sets to capture these aspects. Product design characteristics and liberation behaviour have hence been modelled based on these heuristics in terms of (van Schaik and Reuter, 2010):

- design tables (input definitions for recycling) that define the mass and material connections derived from the design in real-time;
- shredder connection tables defining the remaining connections of the design after shredding (modelling the particle composition after shredding);
- shredder liberation tables defining the degree of liberation for the different materials and connections as a function of joint type and intensity of shredding (modelling the degree of liberation – pure and impure particles as well as the ratio of different materials in the impure particles).

This approach allows design-driven and process-specific modelling of liberation in order to predict the degree of liberation and particle creation and composition by predicting multi- and mono-material composition of particles after shredding as a function of design choices (which can vary accordingly). This is crucial in applying DfR, since this determines recyclate quality, a decisive parameter for the efficiency of subsequent separation and metallurgical processing efficiencies and hence recycling/recovery rates, toxicity, economics, etc.

Table 9.4 gives a selection of some typical connection types (as selected for, e.g., functionality by the designer) and their liberation behaviour if they pass through a shredder/cutter that breaks post-consumer goods apart. This table also shows some examples of the combined effect of connection

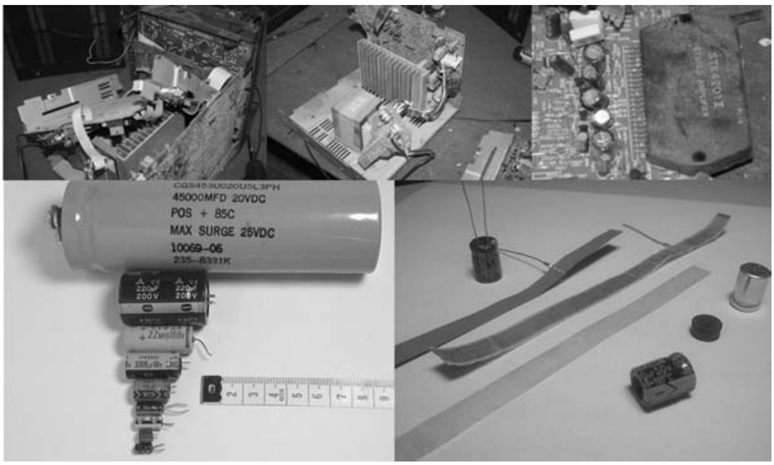
Table 9.4 Characteristics of connection types related to their specific degree and non-randomness of liberation behaviour after a shredding operation (continuing from van Schaik and Reuter, 2007) with examples for different connection complexities, properties of connected materials, homo/heterogeneity of connection, etc.

Connection types	Before shredding	After shredding	After shredding	Liberation behaviour
Bolting/riveting				• High liberation • High randomness
Gluing				• Medium liberation • Medium randomness
Coating/painting				• Low liberation • Low randomness of liberation
Foaming				• Medium liberation • Medium randomness
Examples (including effect of characteristics of connections)				
Connected materials/ components of different levels of complexity				• High/medium liberation from structure • High/medium randomness (both depending on joint type and connected materials)
Heterogeneous/ high number of connections per surface area				• Low liberation on component • Low randomness
Material properties, low complexity, low number of joints				• High liberation • High–medium randomness (depending on joint type and connected materials)

type, connected materials and/or complexity/heterogeneity of the design in relation to liberation behaviour. These examples reveal, for example, the difference in liberation of the complex PWB from the structure of the product (e.g. the PWB liberating from the steel or plastic casing to which it has been attached) and the complexity of liberation (poor liberation) of the multi-materials/components/compounds on the PWB itself (see Fig. 9.10). Table 9.4, inclusive of the examples, provides some insight into the enormous complexity and variation of liberation and particle composition (physical and chemical) after shredding/cutting as a function of the large variety of design/connection characteristics and the combination thereof. The heuristic rules and functional relationships as illustrated in this table provide the design dependent values to populate 'shredder connection' and 'shredder liberation tables' in the recycling model for the prediction of liberation behaviour.

In summary, the enormously complex particulate systems of recycling as governed by product design is described in this physics and practical and industry calibrated manner, capturing the influence of design on recyclate quality and recovery/losses of materials. This approach and level of detail are critical in pinpointing of design deficiencies and possibilities related to recycling performance (both sorting and metallurgical recovery) to improve resource recovery from products such as WEEE/e-waste.

Embedding this all into a dynamic framework provides a simulation approach that uniquely permits the evaluation of the recyclability of EoL products already during the design phase. This will be discussed in Section 9.6.



9.10 Different levels of material connections and material combinations (both physical and chemical) of printed wire boards in e-waste.

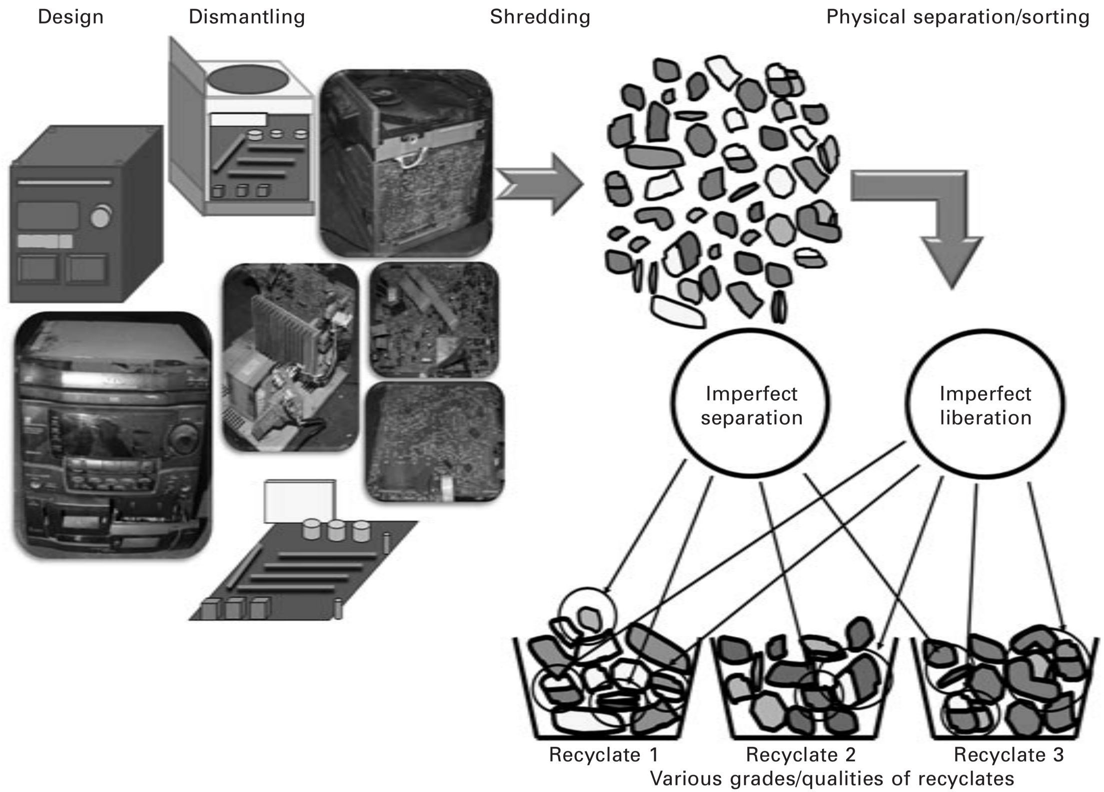
9.4 Automated and manual sorting of WEEE products

The efficiencies of physical sorting processes will be discussed as being governed by physics of separation, the properties of the different materials present in the shredded product and the composition of intermediate recycling streams (recyclates). Different technologies for sorting will be included in this section. Also the role of the informal sector, i.e. hand sorting, will be discussed briefly.

9.4.1 Physics of automated sorting and particulate nature of recycling

Physical sorting processes are governed by physics of separation and hence by the physical properties of the different materials present in the (shredded) particles and consequently of the (intermediate) recycling streams. It is important to realize that commercial recycling systems never create pure material streams (as discussed by van Schaik and Reuter, 2004) and never achieve 100% material recovery (recycling) during physical separation as dictated by the laws of physics (and statistics) of separation. This is clearly depicted by Figs 9.11 and 9.12. The separation efficiency of the individual mono- and multi-material particles is determined by the actual composition of the particle and the ratio of the different materials as these affect their magnetic, density, electric, colour, conductive, etc. properties that govern their physical separation. This implies that the separation efficiency needs to be accounted for as a function of the particle composition, rather than assuming that only pure particles are present in the streams as is the case in commonly applied LCA and MFA methodologies and similar bulk flow approaches, as reviewed by Reuter (2011) discussing what has been accomplished to achieve a physics based link between product design and resource efficiency. Examples of these first principles are material breakage/shattering/liberation laws of comminution as a function of material connections, related to particulate characteristics of recyclate flows (as discussed in Section 9.3), sorting physics (Section 9.4) and chemistry and thermodynamics of high temperature processing and recovery of resources from recyclate streams (Section 9.5). These simpler approaches define separation efficiency only for the different individual materials. This does not reflect industrial reality by ignoring that recycling streams are a complex combination of materials, which cannot be separated by physical separation and hence drastically affect the quality of the streams.

This argument holds even more for the minor critical (see Table 9.1) and potentially toxic elements, which are often present in low concentrations, complex connections and cannot be ignored for their scarce/important and/or



9.11 Schematic overview of fundamental principles of product design and liberation in relation to physical separation (efficiency is a function of particle composition after shredding determined by product design and material liberation during shredding).

(a) (b) (c)

9.12 Recyclate quality from WEEE product due to inevitable imperfect separation and liberation: particles, distributions of (a) ferrous recyclate; (b) aluminium recyclate and (c) plastics recyclate.

potentially toxic and harmful nature. For the latter, control and monitoring are imposed in Annex II of the WEEE Directive. These minor elements can be present with different appearances in the product, either contained in different physical materials (e.g. Br/F containing flame retardants in plastics, Sb containing flame retardants in plastics and CRT glass), as material/compound in the product (such as RE(O)s in fluorescent powders of lighting and CRT TVs) or as complexity connected (or chemical contained material) on complex components such as PGMs, PMs and REs (in different components) on PWBs.

During physical sorting processes (and also during partial dismantling) connected materials of a different nature could be 'dragged' along with the (un-liberated) physical particles to various recyclate streams where their destination and behaviour need to be predicted in order to control the dispersion and recovery of toxic elements. This has been done in recycling simulation models as developed by Reuter and van Schaik (2010, 2007) as will be discussed in this chapter. Examples of this are:

- plastic with flame retardants connected to steel ending up in the steel stream and being processed in the steel convertor;
- non-liberated copper from, e.g., an electromotor ending up with the ferrous fraction in a steel convertor, lowering the quality of the steel produced;
- REs on PWBs finding their non-recoverable way to the slag in copper/lead/precious metals processing;
- PWB with all contained materials getting lost in the recyclates of the commodity materials.

9.4.2 Modelling of physical separation

Reuter and Van Schaik have captured and modelled this separation of physical sorting as part of the complete recycling system, which links design to metallurgical furnace technology (Reuter *et al.*, 2006; Van Schaik and

Reuter, 2010, 2007, 2004). Separation efficiencies for the different individual processes and pure materials have been based on separation physics and have been derived from statistically sound (confidential) plant data, which has been calibrated against various literature sources. The separation efficiencies for the multi-material particles are a function of the recovery factors of the different pure materials present in the recyclate and particles and are calculated for all physical separation processes for all multi-material particles (material connection classes) according to a weighted average as given below (see Eqs. 9.1 and 9.2):

$$R_{i,y}^{l} - \frac{\sum_{k} R_{i,y}^{k} \cdot F_{i}^{l,k}}{\sum_{k} F_{i}^{l,k}}$$

$$R_{i,x}^{l} - \frac{\sum_{k} R_{i,x}^{k} \cdot F_{i}^{l,k}}{\sum_{k} F_{i}^{l,k}} \qquad [9.1]$$

where

$R_{i,y}^{l}$, $R_{i,x}^{l}$ recovery factor (separation efficiency) for particle composition (including liberation) class *l* for unit operation *i* to intermediate and recyclate output streams *y*, *x*, etc.

$R_{i,y}^{k}$, $R_{i,x}^{k}$ recovery factor of pure material/element *k* for unit operation *i* to stream *y*, *x*, etc.

$F_{i}^{l,k}$ input steam composed of materials *k* in particle composition class *l* to unit operation *i*

in which (maintaining closed mass balances for all connected and liberated materials):

$$R_{i,y}^{k} + R_{i,x}^{k} + R_{i,z}^{k} - 1$$

and

$$R_{i,y}^{l} + R_{i,x}^{l} + R_{i,z}^{l} - 1 \qquad [9.2]$$

This description and modelling of the efficiency of the physical recycling processes ensures that the actual composition (and therefore quality) of each of the recyclate streams in every stage in the recycling system is captured as a function of design and shredding intensity determined particle composition and physics of separation and the input to metallurgical (and/or thermal) treatment processes is predicted based on industrial reality.

Physical sorting processes (or so-called post-shredding technologies) could be applied in various plant structures and possible combinations. Sections 9.4.3 and 9.4.4 give an overview of available sorting processes. A brief description of available dry and wet sorting techniques (as described by Reuter *et al.*, 2005, 2001, 2002) is given in these sections.

9.4.3 Dry separation methods

- *Magnetic separation:* based on the generation of magnetic forces on the particles to be separated, which are higher than opposing forces such as gravity or centrifugal forces. This principle is used to separate ferromagnetic particles from crushed scrap mixtures.
- *Eddy current separation:* is a particular form of magnetic separation. An alternating magnetic field induces electrical eddy currents on a metal particle. This results in a magnetic field whose direction is opposite to the primary magnetic field. The exchange interactions between the magnetic fields result in a repulsive force on the metallic particle; the net effect is a forward thrust as well as a torque. This force and hence the efficiency of separation is a function of the magnetic flux, or indirectly of the electrical conductivity and density and the size and shape of the metallic particles.
- *Air separation/zigzag windsifter:* Air-based sorting technique, which separates the light materials from the heavier. The most prominent application is in shredder plants producing the shredder light fraction, or in fridge recycling, removing among others the polyurethane (PUR) foam from the shredded scrap.
- *Screening:* Separation of the scrap into different particle size classes is performed to improve the efficiency of the subsequent sorting processes and/or to apply different processing routes for different size fractions (based on material breakage and hence distribution over various size fractions).
- *Fluidized bed separation:* A fluidized bed of dry sand is used to separate materials based on density. This technology is in principle a dry sink-float separation, which is still hampered by several difficulties (tubular or hollow particles filling up with sand and tend to sink; formation of unsteady current due to the use of high velocity air, etc.). The fluidized bed could also be heated for simultaneous de-coating and combustion of organic material.
- *Image processing (including colour sorting):* Colour sorting technologies, which sense the colour of each particle and use computer control to mechanically divert particles of identical colour out of the product stream (red copper, yellow brass, etc.). A complicating issue is that shredding results in mixtures of particles that show a distribution in composition, size, shape, texture, types of inserts, coatings, etc. The variance of these properties complicates identification that is solely based on this principle.

- *X-ray sorting:* Dual energy X-ray transmission imaging (well known for luggage safety inspections at airports) identifies particles based on the average atomic number, particle shape, internal structure (e.g. characteristic variations of thickness) and presence of characteristic insert material. It is rather sensitive to particle thickness and surface contaminations.
- *LIBS (laser induced breakdown spectroscopy) sorting:* A series of focused ablation laser pulses are delivered to the same spot on each particle. A pulse of an ablation laser vaporizes only the first nanometres of the surface, i.e. the first pulses are necessary to clean the surface of oxide layers (different composition than the mother metal), the last pulse vaporizes a tiny amount of metal generating a highly luminescent plasma plume. The light from the plasma is collected and analysed to quantitatively determine the chemical composition. This determines to which bin the particle is directed (e.g. by air pulse).
- Other dry separation processes include ballistic sorting, wire sorting, electrostatic sorting, etc.

9.4.4 Wet separation methods

- *Sink-float:* This sorting technique is based on density difference of the materials. A heavy medium consisting of a suspension of, e.g., fine haematite or FeSi in water separates high density particles (sink) from light materials (float). The slurry is regenerated (FeSi is ferromagnetic); however, losses occur to the scrap, hence slightly increasing the iron content of the sorted scrap.
- *Heavy medium cyclones:* Centrifugal forces are used to separate materials with different densities.
- Other wet separation processes include e.g. jigging.

9.4.5 Role of the informal sector

The role of collection and sorting in the informal sector should be carefully considered. The type of infrastructure which is available in a region should ensure that recycling can happen – this implies a sufficient market to supply the recycling system, take-back systems, collection, understanding the global flows of materials, manual/automatic sorting, formal vis-à-vis informal recycling, metal recovery, transparency in the system, suitable legislation that enables (or limits) recycling, etc. Optimization and (fine) tuning the balance of manual dismantling and the opportunities of the informal sector versus the possibilities and the limits of automated/physical sorting as discussed in this section could play an important role in maximising the recovery of resources from e-waste/WEEE.

9.5 Metallurgical processing

The role of metallurgical processing as closure of the material cycle of products is the topic of this section. The link between design, liberation, recyclate quality, sorting efficiency and metallurgical process performance will be discussed briefly, including some examples for different metals in WEEE. This section will give some detail on the technology and issues in metallurgical processing.

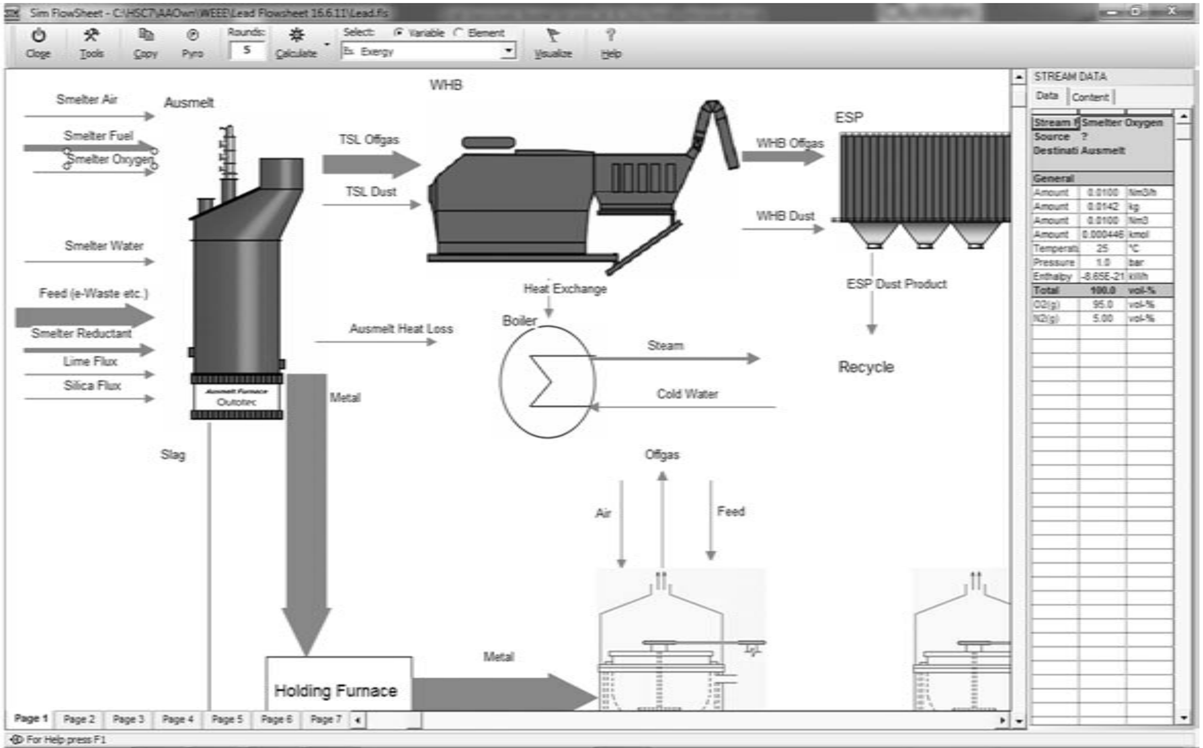
9.5.1 Pyrometallurgical processing

Figure 9.13 provides a typical overview of a section of a pyrometallurgical plant containing a smelter and various ancillary equipment such as a waste-heat boiler (WHB) that recovers heat from the offgas and produces steam (e.g. to generate electricity), an electrostatic separator (ESP) that recovers fine dust (not shown are further dust removal systems as well as sulphur and other environmentally required element/compound capture) and various other metal refining reactors (only partially shown).

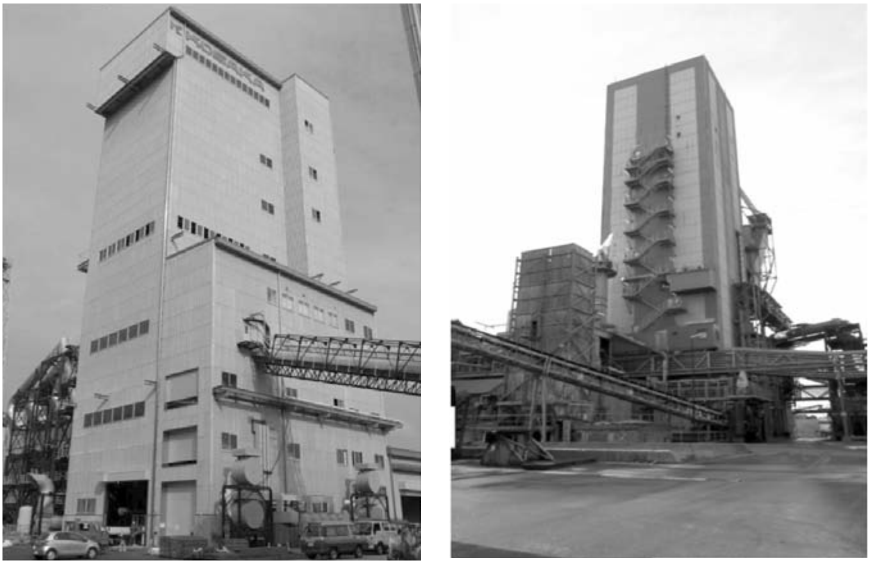
From Fig. 9.6 it should be clear that WEEE consists of various elements from the periodic system, present as metals and various compounds. The way these are distributed among the different phases, as alluded to in Fig. 9.13, is determined by thermodynamics and the type of technology used. The best available technology (BAT) (see Fig. 9.14) tends to reach the thermodynamic limits while poorer processes will not optimally distribute the elements and compounds between the phases for optimal economics and resource efficiency.

Figure 9.15 shows the relative stability of some oxides of indium and tin, which have a direct effect on their recovery and recycling rate due to the various different chemical species that In and Sn can appear in when processed because of their oxidation states, vapour pressure, etc. It is clearly the understanding of the thermodynamics within the technological/economic context that determines how well indium and tin are recovered in the appropriate phases for further processing. Usually operators of BAT do this excellently and hence operate most resource-efficiently as they understand these fundamental issues very well.

The example in Fig. 9.15 shows the various compounds of indium and tin and their behaviour under different temperature conditions under different carbon starting values (i.e. if little carbon it is more oxidizing, if more it is more reducing). It is clearly evident that under more reducing conditions more indium metal is produced, while tin oxide is readily reduced to metal. Various volatile species of indium oxide and tin oxide exist and, depending on the gas flow through the system, more or less is removed to the gas phase and later oxidized to flue dust.



9.13 A typical section of a pyrometallurgical Best Available Technology plant for the smelting of an arbitrary feed, producing a metal (or matte/speiss) phase reaching temperatures of around 1250 °C, a slag (oxide molten material often used as building material) phase reaching similar temperatures as metal, an offgas (reaching very high temperatures under certain conditions) and a flue dust (also shown is the Exergy flow) (HSC Sim 7 – www.outotec.com)



E-waste and copper recycling Dowa (Japan) (a)

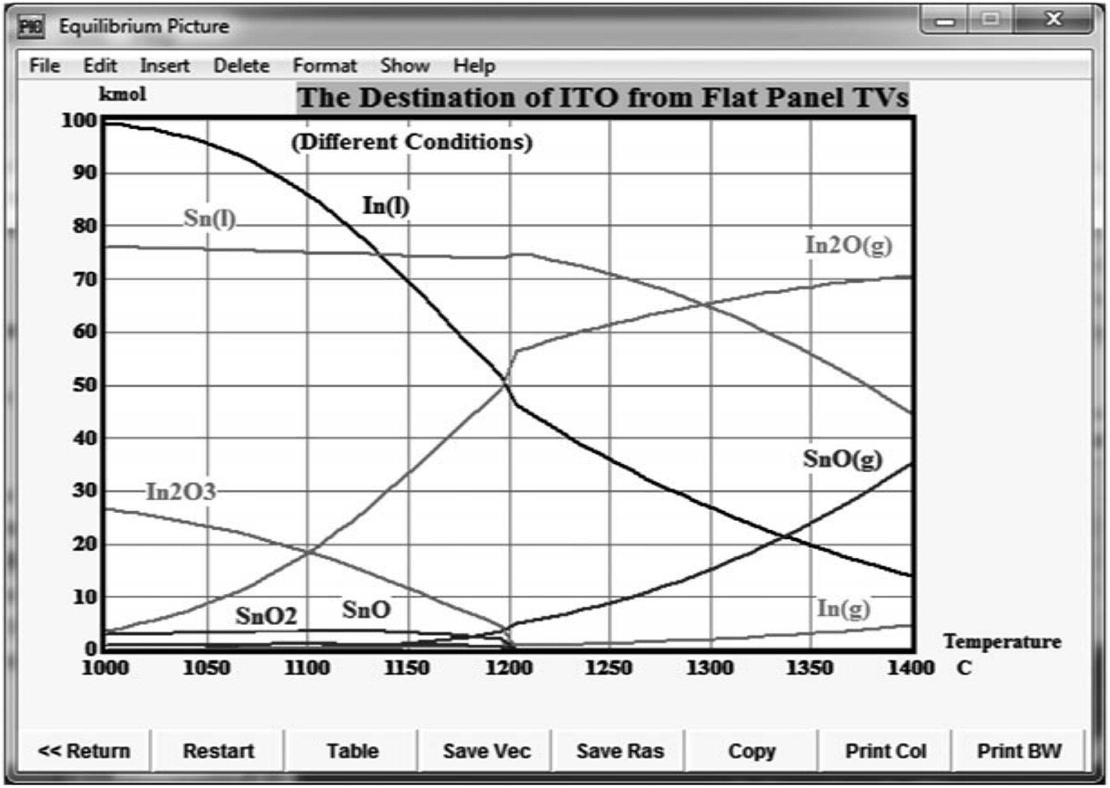
Lead battery recycling Recylex (Germany) (b)

9.14 Typical plants of the nature schematically shown in Fig. 9.13 with various feed conveyors and offgas handling systems shown (www.outotec.com).

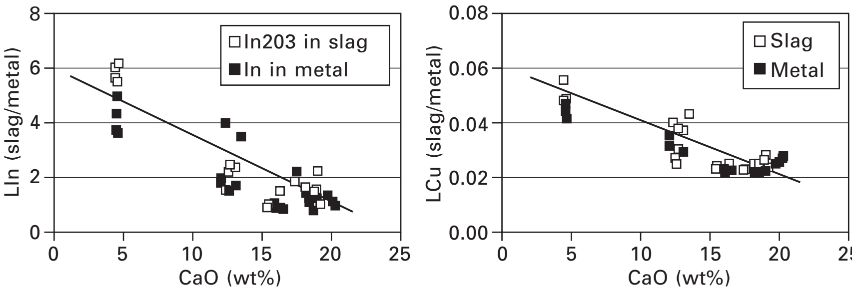
Figure 9.15 shows the distribution of elements and compounds into different phases for ideal conditions. The various oxides of indium and tin can dissolve in slag and create non-ideal solutions with the other oxide compounds within the molten slag (which reaches temperatures in non-ferrous metallurgy of around 1250 °C). Figure 9.16 shows that if the lime (CaO) content in the slag changes for the given experimental conditions the distributions are further affected, complicating things further.

In addition to the above conditions of separation it must be clear that all the material must be molten so that it can be properly reacted and also removed from the furnace. This implies that the molten slag must have a sufficiently low viscosity and hence all must be molten. However, molten slag mixtures of $CaO–FeO–SiO_2–Al_2O_3–MgO$–metal oxides are tricky liquids that, depending on the composition, will melt earlier or later. Figure 9.17 clearly shows the marked influence alumina (Al_2O_3) has on the melting point of slags. Usually alumina is created from aluminium that reports with e-waste to the smelter. Hence removal of aluminium from e-waste is beneficial for smelting and obviously also, owing to aluminium's high footprint, better to recycle through separate remelting and refining.

It is obviously the intent to recover valuable metals into a metal phase from which they can be recovered by suitable refining. Some metals, such as



9.15 The stability of some oxides of tin (Sn) and indium (In) under different operating conditions. (HSC, www.outotec.com).

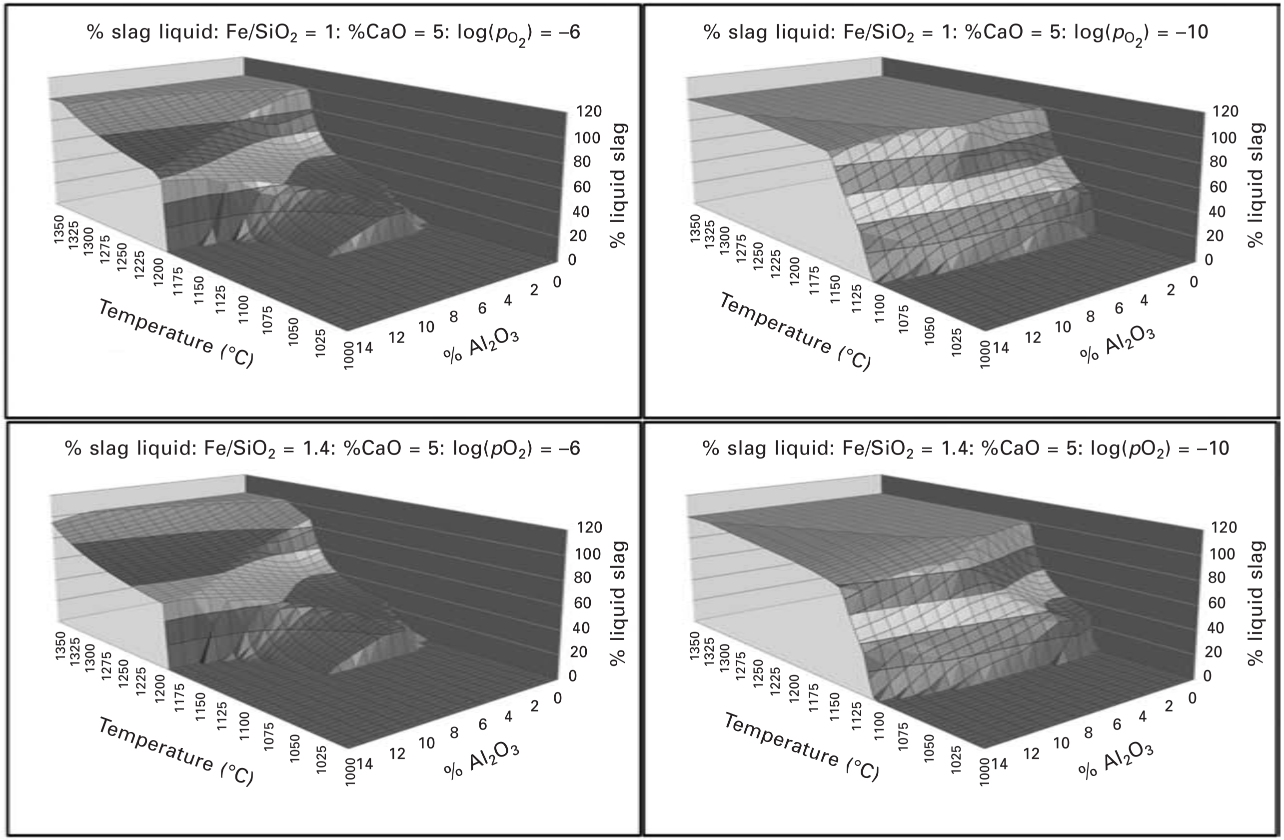


9.16 The distribution of indium and copper between metal and slag as a function of lime addition at 1300 °C, Fe/SiO_2 = 1.1–1.2 and log $(p_{O_2}) = -7$. (Anindya *et al.*, 2011)

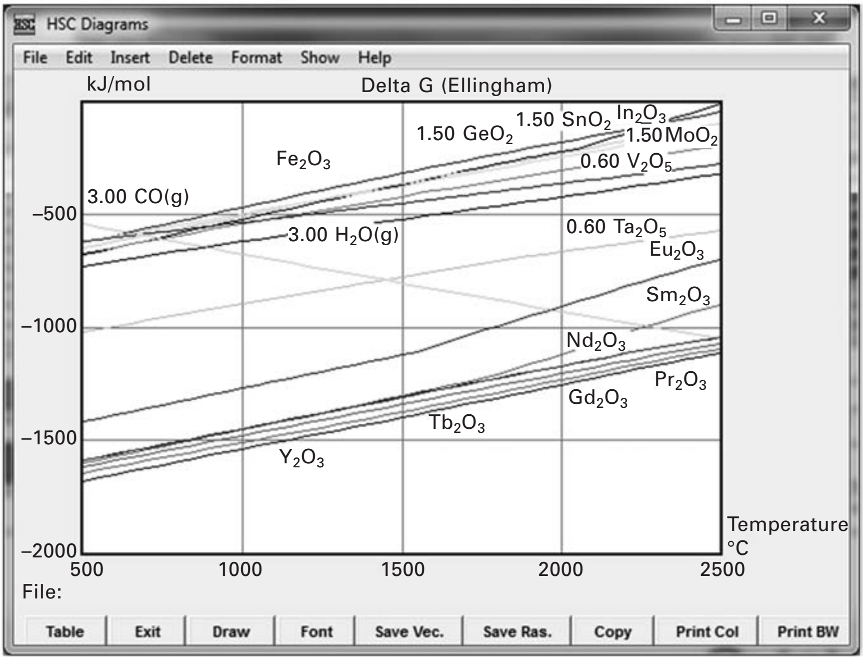
aluminium, create such stable oxides under non-ferrous smelting condition, that they inevitably report to the slag and are lost from the material cycle. Their concentration is often too low in the slag to recover economically.

Figure 9.18 is an Ellingham plot of various oxides, i.e. delta *G* vs. *T*. The more negative the values the more stable these oxides are. Where the CO(g) line crosses the plots for the oxides is the temperature at which carbon can reduce the oxides, which is clearly evident for oxides such as Fe_2O_3, which lies in the top group. For the various rare earth oxides this will clearly be less easy (note that there are various sub-oxides of some rare earths that can also be shown) to reduce to metal with carbon as reductant. The result of this is that rare earths will report as oxides to the slag in smelting operations and hence have to be removed before reaching the smelter, very much like aluminium that becomes alumina and is lost. What this also indicates is that some metals are better recovered through hydrometallurgical ways than pyrometallurgical processing due to their stability.

From the above brief discussion it should be clear that elements behave differently in reactors which subsequently affect their recovery and ultimately their recycling rate. This chemical affinity and compatibility for recovery under certain conditions can be succinctly summarized in a compatibility matrix. Table 9.5 depicts the recoverability for different critical elements as a function of their application in various WEEE/e-waste products. It reveals that recovery is dependent on the design of a product, i.e. the combination and location of materials on separate and/or connected components, and will differ for different WEEE products as well as the selected recycling route and technology available. As an example Table 9.5 shows that tungsten and tantalum as present in getters (in CRT TVs and lighting) can potentially be recovered when separated from the product (dismantling from getters) and processed in appropriate technology. However when processed together with the other metals, substantial losses of these elements to non-valuable phases will occur due to the stability of the oxides (see Fig. 9.18). The



9.17 Different melting conditions for FeO_x–SiO_2–CaO–Al_2O_3 slags for different oxygen partial pressures (left oxidizing and right reducing) (FACT Sage 6.2 1976–2010 Thermfact and GTT-Technologies).



9.18 Stability of various compounds in e-waste – the more negative the lines the more stable the oxides (HSC Sim 7.0 – www.outotec.com).

same applies to the various REs. Figure 9.18 shows the high stability of the oxides of the various REs, implying that when processed in high temperature pyrometallurgical processes, these will report to the slag. Only when separated from the product and processed in suitable (hydrometallurgical) technology, recovery might be possible. Hence Table 9.5 shows that depending on process route followed recovery or losses are possible. The light and dark boxes and combination of shading indicate that the processing, design, recycling infrastructure (including the well-integrated role of the informal sector), etc. of these materials and products need careful attention. This is especially the case for closely/complexly linked metals (e.g. PGMs, PMs and REs on PWBs) where the choice to recover one metal will result in the other metal being lost. This is driven by the thermodynamics and technology as well as by design considerations. Table 9.5 hence also gives technology based DfR information for the different included products and materials applied.

9.5.2 Hydrometallurgical processing

It is often wise in WEEE processing to do the first rough separation pyrometallurgically, especially also as it then utilizes the plastic content

Table 9.5 Compatibility matrix as a function of metallurgical recovery

Recoverability* (per equipment/ application)	PMs		PGMs		Rare Earths (Oxides)			Other					© MARAS
	Ag	Au	Pd	Pt	Y	Eu	Other REs	Sb	Co	In	Ga	W	Ta
Washing machine													
Large household appliances (excluding fridge)													
Video recorder													
DVD player													
Hifi unit													
Radio set													
CRT TV													
Mobile telephone													
Fluorescent lamps													
LED													
LCD screens													
Batteries (NiMH)													

*Recovery is a function of processing route, product design, etc. The table gives the recovery for the present most likely route, but could change if suitable technology exist.

Recovery possible	If separately recovered and/or if there is appropriate technology and recovery available.
Limited recovery/recovery under certain conditions	If separately recovered. Partial or substantial losses during separation and/or processing/metallurgy. Recovery if appropriate systems exist.
No separate recovery	Pure recovery not possible. Lost in bulk recyclates during separation and/or during metallurgy into different non-valuable phases.
For a combination of colours	Depending on process route followed high recovery or high losses possible. Needs careful attention to design, infrastructure, legislation, etc. This is especially possible for metals closely linked where one metal can be recovered while the other due to this selection of recovery then goes lost. This is driven by the thermodynamics, technology, design, etc.

as an energy and reductant source from recyclates that inevitably contain 'impurities' as shown in previous sections. This permits a rough cut of the elements to be made while taking care of most of the 'nasty' materials, compounds and elements. These are recovered well in the offgas system as depicted by Fig. 9.13. Subsequent processing takes place in well-developed hydrometallurgical refining.

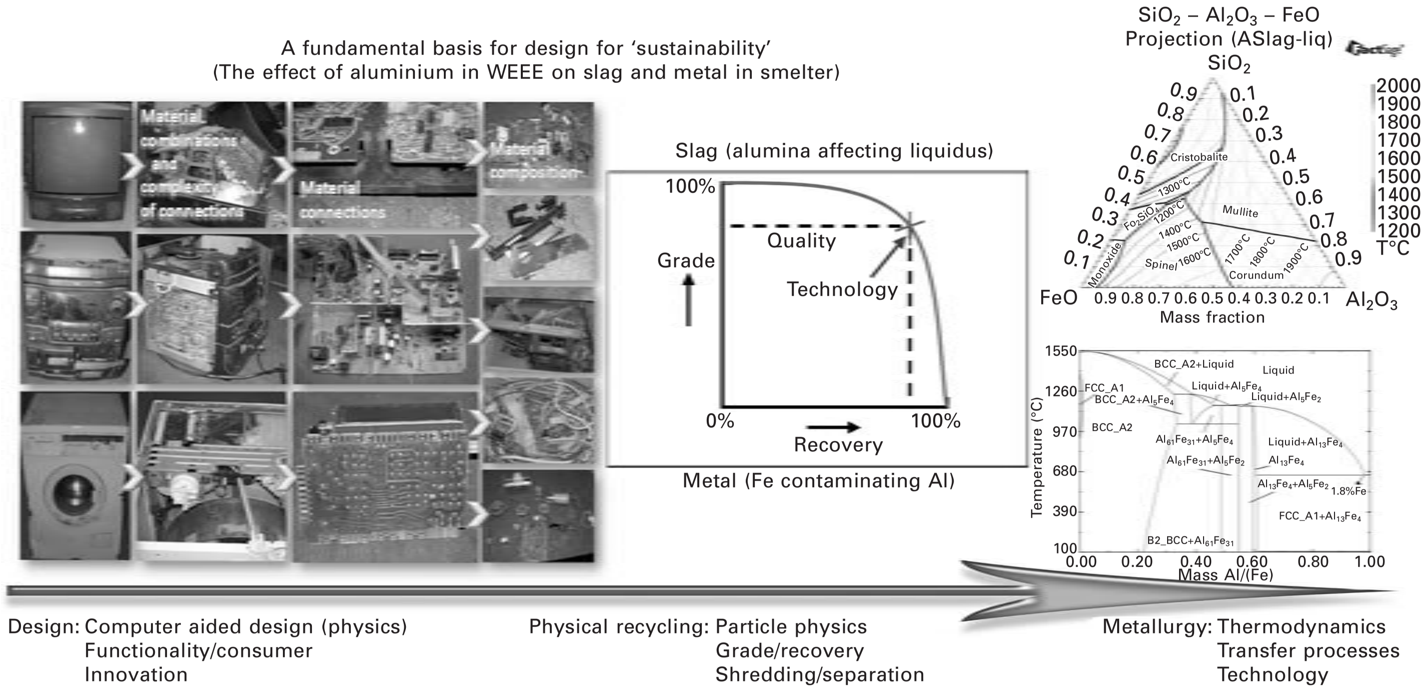
While there may be advocates for doing all recycling of e-waste hydrometallurgically, it must be noted that recovery due to the intimate connections of metals in WEEE/e-waste will never be 100% (due to the functionality of various components). In addition an impure PWB will be the result after leaching, which then has to be processed anyhow by high temperature as it will contain various rests of metals, compounds, etc. that could not be reached by leaching agents such as sulphuric, hydrochloric and nitric acids. In addition all leaching solutions will have to be cleaned before they can be reused or be disposed.

The reader is referred to typical texts such as *Ullmann's Encyclopaedia of Industrial Chemistry* for further details on the standard techniques to refine various metals hydrometallurgically.

9.5.3 Linking product design to metallurgy

The interconnected system of design, particulate quality, manual and automated sorting and metallurgical processing efficiency determine the ultimate performance of recycling. Insight into this provides technology and industrial process driven DfR (see Fig. 9.19). Table 9.5 gives a clear indication of these possibilities and limits of the recovery of (critical) materials by pinpointing the (in) compatibility of different materials in e-waste products on the basis of metallurgical recovery. This table provides technology-based DfR information and indicates for which products and material combinations DfR and/or optimized processing routes should be considered. Figure 9.6 illustrates the compatibility of materials based on metallurgical process technology, whereas the WEEE wheel of Fig. 9.3 clearly depicts which combination of materials can be processed and recovered together. The base metals in the inner ring determine what recyclates can be taken up in industrial furnace technology, at the same time depicting the range of materials, which can be recovered from recyclate streams (mixtures of materials) and which will become lost due to process chemistry, thermodynamics and kinetics.

Metallurgical simulations above have shown the limits and possibilities for recovering critical elements from E-waste. In smelting operations it will, for example, be less easy for the various rare earth oxides to be reduced to metal with carbon as reductant. The result of this is that rare earths will report as oxides to the slag in smelting operations and hence have to be



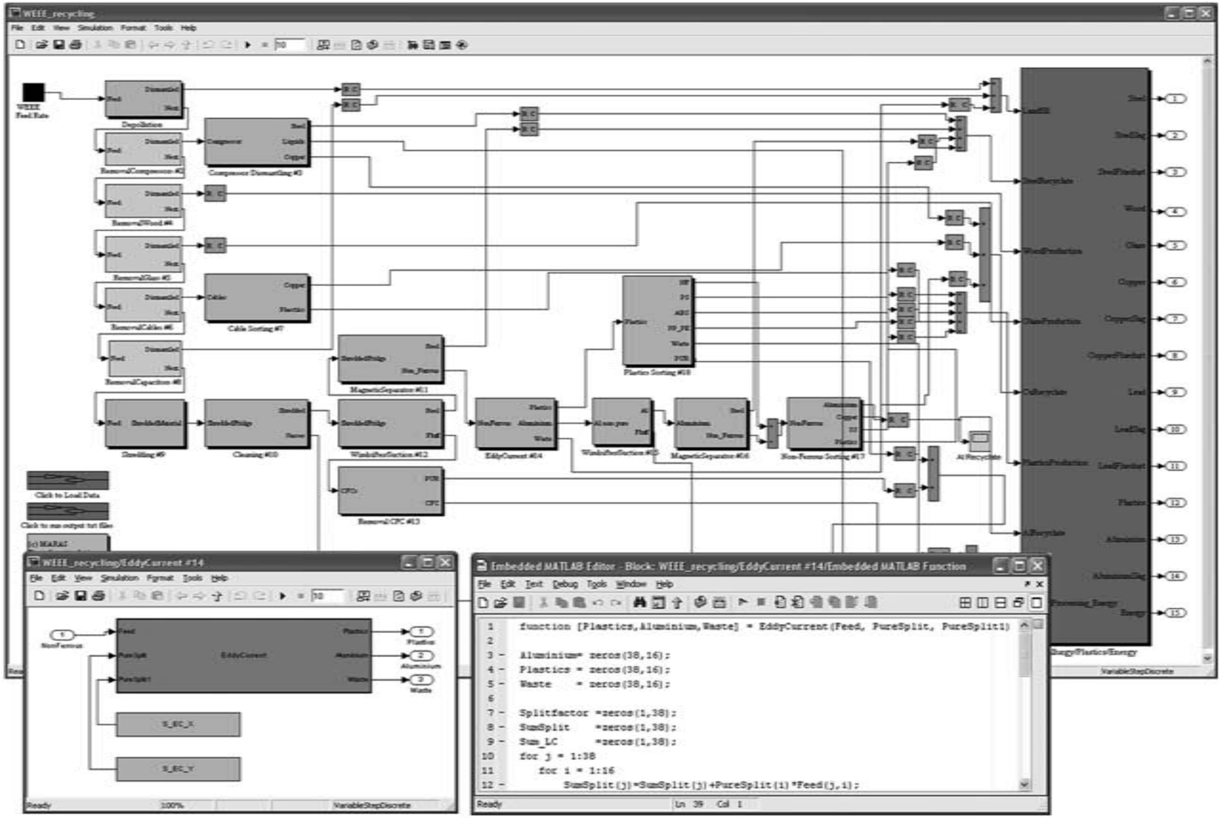
9.19 The interconnected system of design, particulate composition, physics of sorting and metallurgical thermodynamics is the basis for DfR.

removed before reaching the smelter. This indicates that some metals are better recovered through hydrometallurgical ways than pyrometallurgical processing due to their stability. The marked influence alumina (Al_2O_3) has on the melting point of slags has also been shown, which negatively affects the operation conditions of the furnace. Alumina is usually created from aluminium that reports as non-separated and/or non-liberated material with e-waste to the smelter. Hence removal of aluminium from e-waste either by sorting or well-considered design is beneficial for smelting and obviously also, owing to aluminium's high footprint, better to recycle through remelting and refining. Also examples on the extent to which indium, tin and gallium can be recovered have been shown.

9.6 (Dynamic) modelling recycling systems performance

Since most materials are applied and combined in complex multi-material products, rather than flowing as single materials through the consumer system, material recycling and recycling product flows need to be addressed from a product perspective rather than to address single materials in order to deal with the industrial reality of closing and controlling resource/material cycles. The above show that simplistic approaches that describe the material flows as singular, non-connected materials and recyclates do not reach enough depth to deal with the complexities and challenges of physical and metallurgical recovery of resources from WEEE/e-waste, owing to the complex nature of the product design and multitude of different materials applied and (chemically) connected in this. Therefore this section will discuss in some detail the required and developed models to optimize (design for) recycling of WEEE (see Fig. 9.20).

The theoretical aspects discussed and explained in the above sections highlight the importance of capturing the degree of liberation, recyclate and output quality and the effect on physical, metallurgical and thermal separation performance when assessing resource cycles, performing DfR and monitoring the performance and toxicity of recycling systems from WEEE goods. Recycling models will be discussed (Reuter *et al.*, 2006; van Schaik and Reuter, 2010, 2007, 2004), which shed a physics based light on the linkages between product design, recycling (sorting) and process metallurgy and underpin resource efficiency with a theoretical basis, which is an important tool to maintain/safe-guard resources used in high tech consumer products (including critical/'scarce' elements) in the material and energy cycle, all as a function of time. These models and discussed principles are fundamentally based on the conservation of mass, elements, compounds, particles, groups of materials, as well as on physics, thermodynamics, chemistry and mass transfer between phases. Based on some examples the versatility and the



9.20 Example of (dynamic) simulation model for the recycling of WEEE including different manual and physical recycling options, a range of final treatment processes (metallurgical processing, thermal processing, plastic processing, etc.) and an example of the layered model structure showing the detail of different shredding and sorting options.

type of results that can (and have been) be achieved with this approach will be illustrated.

9.6.1 Critical materials in e-waste/WEEE

The simulation models typically also include the recycling of fluorescent lamps and LEDs consisting of a variety of materials including RE elements, indium (In) and gallium (Ga). The fluorescent powders (also called phosphors) generally consist of a host lattice ($Ca_5(PO_4)_3(Cl,F)$, $BaMgAl_{10}O_{17}$, Y_2O_5, $LaPO_4$, $Y_3Al_5O_{12}$, YVO_5, etc.) doped by a few per cent of an activator, which can be the metal ions (e.g. $Pb^{2+}/Mn^{2+}/Sb^{3+}$) or REs (e.g. $Eu^{2+}/Tb^{3+}/Ce^{3+}$) (Van den Hoek *et al.*, 2010). Typically the phosphors from fluorescent lamps will be physically recovered easily from the inside of the tubing (Rabah, 2004; www.indaver. be; www. alba. info), while hydrometallurgical processing technology recovers the REs (McGill, 2005). LEDs on the other hand are in general a compact design of organic materials and phosphors and would require a different path. In and Ga are recovered to an extent in normal pyrometallurgical (high temperature) smelting operations (e.g. during e-waste/copper scrap recycling (Anindya *et al.*, 2011)) of which there are a number of globally; however, the REs would go lost in the slag phase of the smelters.

9.6.2 Application and results of recycling models

The dynamic recycling models for e-waste/WEEE have, among others, the following applications:

- Prediction/calculation of recycling and recovery rates (recycling performance) and hence estimating resource efficiency of different e-waste products for all different materials present (in both physical and chemical compounds, including recovery of metals/materials and/or presently scarce/critical metals, toxic materials, etc.); as well as for different input mixtures of recycling plants (varying mixture/ratio of different products, such as the varying mixture of washing machines, dishwashers, wash dryers, ovens, etc. in the large household appliances (LHHA) flow);
- Prediction/calculations of mass flows of produced recyclates/recycling products (%/kg);
- Prediction of grade (quality/composition) of all (intermediate) particulate (liberated/unliberated/complex) recycling streams (such as steel recyclate, copper recyclate, plastic recyclate, etc.) and recycling products (metals, matte, slags, speiss, flue dusts);
- Prediction of the recovery of minor/scarce metals of great importance to enabling sustainable energy and other high tech applications;

- Identification of the dispersion, occurrence and appearance (chemical phases/compounds) of possible toxic/harmful elements in different recyclates and recycling products (also determining whether a toxic material is still toxic or inert after processing).

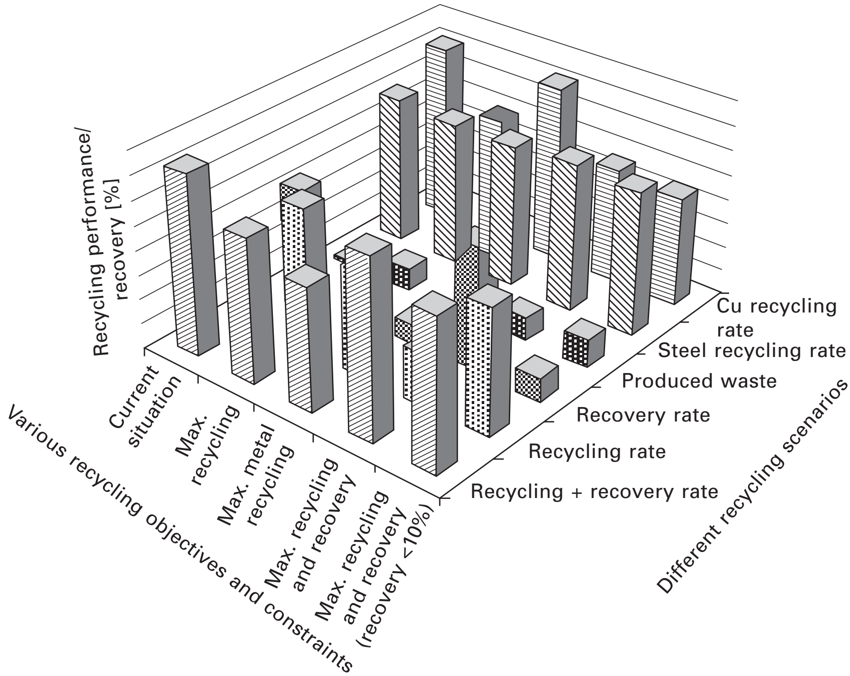
The recycling performance (including the variables listed above) have been formulated for existing and alternative recycling routes (including different recycling plants/flow sheets concepts, combination and arrangement/choice of processes and/or dismantling versus shredding and sorting, etc.) within statistical bandwidths of design, plant input (different products, different and time changing product ratios, weights and compositions – see Section 9.1) and processing variations governed by physics. This all is required to cover the distributed and time-varying properties of EoL-product populations, changing designs and practical and industrial reality of recycling processes (Reuter, 2011). The models can be/are used for informing original equipment manufacturers, guiding consumer and policy on a physics based C2C basis to make resource-efficient decisions on rather daunting and complex problems. Some examples of derived results are discussed below.

Recycling rate predictions for different objectives of recycling

Figure 9.21 gives an example of recycling performance simulations showing the bandwidth of recycling rates as a function of the parameters of the recycling system (dependent on the objective of recycling and constraints). It illustrates the achieved recycling performance expressed in different terms (total product recycling and recovery, recycling rate of individual metals, etc.) for different recycling objectives and/or constraints, such as the recycling/ recovery rate and corresponding metal recycling rates (including recyclate and metal quality) when striving for (i) optimal sum of recycling and recovery, (ii) optimal recovery of metals, (iii) taking into account legislative restrictions to the percentage of energy recovered from the product content, etc.

Dynamic product and material recycling rate predictions

Figure 9.22 shows the predicted recycling rates for an e-waste product over time, being a function of changing EoL product populations (different types of products, from different production years) and changing product weights and material compositions thereof as discussed in Section 9.1. It depicts the capability of the model to capture the dynamic nature of product recycling and predict recycling rates (and hence resource availability from it) in future, which is imperative to drive changes and improve recycling performance, apply DfR, etc. over time. Figure 9.23 underpins this, by giving

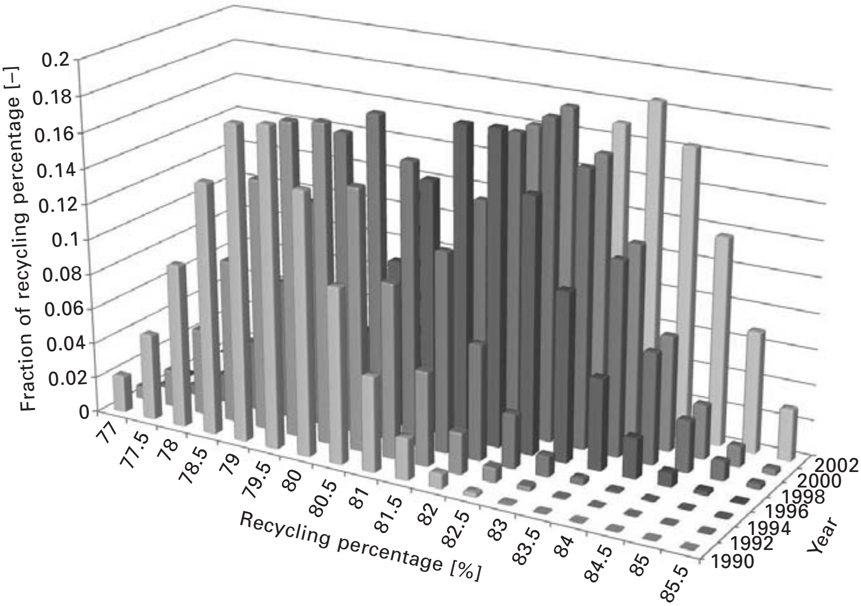


9.21 Recycling performance calculations (expressed in overall and material recycling/recovery rates, produced waste and recycling rates of steel and copper) as a function of various objectives, constraints and scenarios (figures on the *Y*-axis have been removed for confidentiality reasons).

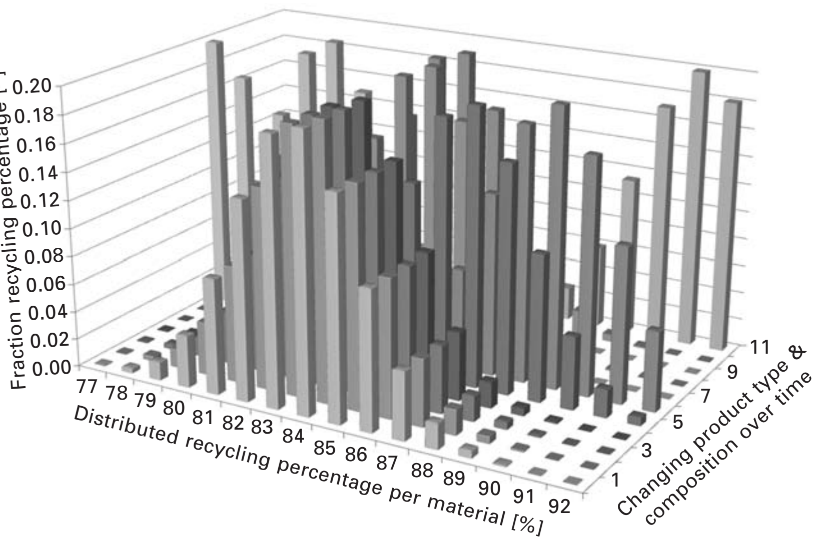
an example of calculated recycling rates for the different materials present in these products.

Mass flows of produced recyclates/recycling products and distribution/ dispersion of (critical) materials over different recyclate streams

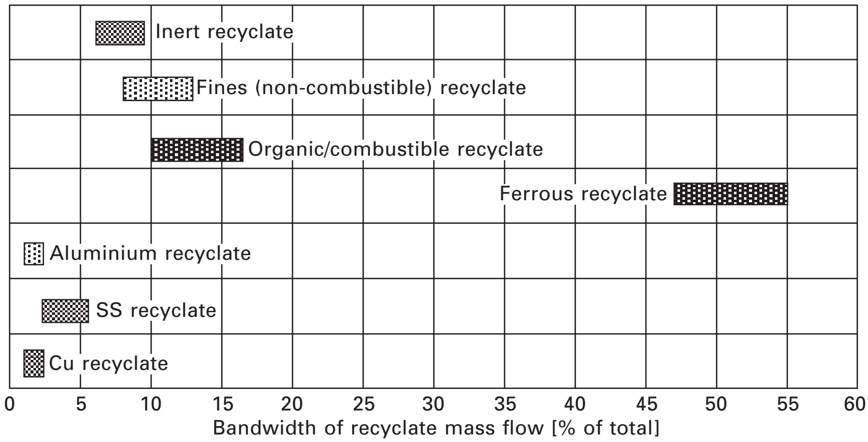
Key to the simulation/optimization models is that they produce closed mass balances for each liberated and un-liberated mineral (physical material) and (chemical) element as a function of design as the basis for recycling/recovery rate predictions linked to product design choices. This differs fundamentally from the more simplified approaches such as LCA and MFA, which rely simply on total element and material flows, hence are not providing the required depth to capture and predict the mass flows of recyclates and recycling products including the presence of contaminants and dispersion of (critical and/or toxic) materials during recycling. Figure 9.24 shows as an example the calculation of the mass flow (relative to input/output of plant) of a selection of produced recyclate streams from the recycling of



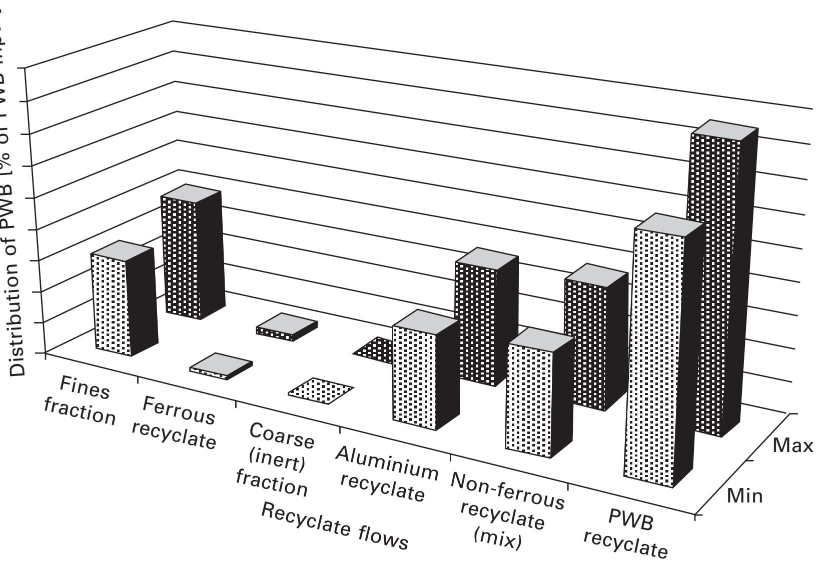
9.22 Dynamic distributed recycling performance calculations of an e-waste product over time (showing distributed recycling rates as a function of distributed: material liberation, range of products and changing designs, complex interlinked materials in product design, quality of recyclates (all of a mean and standard deviation) to name a few.



9.23 Dynamic recycling rates per material (total recycling rates given in Fig. 9.22) as a function varying product weights and compositions and plant input over time.



9.24 Bandwidth of various produced recyclate streams (percentage of total plant input/output).



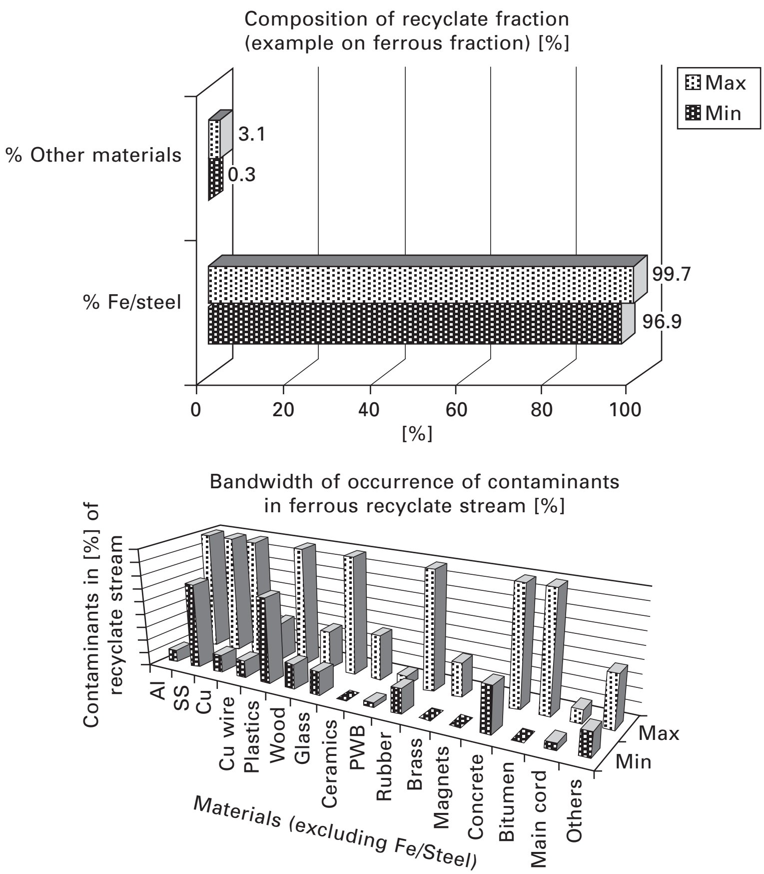
9.25 Example of calculated distribution/dispersion of PWB over different recyclate streams (figures on the *Y*-axis have been removed for confidentiality reasons) (percentage of input PWB).

an e-waste stream. These predictions include a bandwidth of the results as a function of changing processing conditions, input composition (based on changing mixture of plant input, changing product weight, composition, etc.). Figure 9.25 gives an example of the prediction of the dispersion of PWBs to various recyclate flows due to the low quantity and connected nature of

PWBs in the design and the focus of the recycling of the illustrated product on the recycling of commodity metals in order to comply with the recycling/recovery quotas as imposed by the EU WEEE Recycling Directive.

Quality of recyclate streams and recycling products

Figure 9.26 gives an example of the calculated quality of a ferrous recyclate. This example illustrates that the quality/composition (grade) of recyclates is not only calculated based on its ferrous content, but also includes the different other materials/contaminants present in the recyclate streams, owing to imperfect separation and liberation (as depicted by Fig. 9.11). This is also of importance in tracing the recovery/dispersion of all different materials.



9.26 Quality of ferrous recyclate stream including the quantification and specification of the composition/contamination of the recyclate streams.

On this basis, also the chemical composition of these recyclates can be predicted (e.g. based on alloy composition of different metals, present minor elements, chemical compounds, etc.) in order to predict the quantities and composition (based on chemical composition/phases of the materials) of recycling products (metal, matte, speiss, slag, flue dust, off gas). These quality predictions provide the basis for (i) evaluation of the marketability/economic value of the produced recyclates from dismantling and physical separation (e.g. smelter-charge for the streams that report to smelters and revenues in further processing (e.g. copper metallurgy)), (ii) a scientifically based estimate of the toxicity of each recyclate stream (based on the combination of materials in each particle), (iii) assessment of applicability of the slag and/or requirements for further treatment and (iv) assessment of toxicity of the output streams (e.g. leaching behaviour and/or landfill costs).

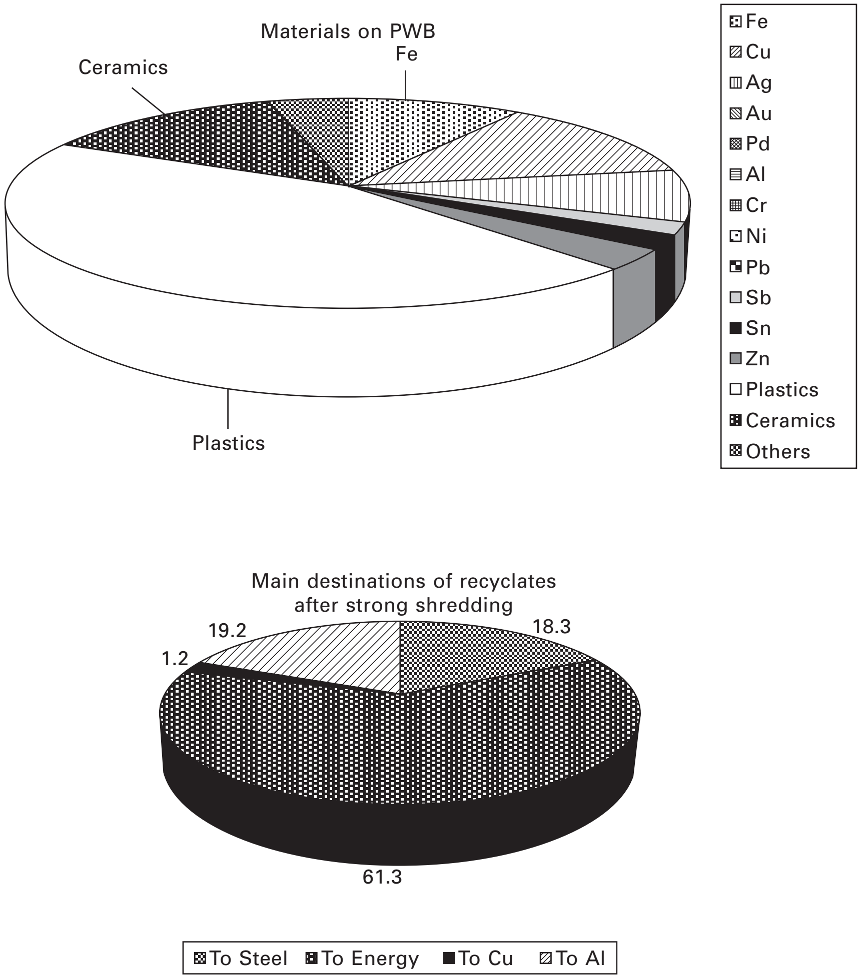
Prediction of the impact of different operating modes of technology on the total recycling of minor and some commodity metals

Since all materials and streams are described separately in the model, the recovery of all elements (see Figs 9.22 and 9.23), including the minor/critical elements and the achieved recycling/recovery rates thereof can be predicted (see Figure 9.27). The example in this figure illustrates the true predictive nature of the dynamic simulation models. Calibrated with plant data from various sources, this simulation shows what the effect is of no-shredding, medium and high shredding on the recovery of valuable minor metals as well as commodity metals from PWBs. Figure 9.27 shows that the maximum precious metals, copper and tin will be recovered if the PWBs are directly smelted in a copper smelter; however the recovery of steel and aluminium is then low as these report to the slag. Although shredding has more positive effects for aluminium and steel recovery than for other valuable elements, it is clear that most material when shredded does end in energy recovery due to its uneconomic recyclate quality; the consequence being that most metals that are connected to the organic material are also then lost if not liberated. These predictions can be applied to discuss or support the work of Guo *et al.* (2009) reviewing the recycling options for PWBs. These findings are also corroborated by industrial trials (Chancerel *et al.*, 2009; Hagelüken, 2006).

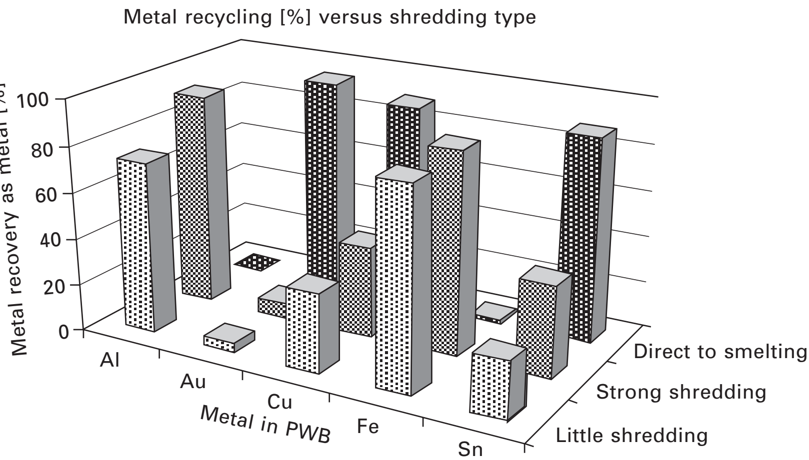
Summarised, it can be concluded that the physics-based approach as discussed here, from which the actual recovery of individual materials and energy can be calculated (as is for example required by EU WEEE Directive) is crucial for prediction of the recovery and control of the actual distribution of commodity, critical, toxic and/or contaminating substances into different individual particles and the various recycling streams and their destination after final (metallurgical or thermal) treatment. This provides an accurate and reliable basis for the control and assessment of resource efficiency, toxicity and the related environmental/eco-efficiency consequences; hence crucial for monitoring and quantifying progress in time.

9.7 Conclusions

This section will provide a summary of the key issues that limit recycling and what measures will maximize resource efficiency for WEEE/e-waste. Also some guidelines for design for recycling and sustainability will be provided (Reuter, 2011).



9.27 Metal recycling rates predicted by the recycling model for different metals for the recycling of disassembled PWBs either being directly fed to a copper smelter or shredded with varying intensity.

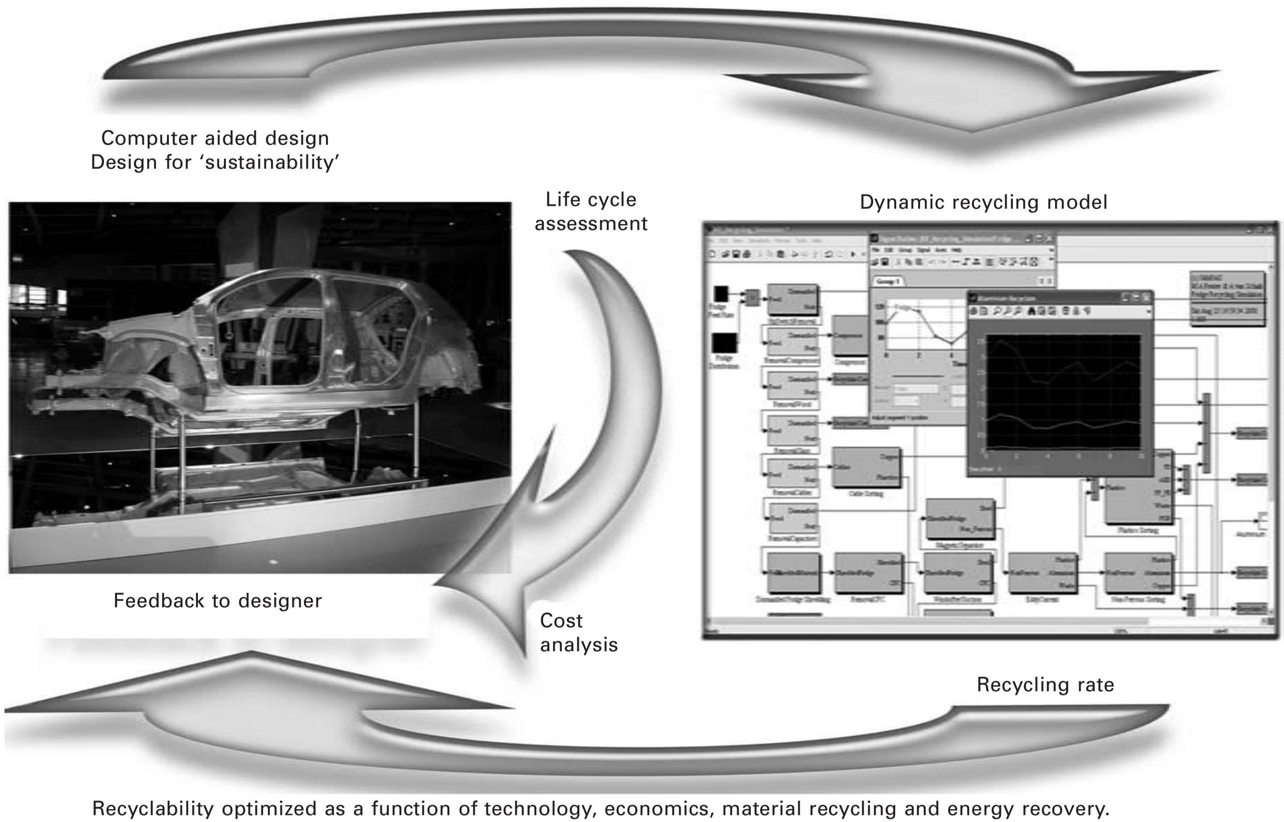


9.27 Continued

Safe-guarding resource availability and the material flows into the high tech ‘sustainable’ products requires well-designed systems, which capture resources from EoL products and recycles them back into new applications. Understanding the impact of product design and recycling system performance on this closure of material cycles, or in other words making society more resource efficient requires a deep understanding reflected by the presented first principle approaches. Making C2C/sustainable societies possible requires more than just catchy words; it needs a techno-economic understanding on how to realize resource efficiency.

Ultimately approaches that predict and optimize resource recovery and ‘close’ material loops must be able to highlight and teach the limits and also opportunities of recycling. The key to recycling is to understand the physical separation and linked metallurgical processing. This has been realized by the detailed and physics based description and understanding of the complex field of shredder particle liberation as a function of product design choices. Subsequent modelling of physical recycling separation technology characterized by a large number of highly and often non-normally distributed parameters, is a key aspect to advance resource efficiency. These distributed parameters include particle size, material combinations (liberated, unliberated and/or joined), chemical interactions, physical properties, etc. The ultimate recovery or losses/dispersion of materials, including minor/critical resources, is determined by all these aspects, affecting the quality of recyclates and particles, whereas the second law of thermodynamics determines the ultimate recovery rate of the materials in complex products such as e-waste and other multi-material consumer products such as cars within the constrained environment of the current economic system.

Figure 9.28 illustrates how this knowledge has been applied to perform



9.28 Design for recycling and recycling rate calculations on a physics basis linked to CAD and LCA software in the EU 6th framework project SuperLightCar (with VW, Opel, Daimler, Volvo, Porsche, Fiat, etc.).

DfR for the SuperLightCar (SLC, 2005–2009) by linking recycling models to LCA software and CAD systems, hence being able to predict recycling rates, recovery per material, recyclates and recycling products (including quality) as a function of design choices and changes for different design concepts in real-time.

The integration of systems discussed here highlights the importance of technology systems and hence creating a physics based exploration platform for systems innovation. This basis supports a techno-economic evaluation of systems inclusive of the physics of the systems and hence providing an enabling technology for 'sustainability'. This type of detail is required to reveal on a physics basis the opportunities and limits of recycling.

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10 Mechanical methods of recycling plastics from WEEE

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Abstract: This chapter discusses the techniques used for mechanically recycling waste electrical and electronic equipment (WEEE). Discarded personal computers (PCs), TVs, kitchen and audio equipment are among the most popular items to be recycled, yielding valuable polymers such as acrylonitrile butadiene styrene, polycarbonate and different varieties of polystyrene. The process of mechanical recycling is to collect, sort, size reduce, separate and densify these wastes, economically and effectively. The effectiveness of separation techniques such as flotation, hydro-cyclone, air tabling, near infra-red and electrostatic sorting are examined. The variations in effective WEEE collection and treatment among European Union member states are also discussed. Future work with WEEE plastics is based on the acceptable use of immiscible polymers through processing or chemical modification. An alternative area of research is to make the polymers easier to separate and research appears to be ongoing to minimise the use of different polymer types in a product, making the recycling process far simpler.

Key words: waste, polymers, separation, sorting, thermoplastic.

10.1 Introduction

This chapter discusses the practices for mechanical recycling of waste polymers from electrical and electronic equipment (EEE), the principle of the techniques and the equipment used in these processes. The materials considered here are commonly available thermoplastic polymers that are likely to be recovered from the recycling of electrical and electronic equipment. The waste materials discussed originate from domestic post-consumer waste streams; however, industrial waste materials of a similar nature could also be recovered using these techniques.

The mechanical recycling methods discussed in this chapter were developed for a variety of plastic waste from different manufacturing processing methods including injection moulding, extrusion and some of the lesser used processes such as compression moulding or blow moulding that are rarely used in the manufacture of EEE. Recycling materials from waste electrical and electronic equipment (WEEE) sources enable valuable savings on energy and depleting resources. Table 10.1 shows the energy savings for different recycled material types with amounts of recovering waste plastics of over 80% (Cui & Forssberg, 2003).

Mechanical recycling methods are growing in popularity as every person who comes into contact with domestic or industrial recycling schemes has an influence upon the end result. Techniques are often used that do not affect or change the base properties of the material being recycled (Dodbiba *et al.*, 2002) and a high purity end product can be achieved. The impact of personal sorting can reduce subsequent work efforts that positively affect the cost and effective segregation of the waste that in turn will improve the purity of the final waste material (Anon, 2006a).

Table 10.2, adapted from Bernstad *et al.* (2011), illustrates the origin of electrical and electronic feedstock types from 2006 to 2009. It is clear from the data that one-third of the recovered waste materials come from personal computers (PCs) and nearly 20% from TVs. Waste from TVs and PCs account for over half of the total, and are therefore easier to manage into recycling systems than lower volume products.

Table 10.1 Energy saving for recycled materials

Materials	Energy savings (%)
Aluminium	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Various plastics	>80

Table 10.2 Source and percentages of WEEE feedstock

Type of WEEE	% of source separated WEEE
PCs, inc accessories	34
TVs	17.8
Food preparation	11.3
Audio hifi	7.9
Vacuum cleaners	6
Lamps	5.3
DVD/VHS players	3.8
Miscellaneous, including toys, telephones, music, games and cameras	3.3
Light bulbs, including low energy and fluorescent	3.14
Personal care	3.02
Musical keyboards	3
Cables	2

Research indicates (Dodbiba *et al.*, 2008) that TVs are typically made up of 51% glass, 12% steel, 8% copper, 2% aluminium, 3% printed circuit boards, 6% polystyrene, 3.5% polyvinyl chloride and 1% polyethylene. The typical material waste fractions from all researched WEEE products are listed in Table 10.3 (Ongondo *et al.*, 2011).

There appears to be no consistent data on the types and quantities of polymers collected from WEEE schemes; however, the most common are engineering grades. Engineering polymers are materials which exhibit good mechanical and thermal properties in a wide range of conditions (Tarantili *et al.*, 2010). Some typical examples used in electrical and electronic equipment are highlighted in Table 10.4 and denoted by asterisks. Research conducted by Schlummer *et al*. in 2007 has characterised polymer fractions collected from WEEE. The summarised results are shown in Figure 10.1.

The Waste & Resources Action Programme has also conducted studies to identify the polymer fractions collected from WEEE feedstock. Polystyrene (PS), high impact PS, and acrylonitrile butadiene styrene (ABS) accounted for more than 49% of all the polymers identified, whilst polypropylene (PP) accounted for only 23% (Freegard *et al.*, 2006). While there is variability in the data due to different studies, the type of WEEE product being recycled, geographical issues and local collection schemes, it is clear that engineering polymers are high on the list of materials being recovered.

The processes for mechanical recovery of differing polymer types are very similar, the only difference being the contamination nature of the final recovered polymer type. If similar materials are used in the production of electrical and electronic items, there is less potential for contamination in the recycling system.

10.1.1 WEEE polymer types

There are numerous thermoplastic materials used in EEE, commonly used types, abbreviations, typical applications and material density range, are listed in Table 10.4 (Cui & Forssberg, 2003; Makenji, 2010; Matweb, n.d.).

Table 10.3 WEEE materials and % fractions (adapted from Ongondo *et al.*, 2011)

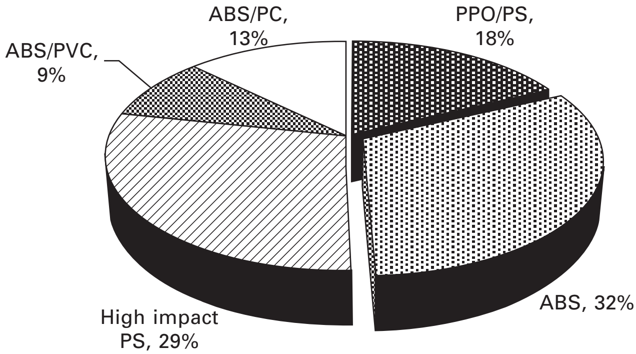
Material type	% Fraction
Metals	60
Plastics	15
Cathode ray tube (CRT) & liquid crystal display (LCD) screens	12
Metals/plastic mixture	5
Pollutants	3
Cables	2
Printed circuit boards	2
Others	1

Table 10.4 Polymer types, abbreviations and applications

Polymer	Abbreviation	Typical applications	Density (g/cm^3)
*Acrylonitrile styrene acrylonitrile	ASA	Housings, trim	1.00–1.20
Acrylonitrile butadiene styrene	ABS	Housings, trim	0.35–1.26
Acrylic	PMMA	Lenses, lighting	1.05–1.20
Polytetrafluoroethylene	PTFE	Gears, bearings	0.30–0.60
Liquid crystal polymer	LCP	Coatings, RF shielding	1.38–1.82
Polyacetal/acetal	POM	Gears, bearings, insulators	1.40
*Polyamide/nylon	PA	Structures, clips, casings	1.05–1.15
Polyamide-imide	PAI	Bearings, insulators, connectors	1.45
Polybutylene terephthalate	PBT	Switches, connectors, insulators	1.10–1.60
*Polyethylene terephthalate	PET	Films, screens	1.40
*Polycarbonate	PC	Screens, casings	1.20
Polyethylene	PE	Packaging	0.90–0.96
*Polyetheretherketone	PEEK	Hinges, switches, membranes	1.25–1.30
Polyetherimide	PEI	Sensors, connectors	1.30–1.70
*Polyphenylene oxide	PPO	Housings, valves	1.10–1.30
Polyphenylene sulphide	PPS	Connectors, housings	1.35–2.26
Polypropylene	PP	Packaging, cases	0.90–0.91
Polystyrene	PS	Housings, trim	1.05–1.13
*Polysulphone	PSU	High temperature applications	1.24–1.40
Polyurethane	PU	Connectors, coatings	1.05–1.25
*Polyvinylchloride	PVC	Seals, trim	1.39–1.40
Styrene-acrylonitrile	SAN	Housings, trim	0.91–1.17

Some polymers may be blended with other types to improve properties or to reduce cost. These polymers when blended together, without modification, will give poor properties owing to their immiscible natures. For selected polymers, compatibilisers such as maleic anhydride may be used to improve their miscibility, which in turn will improve the material properties; however, this will increase costs (Mark, 2007).

Thermoset polymers used in EEE, such as epoxies, phenolic, polyurethanes and polyesters, can also be mechanically recycled using the techniques described in this chapter. The polymers described in this section can be compounded with organic or inorganic, particulate or fibre fillers to enhance properties or to reduce material cost (Mark, 2007). Filled polymers are labelled in accordance to ISO 1043 (ISO, 2000) to identify the type, form



10.1 WEEE polymer material types (ABS, acrylonitrile butadiene styrene; PC, polycarbonate; PS, polystyrene; PVC, polyvinylchloride; PPO, poly (*p*-phenylene oxide)).

Table 10.5 Identification of different materials and forms of fillers (ISO, 2000)

Symbol	Material	Symbol	Form or structure
B	Boron	B	Beads, spheres, balls
C	Carbon	C	Chips, cuttings
D	Alumina trihydrate	D	Fines, powder
E	Clay	F	Fibre
G	Glass	G	Ground
K	Calcium carbonate	H	Whisker
L	Cellulose	K	Knitted fabric
M	Mineral, metal	L	Layer
N	Natural organic, e.g. cotton, sisal	M	Mat (thick)
P	Mica	N	Non-woven (fabric, thin)
Q	Silica	P	Paper
R	Aramid	R	Roving
S	Synthetic organic	S	Flake
T	Talcum	T	Twisted or braided fabric, cord
W	Wood	V	Veneer
X	Not specified	W	Woven fabric
Z	Others not included in this list	X	Not specified
		Y	Yarn
		Z	Others not included in this list

and quantity of the filler present, e.g. GF30%. 'G' denotes the filler type (glass), 'F' the form of the filler (fibre) and the level of the filler present. Table 10.5 shows the filler types that are typically used and the identification of the forms of the fillers used.

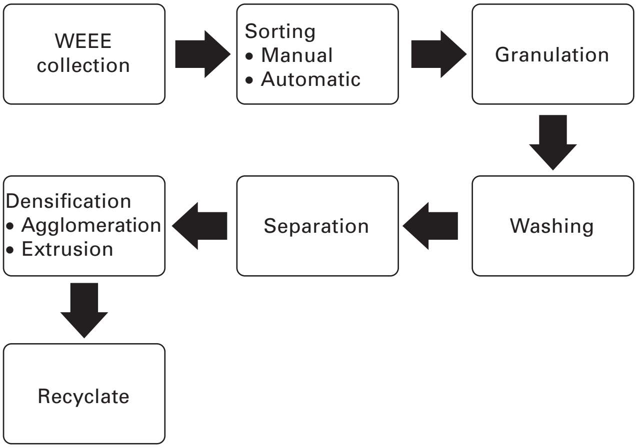
10.2 Introduction to waste collection and sorting

Once the WEEE products have been collected from domestic, centralised collection points, retailer or industrial sources, they undergo sorting, size reduction, further separation and preparation into a usable material. The initial sorting is generally a 'rough' segregation of differing material types, as listed in Table 10.3. Granulation of the product reduces the material to a manageable size before further separation. This second separation stage is a more refined process to segregate the polymers into discrete family types using density, tribo-electric, spectra and visual characteristics of the waste. Once the materials are separated into their individual generic types their density is increased, especially if the waste is in film or low bulk density form. This is necessary in order to produce a usable pellet or alternatively the material may be extrusion compounded, which is the most common technique for compounding a number of different types. The overall recycling process, illustrated in Fig. 10.2, produces a final product known as a recyclate and can be reused to remake a new product.

10.2.1 Waste collection

WEEE products are collected within the European Union at municipal waste collection sites where they are identified and segregated from other waste material. Household products account for 87% of all of the WEEE collected (Council of the European General Secretariat, 2008). The responsibilities for the collection lie with the electrical and electronic producers, retailers, distributors and by local municipalities. Table 10.6 illustrates the physical collection and financial responsibilities by EU member states (Council of the European General Secretariat, 2008).

Generally WEEE materials follow a simple route of collection or are transported to a municipal waste facility and then transferred to a centralised



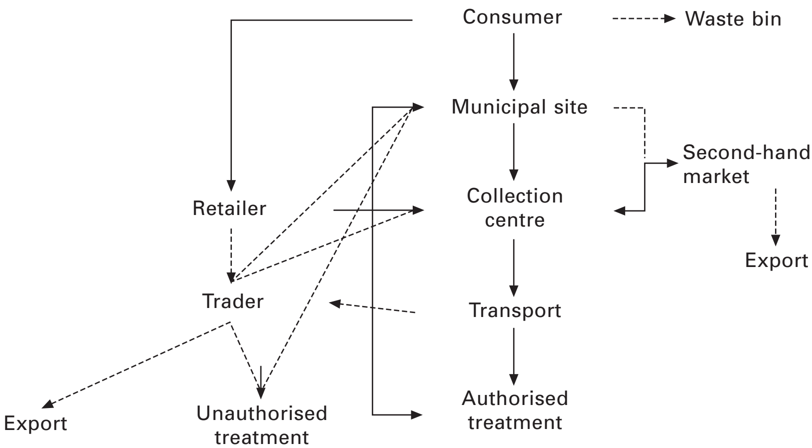
10.2 Flow diagram of the mechanical recycling process of WEEE polymers.

Table 10.6 Physical and financial responsibilities of WEEE for EU states

	Physical responsibility			Financial responsibility		
	Distributor	Municipality	Producer	Distributor	Municipality	Producer
Austria	✓	✓	✓	✓		✓
Belgium	✓	✓		✓		
Bulgaria			✓			✓
Cyprus			✓			✓
Czech Republic	✓		✓	✓		✓
Denmark		✓			✓	
Estonia	✓		✓	✓		✓
Finland	✓		✓			✓
France	✓	✓	✓	✓		✓
Germany		✓			✓	
Greece			✓			✓
Hungary			✓			✓
Ireland	✓	✓		✓		✓
Italy	✓	✓		✓	✓	
Latvia	✓			✓		
Lithuania	✓	✓	✓	✓		
Luxembourg	✓	✓		✓	✓	
Malta	✓		✓	✓		✓
Netherlands	✓	✓		✓	✓	
Poland	✓			✓		
Portugal	✓	✓	✓	✓		✓
Romania		✓			✓	
Slovakia	✓		✓	✓		✓
Slovenia	✓	✓		✓	✓	
Spain	✓	✓				✓
Sweden			✓			✓
UK	✓		✓	✓		✓

collection centre ready for treatment. This system can be problematic as some WEEE is traded or treated at unauthorised facilities or exported outside the EU. It is reported that almost 25 000 tonnes were exported in 2008; however, the material is treated under the WEEE Directive and is therefore classed as being legally managed. Figure 10.3 shows a typical flow of materials during the initial collection phase of the process. In this process the solid lines represent routes that have been accounted for. The unaccounted material represented by dotted lines, accounts for up to 74% of all of the WEEE material available (Council of the European General Secretariat, 2008).

Figure 10.4 shows the waste collected at the SIMS WEEE recycling facility based in Newport, South Wales. The image shows the mixed and contaminated nature of the waste materials and highlights why sorting is



10.3 Typical WEEE collection system (adapted from Council of the European General Secretariat, 2008).

10.4 SIMS WEEE recycling facility, Newport, South Wales (image courtesy of SIMS Recycling Solutions).

required to enable the materials to be extracted into their valuable fractions (SIMS, 2011).

10.2.2 Manual separation and sorting of WEEE polymers

Manual separation uses people to sort the waste by hand. Waste is transported via conveyor belts that pass by operators who sort into bins. Different operators may 'pick' different materials or just one material type depending

10.5 Photograph of a manual WEEE separation facility (image courtesy of SIMS Recycling Solutions).

upon the facility. This type of facility can accurately segregate waste with up to 95% efficiency (Kreith & Tchobanoglous, 2002) and requires a low capital investment.

This process has the disadvantage of being labour intensive and effective training is required to improve the quality of the waste and minimise potential contamination (Waite, 1995). Figure 10.5 illustrates the manual separation process at a SIMS recycling facility (SIMS, 2011).

Owing to the labour intensive nature of this sorting method it is more likely to be used in countries where there is a low cost base for manual labour. A common undertaking by high wage or developed countries is to send waste to low wage countries to manually sort the waste and remake products destined for developed countries (Beukering, 2001).

10.2.3 Automated separation and sorting of WEEE polymers

An alternative method of waste separation uses automated equipment and has been commercially available for a number of years. The process uses the physical characteristics of the waste to determine its type and appropriate separation route. These systems are more cost effective to operate but the quality of the waste is generally lower if the feedstock source is variable. If, however, the feedstock from a single product type is closely controlled, the recovered material will be of a higher purity.

The process adopted by SIMS Recycling Solutions for recycling up to 700 000 fridge freezers per annum is as follows (SIMS, 2011):

- Upon arrival, glass, wood, cables, mercury switches and other contaminants are removes from the fridge freezers.
- The cooling fluids that contain ozone depleting substances (ODS) such as chlorofluorocarbons, are drained under controlled processes for sound environmental disposal.
- The units are then placed on a conveyor belt and fed into the recycling process. This is conducted in a sealed nitrogen-rich atmosphere which serves the dual purpose of reducing the risk of explosions and providing a carrier medium to capture the ODS.
- A sieving technique is used to separate and extract the polyurethane foam from the other material to a typical size of 2 mm. The foam acts as the insulating material in the cavities of the walls and door of the fridge and it contains the majority of ODS within a fridge.
- The polyurethane foam is heated and dried to maximise the liberation of ODS within the granulated foam.
- The ODS gases are released into a nitrogen-rich atmosphere where they are collected and reduced in temperature to –180 °C to allow the nitrogen and ODS to be separated through condensation. The ODS is then collected for destruction and the nitrogen is recycled for further use.
- The ODS gases are shipped in canisters for sound environmental destruction by heating them to 2000 °C at which temperature the gasses are broken down into gas and ash.
- Once the ODS have been removed from the fridges they are further processed to separate the plastics, ferrous and non-ferrous metals in the same way as general WEEE.

In an automated facility high and low density wastes are separated by using this difference in density. The waste products move along a conveyor belt, the higher density materials are allowed to drop down an incline through a curtain using gravity and the lighter materials remain on the inclined conveyor. Sensors are used to detect chloride ions in PVC which are then ejected to a separate container. The remaining waste is carried along the conveyor and granulated to a small flake size (Waite, 1995).

10.2.4 Size reduction and granulation

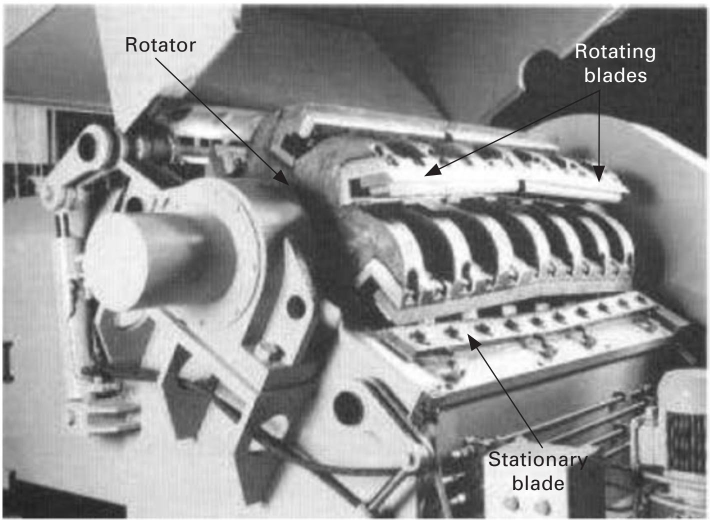
Some early research focused on automated dismantling of WEEE (Kopacek & Kopacek, 1999); however, this does not appear to have gained much popularity in the recycling industry due to the complex nature of dismantling different product types. Common size reduction is completed through granulation and individual material fractions are then separated. This approach also enables a high throughput (Zuidwijk & Krikke, 2008).

During the first stages of the granulation process large bales of waste are broken down by shredding them to 25–50 mm. The shredded waste is then granulated to a particle or flake approximately 3.2–9.5 mm. The granulation process also frees any product labels which are then removed along with any loose debris. An image of a granulator with the blades exposed is shown in Fig. 10.6.

Granulation is based on a rotary cutting system. The equipment needs to have mechanical stability, quick blade change, easy cleaning and high performance. Granulators are of a welded construction and bearings are fitted externally to prevent grease contamination or the potential of dust fines entering the bearing. The screen must be easily interchangeable to allow for different flake sizes as required. The blades create a double angle cut and are located diagonally to the rotor in a straight line with the stationary blade set at the same angle as the rotary blades, but in the opposite direction.

The rotary and stationary blades are set apart to a pre-set gap between each other. The blades are ideally fixed into the machine to allow fast change overs. The processing of polymers with fillers through the granulator will significantly wear the blades and thus will require regular removal and sharpening. The screen enables the granulated waste to fall through by gravity (Brandrup, 1996). The size of holes provisioned on the screen dictates the size of the granulate particle.

Other granulation types are profile, rotary, feed, edge, large and pipe, developed for use where certain product types may not efficiently granulate



10.6 Image of a plastics granulator showing the exposed blades (image courtesy of Herbold USA).

in a standard set up (Goodship, 2007). Any fibres in composite WEEE materials will become damaged during granulation and subsequent process steps such as extrusion compounding and injection moulding will damage fibres further.

10.2.5 Waste washing

The granulated WEEE is then passed through a washing tank where the waste is cleaned to remove adhesive residues from labels and dirt debris. Water and surfactants are typically used in this process. NOREC uses acetic acid ester in its process to remove inks and organic contaminates of waste plastics (Pascoe, 2000). It is reported that the washing process can add approximately £100 per tonne of recycled waste polymer.

The waste is then sieved where the polymer is recovered and fine debris is removed. The water used in the process is normally reused repeatedly and waste materials are thoroughly rinsed and passed through to the separation method (Pascoe, 2000).

10.3 Methods of sorting small particle size polymer waste

This section discusses the different technologies used for the sorting of domestic or industrial WEEE manufactured using plastic materials, following sorting by large fraction, granulation and washing. The different technologies work on the basis of the different characteristics of polymers, density, tribo-electric, spectra or visual aspect. It is quite common for these technologies to be used in isolation, as multiple stages of the same process, or in conjunction with more than one process to provide a continual refinement to the final purity of the output material.

10.3.1 Air table sorting

The air table unit has a porous base provisioned with a velocity controlled air fan on the underside and an eccentric drive that enables vibration in the longitudinal axis. The deck is tilted from the inlet end to the outlet end, which creates a ‘slide slope’. The deck is also tilted from side to side, which creates an ‘end slope’.

The waste polymer enters at the inlet and travels onto the porous deck. The vibration of the deck, in conjunction with the airflow from the fan, causes light materials to float on the deck while denser materials sit in contact with the deck. The dense particles travel uphill with the vibration. At the end of each stroke of vibration the direction of the deck is reversed, and because of the momentum, the denser materials continue up the deck until they exit into a collection bin. Meanwhile the lighter particles move downwards and are collected in a separate collection bin (Anon., 2009). A simplified diagram of the unit operation is illustrated in Fig. 10.7.

Studies by Dodbiba *et al.* (2005) have shown that this technique is more than 85% efficient at separating two different material types when the difference between the material densities is greater than 0.45 g/cm^3. The particle size also has an impact on the effectiveness of the air table. In order to ensure good separation for an equal mix of PP and PET, the particle size should be between 1.59 and 2.38 mm with an airflow velocity of 1.8 to 2.2 m/s.

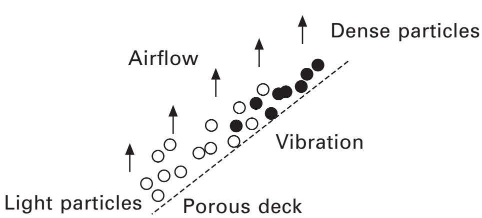
10.3.2 Flotation sorting

Water has a density of 1.0 g/cm^3 and this property can be used effectively and simply to separate light and heavy polymer fractions. Flotation sorting uses a large tank of agitated water with a light detergent which prevents capillary action of the solution. The waste enters at one end of the tank and travels towards the opposite end and either sinks or floats depending upon the density of the material separation that occurs. The material sinks if the density >1 g/cm^3 or floats if it is <1 g/cm^3. Common polymer types and their respective densities are shown in Table 10.4 (Goodship, 2007; Matweb, n.d).

The density of water can be altered by adding methanol or calcium chloride to reduce or increase it respectively. This enables the effective separation of mixed polymer types where the densities are all above or below 1.0 g/cm^3. The solution is optimised to allow higher density materials to sink whilst the lighter materials float. Often tanks are set up in series using a number of different solutions, each one coping with different material density to separate the waste with increasing levels of purity. However, separation issues may still arise when two disparate polymers are present and have similar densities (Burat *et al.*, 2009; Kikuchi *et al.*, 2008).

10.3.3 Hydro-cyclone sorting

Prior to hydro-cyclone, the process sorting steps are the same as the flotation method involving size reduction, cleaning and sieving. Once completed,

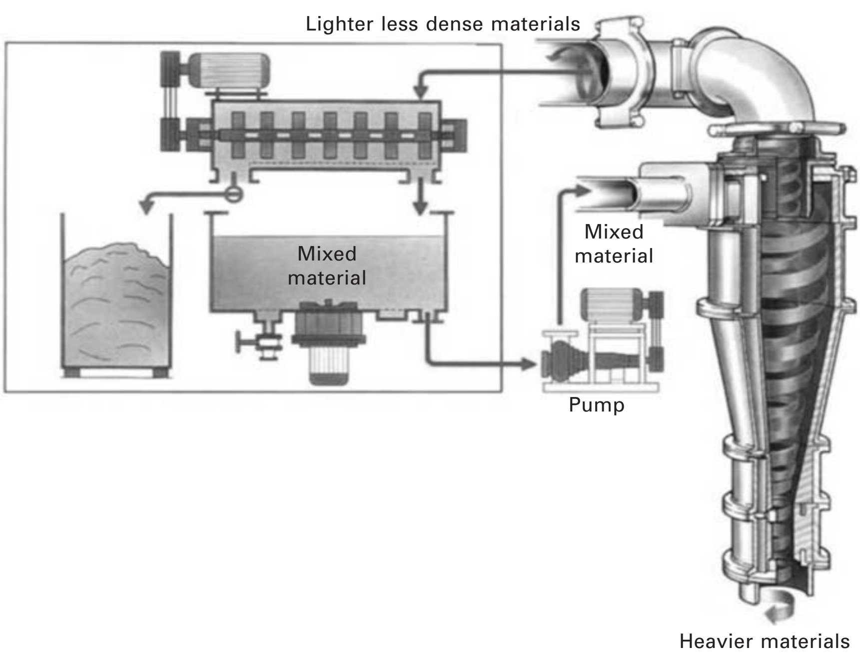


10.7 Simplified diagram of the air table separator.

the waste is mixed with water in order to transport the solution. The water and waste mix is passed through a hydro-cyclone chamber, which are more commonly used in modern recycling and separation facilities, and can be an effective material separation technique.

The mix of waste and water enters the chamber at the inlet and rotates into a vortex which generates a centrifugal acceleration several times higher than gravity. As a result lighter materials move towards the centre, where there is an air interface and a vortex finder that draws off this material at the top of the unit. Heavier materials move towards and along the outer surface and run along a tapered sidewall; these particles take a downward path and finally drop out of the bottom as shown in Fig. 10.8. Often a number of hydro-cyclones are used in series to carry out multiple density separations of the WEEE polymer material. Each process stage of the hydro-cyclone refines the purity of the material (Brandrup, 1996; Coates & Rahimifard, 2009).

The hydro-cyclone separation process has similar issues to the flotation technique as both systems use density properties as a means to make a distinction. Separation capability is better than that of the flotation method. The system is able to identify heavier particles from lighter ones and the transportation medium does not need to be altered by means of chemical modification. Processing the WEEE polymers multiple times will refine the



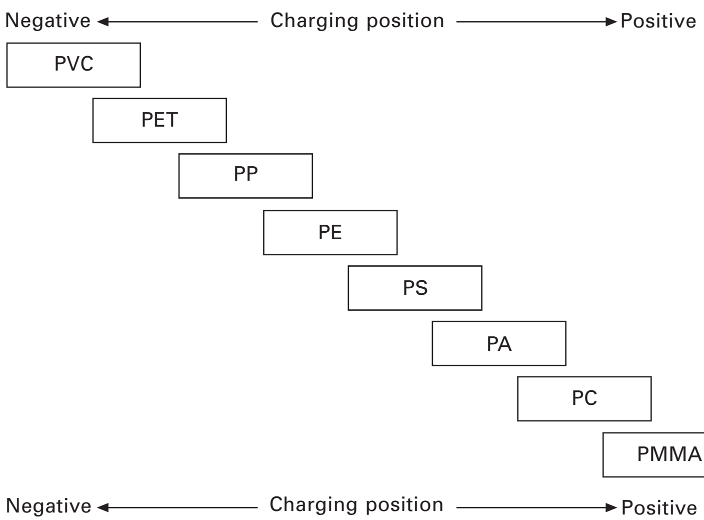
10.8 Diagram of a hydro-cyclone separator (image courtesy of Herbold USA).

waste until an acceptable level of purity is achieved. Up to a 99% separation efficiency can be achieved although the technique will still have difficulty in separating two materials with the same density characteristics (Gent *et al.*, 2009; Kikuchi *et al.*, 2008).

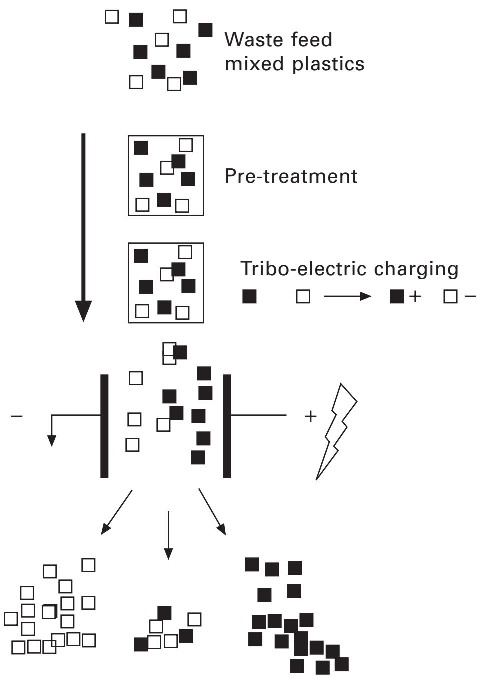
10.3.4 Electrostatic sorting

Electrostatic sorting uses the principles of tribo-electric charging. A 'free-fall separator' relies on the electrical conductivity properties of polymer materials. In this process the materials must be separated as discrete particles and should exhibit different electrical conductive behaviour. The unit works well with distinct material types and similar densities. The material considered for this type of sorting must be both clean and dry. Figure 10.9 illustrates the tribo-electric properties of various polymeric materials. Additives such as fillers and pigments will affect the tribo-electric properties.

Figure 10.10 illustrates the electrostatic process where the waste material is uniformly and simultaneously charged using friction. The selectivity and intensity of the charge can be varied by altering the parameters such as temperature and humidity. The positively or negatively charged particles pass through an electrical field where they are deflected towards an electrode and are separated from each other. The free fall separator operates with voltages up to 120 kV and a current of less than 0.1 mA. The height of the free fall separator can range from one to several metres, depending on the throughput of material. Typically 3 to 5 tonnes per hour are possible with mixed plastics.



10.9 Tribo-electric condition of different polymer types.



10.10 Process diagram of a free fall separator.

Experiments reported by Brandrup (1996) have shown that this technique is effective at separating consumer waste with similar densities that are pigmented or filled. In some instances multistage separation stages may be required to optimise the purity of the sorted waste in conjunction with other sorting techniques.

The performance of the electrostatic separator is far better than the hydro-cyclone or flotation methods as it does not rely on the density characteristics of the waste to facilitate efficient separation. The tribo-electric characteristics of the waste material provide a unique property for the system to facilitate separation. The ability of the system to rely on the electrostatic charging of the waste materials implies that the system would be able to cope adequately with waste polymer materials. Even materials with similar density characteristics would result in a different electrostatic charge enabling separation. Electrostatic separation systems are being used in the USA and in the EU for scrap recycling of automotive waste (Douglas & Birch, 1976; Harper, 2002).

10.3.5 Near infra-red and optical sorting

Near infra-red (NIR) sorting of polymer waste uses a computer-based infra-red spectrometer capable of identifying 1000 spectra of polymers per second

(Brandrup, 1996). The spectrometer measures the electromagnetic spectrum of a polymer and a sorter will then direct the particle into a sorting bin. The wavelength range of the NIR is between 700 and 2500 nm and has a reduced absorbance in bulky items which allows for C—H, O—H, N—H and C—O groups to be characterised in polymers.

The system has a detector head which can be operated manually or automatically. Light from a 5 mm diameter head is focused on the sample material using a quartz condensing lens. A second lens is set at 90° and collects the reflected light. A second detector arrangement is also possible, producing a larger observation plane. The unit has seven light sources with a measuring range of 100 mm in diameter that allows for simultaneous measurements to be made in different viewing angles. The data is measured and the product is separated using a combination of gates and conveyors (Bledzki & Kardasz, 1998; Brandrup, 1996).

This technique is widely used where there are multiple plastic types of similar characteristics and colour. Studies have identified that the polymer content was 34.6% of the total, 87% of the polymers were accurately separated into different types, over half of the waste was black in colour and only 6.8% had visual identification (Dimitrakakis *et al.*, 2009).

Optical-based sorting systems can distinguish either mass, colour or shape of the waste. The waste granules, typically 10 to 150 mm, are assessed by the sorting criteria pre-set by the operator. A CCD camera is used to assess and differentiate the red, green and blue as well as the hue, saturation and intensity of the particle (Tachwali *et al.*, 2007). Pneumatic air jets are used to separate or remove the granule from the bulk of the material. As the system is very specific in assessing the granules the separation can be highly efficient and can be used in conjunction with the NIR technique (Rhyner, 1995).

The system relies on the visual properties of the waste to separate the material and does not use of any of the material properties. In many respects the system is unsuitable when highly mixed WEEE materials are separated. On the other hand if a particular recovered material is the same colour, the system would be able to identify and separate the waste effectively. Such a system would be suitable for a single source or industrial waste where the material is generally known but processed together.

10.4 Conversion of WEEE to a reusable material

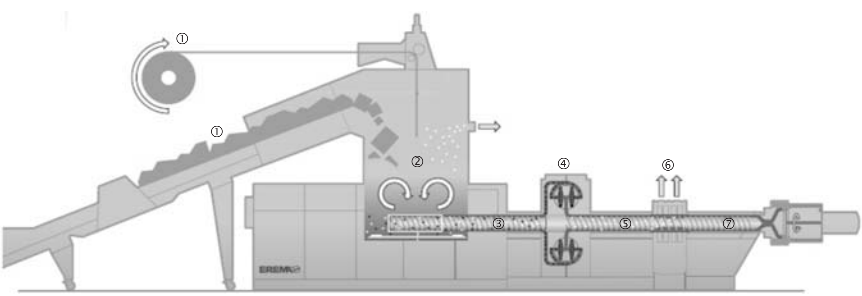
Once the waste material has been collected, size reduced, cleaned and sorted it can then be reused as a valuable resource. It is often re-formed before being sold in order to give it a consistent and aesthetically pleasing appearance. The reformation is often unnecessary and can add cost to the retail price; however, it can also be an opportunity to blend virgin compound or additives to improve the performance of the material. If the waste is in film form it will have a low bulk density and require densification prior to use. The higher density material can then be used in the extrusion process or to manufacture pellets for use in injection moulding and other manufacturing processes.

10.4.1 Densification (agglomeration)

Densification can be used for WEEE film or flake materials by taking a low bulk density material, typically from 100 to 150 kg/m^3, and increasing the density to a more usable or transportable material. There are different methods for densification of waste film; however, they all involve the use of frictional heat, usually under the melting temperature of the polymer.

Pelletisers mix and compress the waste material through a die. The compression exerted on the polymer creates frictional heat which enables the polymer to join together. The polymer exits the die where it is cooled and a rotating knife is used to cut the pellet to length (Shrivastava, 2003). In a pot-type agglomerator the waste is placed into a pot where knives are rotated at very high speed. The high speed knives cause the polymer to heat by means of friction causing the polymer film to shrink and stick together into agglomerates which are cooled and cut into pellets. Another method is the disc compactor. Here the film is softened in-between a fixed and a rotating disc and chopped into pellets (Goodship, 2007; Scheirs & Kaminsky, 2006).

Another type of densification method combines the pot agglomeration technique with extrusion technology and is ideally used for film waste materials. The system is designed and manufactured by Erema of Austria (www.erema.at/en) and illustrated in Fig. 10.11. (1) The waste material is fed into the unit using a conveyor, (2) where the material is cut, heated, mixed and dried. (3) The material is then plasticised and degassed in the extruder (in reverse); and also (4) filtered of any contamination. (5) The material is finally made homogeneous and (6) degassed to remove volatiles in the melt. (7) The material passes through a metering zone on the extruder screw before being pushed through a die to make the desired material form.



10.11 Schematic of the Erema system (image courtesy of Norton Plastics UK).

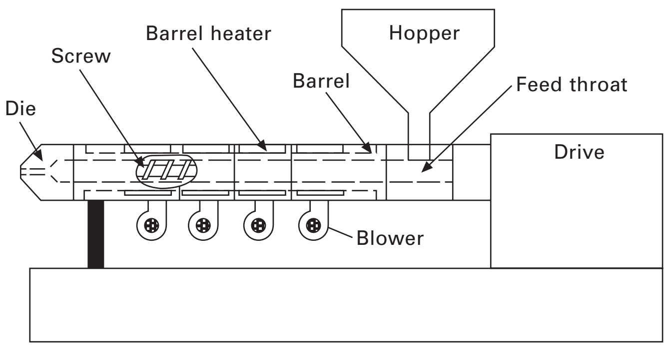
The Erema system is an ideal solution for WEEE polymers. As the waste is typically from a single source it can be re-compounded and reprocessed without the additional and costly steps required for collection, storage and separation. The re-compounded material is then reused in the process or sold as a recycled grade.

10.4.2 Compounding of WEEE using extrusion

Extrusion processing technology is typically carried out on solid particulate material and involves the melting of the polymer into a viscous medium and forcing it through a die, forming it into a net shape. Additives including colourant, antioxidants, fillers, fibres and stabilisers can be added to the molten polymer to achieve the desirable net performance. There are different types of extrusion including single screw, twin screw contra-rotating and co-rotating. The performance of the extruder depends upon the geometry of the screw and the operating conditions. An important element of the extruder is the screw which is typically categorised by a length to diameter (L:D) ratio. Typical L:D ratios are 24, 30 and 36. Screws with high L:D ratios have good mixing capabilities but use a high amount of energy (Chung, 2000).

The process is a linear manufacturing technique that produces pellets traditionally the size of a small grain. Figure 10.12 illustrates a single screw extruder where the barrel, screw, heaters and material hopper are visible. The screw and barrel are generally hardened to prevent wear and tear by fibre reinforced or filled. External heaters are used to enable the barrel to heat up and melt the polymer. Blowers are required on the barrel as excessive shear in the unit may cause excessive heating up of the polymer causing it to degrade.

The lower L:D ratio extruder screws would result in the polymers having a shorter thermal history in the extruder barrel. This may be desirable as it would result in less thermal degradation of the polymer and less mechanical damage of any fillers or fibres that may be present in the material (Wang, 2000).



10.12 A simple schematic of an extruder.

The screw has a number of distinct stages, namely the feed, compression and metering sections. The feed section is the initial part of the screw that the polymer enters and has a constant root diameter, where the flights are generally large allowing the solid polymer to enter the extruder and fill the available volume. The compression section has an increasing root diameter where the melting of the polymer occurs. The melt is compressed and any air or volatiles are forced out of the viscous material back to the entry point of the polymer.

Different polymers require dissimilar compression zone types, PA for example melts quickly and thus has a short compression zone. Polymers which have long melting ranges, such as PE, have long compression zones. The compression of the polymer in this section causes a great deal of shear and thus heating and melting occur. With some polymer types too much compression may lead to excessive shear heating which can result in polymers burning or degrading.

The final metering zone has constant short flight depths and a large root diameter of the screw. By the time the material reaches this section it is typically fully melted, however the short flight depths ensure a high melt shear which ensures all solids are melted and compositionally homogeneous before they enter the die. Traditionally most extruders will have 'general purpose' screws installed. This design works well with most material types and eliminates the requirement of multiple machines or different screw types (Xanthos & Todd, 2002).

A vent is often situated at the end of the extruder to enable air volatiles and moisture trapped in the molten material to escape that may otherwise have a detrimental effect on the aesthetics and physical properties. A melt filter may be used prior to the material entering the die to remove solid contaminates from the recycled polymer prior to it being formed into an article. The molten material would then pass through the die and be cooled to form the pellets or a component.

Single screw extruders are probably the most common type of extruder used in the manufacture of profile lengths or of compounding polymers where fillers or additives are introduced. Twin screw extruders are used with heat-sensitive polymers. The screws are linked and intermeshed enabling the polymer to move from screw to screw with a high degree of mixing, without excessive shear, which may otherwise cause degradation or burning. The material in the screw is moved forward in the barrel causing desirable high pressures at the die entry.

10.5 Effectiveness of the WEEE legislation to date

The WEEE legislation is critical for saving valuable material resources from traditional waste disposal routes. Mechanical methods of recycling these products are currently the most popular method of recovering them, saving more than 80% of energy to remake virgin polymers.

The data in Table 10.7 (Anon., 2006b) illustrates that Norway, Sweden and Switzerland are the largest recyclers and reusers of WEEE materials, however the amount of materials collected differs from the amount originally put onto the market and the amount that is reused. Although Norway recycles the largest quantity per capita, only 45% of that put on the market is actually reused. Only Switzerland manages to reuse 100% of the collected WEEE. Greece demonstrates a recycling rate of 80% due to the high level of using materials that have been collected; however, only 5% of the material originally sold is reused.

The target for EU member states is to reuse 4 kg of WEEE per capita per annum. Of the 23 member states only 11 managed to meet or exceed this target. The disparity between the amount of WEEE put on the market and the amount reused can be attributed to products being exported, traded, treated and reused through unauthorised routes. With some member states the level of reuse is alarmingly low and more needs to be done to ensure it is managed properly to maximise the material yield. To achieve best practice

Table 10.7 2006 EU data on WEEE consumption, collection, reuse and recycling per capita

Country	Put on the market (kg/cap/year)	Total collected (kg/cap/year)	Reuse (kg/cap/year)	Reused/put on the market (%)	Reused/collected (%)
Norway	40	22	18	45	82
Sweden	25	15	14	56	93
Switzerland	19	13	13	69	100
Denmark	32	11	9	28	80
Germany	22	9	7	33	80
Luxembourg	17	8	7	41	85
Finland	27	8	6	23	80
Austria	19	8	6	32	79
Belgium	24	7	6	24	78
Italy	0	12	5	–	43
Netherlands	10	6	4	40	67
Spain	12	4	3	21	64
Hungary	14	2	2	13	75
Lithuania	15	3	2	12	63
Slovakia	10	2	1	10	50
Greece	16	1	1	5	80
France	24	0	0	0	50
Cyprus	20	6	0	0	0
Estonia	14	4	0	0	0
Poland	23	0	0	0	–
Slovenia	14	1	0	0	0
Portugal	12	0	0	0	–
Romania	7	0	0	0	–

the EU needs to ensure that the WEEE collected and reused is comparable to the level put on the market.

10.6 Remanufacturing using WEEE polymers

There are many issues when WEEE polymers are reused, mainly as a result of the mixed and contaminated nature of the recovered materials. Research in this area is approached in two different ways:

- improvement in the separation purity of the recovered materials;
- improvement of the processing of 'mixed' materials.

Research focused on extrusion processing of recovered plastic materials with no sorting (Makenji *et al.*, 2010) revealed that the mechanical properties of the experimental samples were relatively poor. This was due to the disparate chemical and melting nature of the materials making them incompatible during the process. To improve mechanical properties some level of sorting and separation is required to gain a core material purity of >80% (Balart *et al.*, 2005; Tarantili *et al.*, 2010). The mixed or contaminated nature of WEEE is the result of the inaccurate material separation process. Quite often these separation processes are used in conjunction with each other to identify and separate the main component polymer to the highest level of purity.

Studies using the air tabling and tribo-electric separation methods in series with each other have shown that using these two processes result in higher purity than one process used in isolation (Dodbiba *et al.*, 2005). In a study of granulated PP, PVC and PET it was discovered that tribo-electric separation was an effective technique to separate low density PP from PVC and PET. The air tabling was effective at separating PET and PVC where material densities are between 1.3 and 1.5 g/cm^3, overall the studies achieved a final material purity over 95%.

Research using Fourier transform infra-red spectroscopy conducted by Balart *et al.* (2005) has established that virgin ABS and PC does not degrade as a result of the first manufacturing process. It was observed that very little degradation occurred to the recovered resins by comparing them with unprocessed polymers of the same grade. The study also concluded that the materials had reduced mechanical properties when blended at 20 to 80% wt PC, attributed to partial miscibility of the different polymers. In mixes of 10–20% wt PC there was a negligible decrease in mechanical properties for processing conditions similar to typical styrenic materials. The positive results are attributed to the similar rheological properties of the amorphous polymers. When processed with rapid cooling rates the phase separation of the polymers was avoided, resulting in an 'artificial' compatibility. Similar studies (Tarantili *et al.*, 2010) show a good correlation to Balart's research, indicating that processing of ABS with small levels of PC is a viable solution for reusing WEEE.

ABS shows significant potential for WEEE recycling and experiments into processing with small levels of PC have been successful. However, there are problems with voids in the polymer melt which dramatically reduce the mechanical properties of the material. During recent studies (Arnold *et al.*, 2009) concerning the effect of volatiles in a range of ABS sources, it was noted that high levels of voids in the polymer resulted in reduced flexural strength, failure to strain and stiffness. Analysis of emissions during processing showed that the volatile compounds were the results of polymerisation residuals and degradation of the initial service life of the article, rather than reprocessing of WEEE. The experiments showed high levels of void formation during processing and extrusion venting is recommended to remove them during compounding. Little literature exists regarding other polymers as the effort appears to be around the reprocessing of ABS, which is used in huge quantities for WEEE products.

A different approach to WEEE collection and recycling lies in the reuse market for certain product types. Mobile phone reuse is a good example of a family of products having a second life following their primary use.

10.7 Future trends

Mechanical methods for recycling WEEE materials are popular for the following reasons:

- cost effective;
- can handle disparate materials;
- easy to provision and operate;
- can process large volumes of products/materials;
- relatively high levels of purity ~90%.

Current research appears to be focused on refining WEEE polymers or processing the impure recyclate with improved mechanical properties. Some of the studies have yielded excellent results when different polymer separation technologies are used in conjunction with each other. Current research to improve material purity is based on the addition of tracers into the polymer matrix. This enables them to be easily identified using X-ray fluorescence spectrometry (Bezati *et al.*, 2010) or radiofrequency identification (RFID) (Luttropp & Johansson, 2010) during the sorting and separation stages of mechanical recycling. Further research in these areas will continually offer the WEEE recycling industry solutions, striving to improve material purity.

Research around the thermal processing of impure materials is providing an excellent solution for processing disparate materials. Some research into the use of maleic anhydride-based compatibilisers show good mechanical properties; however, it appears to be the result of improved morphology between the different polymers (Elmaghor *et al.*, 2004) and not as a result of the maleic anhydride.

Studies with recovered and reused ABS and ABS/HIPS materials in repeated cycles do not show any significant loss in mechanical properties (Arnold *et al.*, 2009), however, what is not understood is the effect of compatibilisers and additives used to enable mixed materials to be processed together. Further research in compatibilisers and the effect they have on the recycling and material life cycle is needed to assess the benefits they may offer.

Designing consumer products using limited or single material types would have a large positive impact on the purity of WEEE polymer material (Fiksel, 2009). A similar methodology was taken by automotive industry to meet the requirements of the End-of-life Vehicle Directive (Stauber & Vollrath, 2007). The author suggest that product designers should investigate the use of dissimilar materials so that they can be easily separated, enabling more effective sorting of mixed recovered materials.

Schemes such as the mobile phone reusing scheme and eBay are a very good way of reusing WEEE and preserving valuable energy and material resources. These schemes will become increasingly popular and innovative reducing or preventing WEEE from occurring.

10.8 Sources of further information and advice

The list of useful resources below may be of interest to the reader for further information regarding mechanical methods for the recycling of WEEE polymers.

- *Journal of Hazardous Materials*
- *Journal of Polymer Degradation and Stability*
- *Journal of Waste Management*
- www.ec.europa.eu/environment/index_en.htm
- www.eea.europa.eu/data-and-maps/figures/weee-put-on-the-market
- www.environment-agency.gov.uk
- www.legislation.gov.uk/uksi/2003/2635/contents/made
- www.matweb.com
- www.simsrecycling.com
- www.wrap.org.uk

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11
Pyrolysis of WEEE plastics

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Abstract: An important flow of plastics comes from waste from electrical and electronic equipment (WEEE) whose recycling in most developed countries is now mandatory and entails high recycling quotas to be fulfilled. Pyrolysis appears to be an emerging option in WEEE recycling technology, allowing recovery of high value potentially accessible products. Usually the greater the purity of the product resulting from the recovery process, the higher its value: the composition of fuel or chemicals obtained from the pyrolysis of plastic fractions of WEEE depends on the chemical nature of feedstock as well as on pyrolysis operative parameters and conditions, here reviewed.

Key words: waste from electrical and electronic equipment (WEEE), pyrolysis of plastics, fire retardant plastics, printed circuit boards (PCB), recycling.

11.1 Introduction

Electric and electronic equipment (EEE) are items dependent on electric currents or electromagnetic fields in order to work properly, or equipment for the generation, transfer and measurement of such currents. Being characterized by extreme diversity and increasingly fast innovation cycles, their production supports one of the fastest growing domains of manufacturing industry in the world.

Waste electrical and electronic equipment (WEEE) are EEE residues at the end of their life cycle and the amount yearly produced shows an increasing upward tendency: a recent annual estimation for WEEE production in Europe was of almost 6.5 million tonnes, predicting by 2015 an amount of 12 million tonnes (Barba-Gutiérrez *et al.*, 2008). WEEE contain metals, glass and plastics; a significant proportion of WEEE is constituted by printed circuit boards (PCBs), the most valuable fraction of WEEE, which account for 8% by weight of WEEE collected from small appliances (Waste & Resources Action Programme, WRAP 2009) and 3% of the mass of global WEEE (Dalrymple *et al.*, 2007).

In most developed countries collection and recycling of WEEE is now subjected to political decisions; concern about the environment prompts many governments to issue specific legislation about WEEE management, stating high quotas for recycling and recovery. With an average plastic content of about 20–30%, the recycling and recovery quotas fixed by legislation can only be satisfied by including the plastic fraction in recycling and recovery approaches. On the other hand, a large part of the plastics in WEEE contains brominated flame retardants (BFRs), usually with antimony trioxide, to prevent them from catching fire. Contamination of WEEE plastic by BFRs remains a severe issue in WEEE management, has a strong impact on material recycling and thermal treatment because of the possibility of producing extremely toxic halogenated dibenzodioxins and dibenzofurans (Schlummer *et al.*, 2007) and prevents them from being treated by a conventional plastic recycling plant. To preserve and improve the quality of the environment, BFRs in Europe are now limited by a directive on the restriction of hazardous substances; however, WEEE arising now are products put on the market in preceding years, with the average lifetime varying greatly, from 2 years (mobile phones) to around 15 years (refrigerators). Consequently actual WEEE still contains BFRs forbidden in new EEE.

Recycling of WEEE always requires dismantling as a first action to remove valuable or still working spare parts, such as batteries, condensers and PCBs, which are processed separately. The parts that have reasonable value are removed by the dismantlers, and then reconditioned and reused. A shredder stage comes afterwards for an easier waste management. In general, two different polymer fractions are available on the market: well-defined polymer fractions separated from WEEE in dismantling plants (the main part of WEEE plastics) and a mixed shredded residue produced as a by-product in metal recovery processes (Cui and Forssberg, 2003; WRAP, 2006; Schlummer *et al.*, 2007). PCBs removed during dismantling follow a separate recycling scheme.

So far recycling of WEEE is an important subject in terms of potentially recovering valuable products: in principle the greater the purity of the product that results from the recovery process, the higher its value will be and therefore the greater the potential viability of that process. However, even in those countries where WEEE collection and recycling is imposed by law, there is an interest in recovering valuable recycled products because this reduces the dumping fee often required to process this kind of waste stream (Buekens, 2006). Pyrolysis appears to be an emerging option in WEEE recycling technology, allowing the recovery of high value, potentially accessible products such as precious metals, fuel and chemicals.

11.2 Pyrolysis processes and characterization of the pyrolysis fractions

Theoretically, mixed WEEE with an average gross calorific value of 22–24 MJ/kg (Boerringter, 2000) are rather good combustibles; however, plastics are difficult to burn, because of an almost uncontrollable combustion rate. On the contrary, pyrolysis converts WEEE by thermal decomposition (in inert ambient) in three main phases: gases, oils and char which can be used as chemical feedstocks or fuels. Smaller molecules produced by thermal degradation are volatile at elevated temperatures and go to the gas or oil fractions while metals, inorganic fillers and supports generally remain unchanged and accumulate in the residue.

Degradation of the organic part of the wastes makes the process of separating metal and glass fibre fractions much easier and recycling of each fraction more viable. Generally both gaseous and liquid products are mixtures of numerous different compounds.

While the same elements in the same relative amounts as the raw materials are conserved, elements are distributed over the three phases in the pyrolysis products and many variables affect the product distribution, which are summarized in Table 11.1 (Buekens, 2006). The structure of polymers in the feed determines the primary pyrolysis products resulting from the rupture of bonds in the macromolecules followed by molecular or free radical rearrangement. Secondary reactions gradually convert the primary products into more stable alternatives. These secondary reactions occur to a greater or lesser extent depending on residence time, temperature and heat exchanges in the reactor: primary products, i.e. monomers, are favoured by short residence times, more thermodynamically stable products by long ones. The temperature affects the stability of feed and the rate of its thermal decomposition: high temperature (>600 °C) and both vacuum or

Table 11.1 Main factors affecting composition of the pyrolysis products

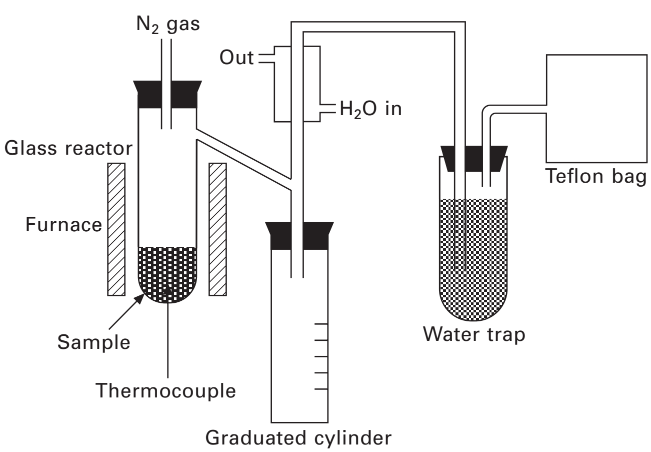
Factor of influence	Effect
Type of plastic or resin	The chemical nature of the resin determines the structure and the relative amount of primary pyrolysis products
Pyrolysis temperature and heating rate	Production of small molecules by bond breaking is favoured by higher temperatures and high heating rates
Pyrolysis time	Conversion of primary products to more stable products is favoured by longer residence times, yielding more residue and secondary volatile products
Reactor type	Reactor type controls heat transfer during pyrolysis, the quality of mixing, residence times of gas and liquid phases
Operating pressure	Formation of coke and heavier products by condensing reactive fragments is favoured by higher operative pressures
Presence of catalysts	Catalysts influence kinetics and mechanisms of degradation so changing the pyrolysis products composition

product dilution favour the production of simple small gaseous molecules, low temperature (<400 °C) and increased pressure lead to more viscous liquid products. In most processes a medium temperature (400–500 °C) is selected where the plastics are in a molten state.

The reactor type is selected mainly on the basis of technical considerations, such as its heat transfer ability and handling characteristics of feed and residue. Fixed bed reactors are the most common in many processes; other processes suggest the use of fluidized bed thermal or catalytic reactors because of their excellent heat transfer and mixing properties, where 'gas phase' processes involve liquid polymer films, distributed over the grains of fluidized bed pyrolysis reactors. Owing to the combined effect of so many variables, usually the product distribution is found only by experiments.

Pyrolysis studies are conducted on a bench scale before being scaled up to pilot (or semi-commercial or commercial) plant: commonly fixed bed reactors are employed as shown in Fig. 11.1 (Hall *et al.*, 2007b). The reactor is purged, the temperature increased to the selected one and then maintained until the pyrolysis is complete. A thermocouple immersed in the plastic bed indicates the pyrolysis temperature. The pyrolysis oils are condensed to liquid products using a cold water condenser often graduated to measure the volume of oil collected as the experiment progresses. Volatiles such as hydrogen bromide (HBr) evolved during pyrolysis are trapped in a flask containing ion-exchanged water. The hydrocarbon gases insoluble in water can be trapped in a gas bag and then analysed. The solid residue remains in the reactor.

Further, each fraction can be collected and analysed in the most appropriate way:



11.1 Fixed bed reactor.

- The residue contains charred material and inorganics: char is oxidisable and can be quantified by measuring the weight loss after combustion of the residue. Scanning electronic microscopy (SEM) and energy dispersive X-ray spectroscopy (EDAX) analyses can be carried out as well to investigate the morphology of the char (SEM) and the elemental composition of the residue (EDAX).
- The liquid pyrolysis oil is currently subjected to separation, identification and quantification of as many possible products by gas chromatography-mass spectrometry (GC/MS). Other analyses can be effected as well, such as Fourier transform infrared spectroscopy (FTIR) to investigate functional groups present in the pyrolysis oil products.
- The amount of water-soluble gases (HBr or bromide salts) trapped in the water flask can be determined by ion chromatography.
- The hydrocarbon gases trapped in a gas bag can be analysed at the end of the pyrolysis using gas chromatography with a thermoconductivity detector (GC–TCD).

A gas chromatography-electron capture detector (GC/ECD) or a high resolution gas chromatography system/high resolution mass spectrometry system (HRGC/HRMS) is used for the identification and quantification of halogenated compounds in the pyrolysis fractions as residual BFRs, their brominated pyrolysis products and chlorinated compounds. Even at low concentrations, all these products are potentially toxic to humans; their detection and quantification in pyrolysis products are preceded by a critical clean-up and concentration step. Identification is followed by comparing their retention times with those of certified standards (Hall and Williams, 2008). Several mixtures of polychlorinated dibenzodioxin and furan congeners (PCDD/F), as well as the toxic polychlorobiphenyl congeners are commercially available; a comprehensive set of standards for polybrominated dibenzodioxin and furan (PBDD/F) analysis are now also offered by the market.

During pyrolysis, the fate of the bromine and antimony content of the plastics is critical, therefore new and improved analytical techniques for analysing these elements products are being sought. Energy dispersive X-ray fluorescent spectrometry (EDXRFS) has been recently successfully tested and results compared to more traditional and time-consuming methods such as bomb calorimetry combined with ion chromatography (EPA method 5050) for bromine and acid digestion combined with inductively coupled plasma–optical absorption spectrometry for antimony (Miskolczi *et al.*, 2011).

Because generally both gaseous and liquid products are mixtures of numerous different compounds, the problem of fractionating these effluents and upgrading them to commercial specifications must be investigated. Often the reactor scheme is modified to collect the volatiles exiting the reactor in a series of condensers at different temperatures such as water-cooled or dry ice cooled condensers to collect any oils and waxes released during the pyrolysis process (Hall and Williams, 2007b). Long tubular reactors followed by a distillation column are used to simulate slow pyrolysis of WEEE (Miskolczi *et al.*, 2008) and fluidized bed reactor to simulate flash pyrolysis (Hall and Williams, 2006).

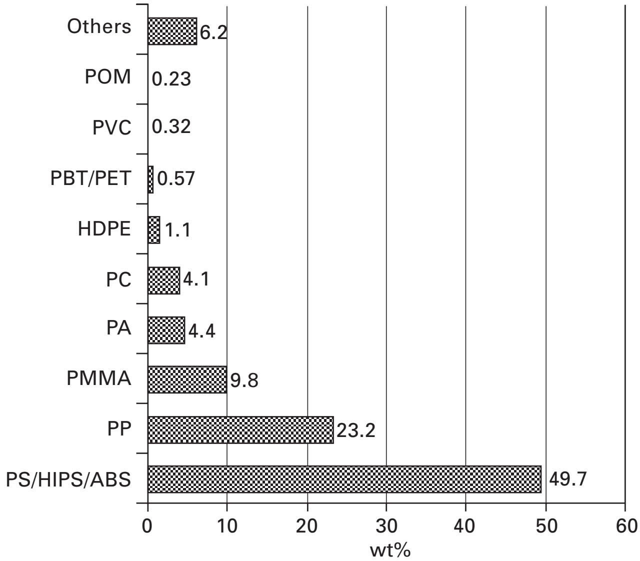
11.2.1 WEEE composition

The diverse range and age of materials found in WEEE and the different collection options (kerbside, drop-off, take-back, etc.) makes it difficult to give a generalized material composition for the entire wastes. As a pure reference data, considering the main categories of materials present in WEEE, ferrous metals account for almost half the total weight, plastics represent 21% and non-ferrous metals, including precious metals, 13% of the total weight, with copper accounting for 7% (Ongondo *et al.*, 2011).

A few attempts have been performed to investigate the plastic composition of selected WEEE, mainly by FTIR (Luda *et al.*, 2002; Schlummer *et al.*, 2007; Taurino *et al.*, 2010). According to three studies reported in WRAP (2006), it was found that around 50% by weight of the total plastic recovered was styrene-based polymer, poly(propylene) (PP) was less than half as common (Fig. 11.2). The styrene-based plastics acrylonitrile–butadiene–styrene terpolymer (ABS), high impact poly(styrene) (HIPS) and poly(styrene) itself (PS), together with PP, are the most common plastics used in moulded equipment housings and casings. Poly(methyl methacrylate) (PMMA) and polycarbonate (PC) plastics, often used in transparent forms, were the next most common polymers.

In contrast, thermosets are the major polymer component in PCBs. Typically PCBs contain 40% metals, 30% organics and 30% ceramics. Bare PCB platforms represent about 23% of the weight of whole PCBs (Duan *et al.*, 2011). However, there is a great variance in composition of PCB wastes from different appliances, manufacturers and of different age, e.g. after removing the batteries and capacitors, the organic fraction represented about 70% in PCBs from computers and TV sets and 20% in those from mobile phones (Hall and Williams, 2007a).

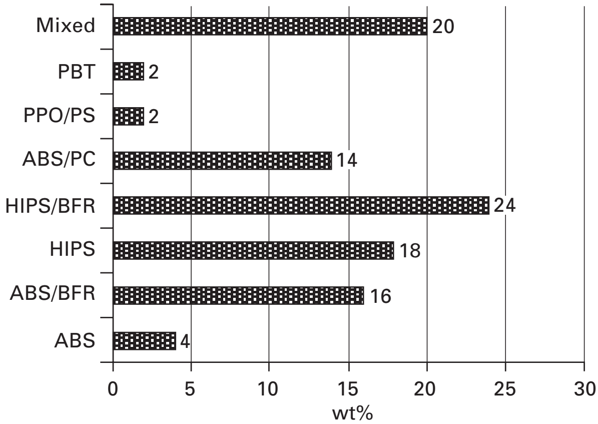
PCBs contain large amounts of copper, solder and nickel along with iron, and precious metals: approximately 90% of the intrinsic value of PCB is in the gold and palladium content. Platforms are usually made with thermoset composites, epoxy resins in particular, containing a high amount of woven glass fibres as reinforcement; in some appliances such as TVs and home electronics, PCBs are often made with paper-laminated phenolic resins and multilayer boards. Precious metals in electronic appliances are contact materials due to their good conducting properties. The content of a typical lead–tin (Pb/Sn) solder used to attach components to the platform ranges



11.2 Plastic typologies in small appliance WEEE (POM, poly oxymethylene; PVC, polyvinyl chloride; PBT/PET, polybutylene terephthalate/polyethylene terephthalate; HDPE, high density polyethylene; PC, polycarbonate; PA, polyamide; PMMA, poly (methyl methacrylate); PP, poly (propylene); PS/HIPS/ABS, polystyrene/high impact polystyrene/acrylonitrile–butadiene–styrene terpolymer.

between 4 and 6% of the weight of the original board. Typically PCBs contain about 5% weight of iron, 27% of copper, 2% of aluminium and 0.5% of Ni, 2000 ppm of silver and 80 ppm of gold; however, there is no average scrap composition and the values actually only represent scraps of a certain age and manufacturer. Additionally, non-ferrous metals and precious metals contents have gradually decreased in concentration in scraps due to the falling power consumption of modern switching circuits (Cui and Zhang, 2008).

The relative quantity of plastics with flame retardants depends on the appliance category and, within the category, on the type of the appliance. The Association of Plastics Manufacturers in Europe (APME) reported that, in the electronic sectors, plastics containing BFR represented 17% of the plastics consumed in this area (APME, 1995). Large white goods (refrigerators, washing machines, etc.) rarely contain BFRs which are however present in brown goods, information technology and office equipment, small household appliances, PCBs, toys and telecommunications equipment, with an average bromine content of 8% and antimony trioxide content of 3–4%. An example is given in Fig. 11.3 where it can be seen that the majority of ABS and HIPS plastics used in shredded screen housing are flame retarded with BFRs



11.3 Polymers from shredded screen housings: average amount of not flame retarded and fire retarded with brominated flame retardant polymers.

(Schlummer and Maurer, 2006). Flame retardants in WEEE polymers are likely to be present in concentrations in the range 5–10% in polymers that are flame retarded (WRAP, 2006).

11.2.2 Pyrolysis fractions and their valorization

For most plastics, pyrolysis begins at around 300 °C. The onset of the pyrolysis reaction is strongly influenced by the presence of additives, such as stabilizers, plasticizers and pigments. Gases and pyrolysis oil come from thermal degradation of the organic part of the WEEE: as a rule, the pyrolysis of plastics follows intricate routes described by a complex set of chemical reactions. While the detailed mechanisms are of scientific interest, an industrial approach is limited to more general considerations, such as the heat effect and the product distribution resulting under particular reaction conditions.

Decomposition modes are driven by the polymer structure, the presence of catalysts and by the pyrolysis temperature. According to the prevailing reaction patterns, the mechanism of degradation can be classified as follows:

1. Decomposition into monomer units (*unzipping*). Since monomers are high value products, this decomposition mode is of large practical interest, typically raising the price several times the equivalent of fuel value. However only a few polymers decompose to monomers, PMMA and polyamide-6 are the examples. However, the monomer generated does not necessarily reach the polymerization grade purity and often is used as a viscosity index improver of lubricating oil, rather than as a monomer (Buekens, 2006).
2. Random fragmentation of the polymer chains into fragments of variable

intermediate length by inter- or intramolecular transfer reactions. Polyethylene (PE) mainly undergoes intermolecular transfer, leading to saturated and unsaturated waxy fragments with a size distribution largely Gaussian, the average fragment length descending when pyrolysis temperature is raised. PP on the contrary undergoes preferably intramolecular transfer reactions forming shorter fragments (Schnabel, 1981; Grassie and Scott, 1985).

3. Decomposition according to both previous schemes combined. PS degrades in such a way producing either monomers or short fragments (Schnabel, 1981; Grassie and Scott, 1985).
4. Elimination of stable molecules from adjacent atoms. Typically poly(vinyl chloride) (PVC) yields hydrogen chloride, poly(vinyl acetate) yields acetic acid and poly(vinyl alcohol) yields water. Such scissions leave contextually unsaturated chains, which often carbonize in the residue.

Most thermosets and other cross-linked polymers follow a different route involving scission of the network followed by cross-linking, so creating a porous charred residue (Conley, 1970; Erä and Mattila, 1976).

The major hetero-atoms in polymers are oxygen, nitrogen, chlorine, bromine and, rarely, fluorine. After plastics pyrolysis, these elements either appear as intermediate organic compounds still incorporating the hetero-element or as stable inorganic compounds, i.e. water, ammonia and hydrogen cyanide, hydrogen chloride, HBr and bromine, hydrogen fluoride. Most of these are hazardous and corrosive and require a careful selection of reactor construction materials, as well as methods to neutralize or inhibit their effect.

Mixed plastics pyrolysis produces monomers and specific petrochemicals. Most monomers are high-purity products that are difficult to attain in plastics pyrolysis. Potential pyrolysis products from polyolefins are blends of different hydrocarbons but they still need to satisfy some common commercial specifications for naphtha, kerosene or gas-oil, according to established standards, i.e. those of the American Society for Testing and Materials (ASTM) or the American Petroleum Institute. Off-specification products have no market, even if blended in small amounts into other streams.

Halogenated substances and flame retardants contained in WEEE are a matter of concern for the potential generation of PBDD/F but on the other side, if conveniently recycled, inorganic halides issued in pyrolysis gases are value products to be removed from gaseous effluents. When scavenged by calcium oxide, calcium chloride or bromide are formed, which have to be reconverted to acidic form successively. Other gases are light hydrocarbon and in the case of polymer-containing heteroatoms such as oxygen or nitrogen, carbon oxide, carbon dioxide and ammonia are obtained. The combustion of pyrolysis gases, after the removal of value products, can provide the heat necessary for the pyrolysis reactor, as pyrolysis processes are often endothermic, involving the breaking of chemical bonds.

In the presence of chlorine and bromine in the original plastics, these elements distribute over gas, liquid and solid pyrolysis output, often reducing the market potential and value of each phase. Studying their elimination is a major consideration in developing processes for mixed plastics.

The char incorporates fillers, pigments, ash and charred material deriving from secondary reactions involving the polymerization of unsaturated products such as dienes and olefins, or coke precursors, such as aromatic. By pyrolysing thermosets and PVC, a charred residue is often obtained, PS has a stronger coking tendency, whereas PE and PP can be converted almost quantitatively into volatiles depending on the pyrolysis conditions. Coke formed by pyrolysis is a by-product only and could be upgraded to activated carbon. Some attempts to do this, mainly at laboratory scale, have been reported only on the activation of pyrolytic char from scrap tyres. In fact tyre scrap yields a very large amount of residue not suitable for other uses (i.e. carbon black) (Li *et al.*, 2005).

11.3 Pyrolysis of printed circuit boards (PCBs)

PCBs often come as a separate fraction of WEEE because, if larger than 10 cm^2, they have to be removed during dismantling and milled to scraps of a few square centimetres for an easier management. The main value in PCBs is their content in copper and precious metals, usually recovered from the scraps by traditional metallurgic processes such as pyrometallurgy, hydrometallurgy and more recently by biotechnology processes (Luda, 2011). However in small appliances, such as mobile phones, dismantling is excessively onerous and the whole items are crushed. Separation of the high value metal fraction (MF) from the lower value non-metal fraction (nMF) is usually carried out by magnetic and eddy current-based separators refined by classifiers where the residual metallic fraction remains in the larger particles. There is interest, however, in the value added by an advantageous recycling of the nMF fraction of PCBs which has been reviewed by Guo and Xu (2009). Pyrolysis degrades the organic part of the PCB wastes, making the succeeding process of separating the organic, metal and glass fibre fractions much easier and recycling of each fraction more viable. Additionally, if the temperature is high enough, the solder melts and can be recovered. The combination of removal and recovery of the organic fraction of PCBs and the removal of the solder aids the separation of the metal components.

The thermal behaviour of epoxy resins, the most common polymer matrix in PCB, has been widely investigated as a basis for pyrolytic recycling. Brominated epoxy resins are less thermally stable than the corresponding unbrominated ones. In thermogravimetry they exhibit a steep weight loss stage at 300–380 °C depending on the hardener, those hardened by aromatic amines and anhydrides decomposing at higher temperature. Mostly brominated and unbrominated phenols and bisphenols are found in the pyrolysis oil; however, the balance of phenols/bisphenols and brominated/unbrominated species depends on the temperature and residence time in the reactor: higher temperatures and longer times making debromination more extensive (Luda *et al.*, 2007, 2010). The degradation of particles larger than 1 cm^2 is somewhat postponed due to the heat transfer limitation (Quan *et al.*, 2009). No significant influence of temperature was observed in products of pyrolysis over 500 °C, both in gases and oil yields (9 and 78% respectively) as well as in the gross calorific value (30 kJ/kg). However the resultant oil was contaminated by polluting elements and must be purified for further utilization (Guan *et al.*, 2008). The boards pyrolysed in a fixed bed reactor at 850 °C were very friable and the different fractions easily separable (Hall and Williams, 2007b).

11.3.1 Vacuum pyrolysis

Recently studies on the application of vacuum pyrolysis to PCBs appear in the literature (Long *et al.*, 2010; Zhou and Quj, 2010; Zhou *et al.*, 2010). They were mostly aimed at recovering solder and facilitating the separation of metals and glass fibres from PCB scraps. Vacuum pyrolysis shortens organic vapour residence time in the reactor and lowers the decomposition temperature, reducing the occurrence of secondary reactions.

The residue of vacuum pyrolysis is easier to manage because about 99% of the original copper is confined in particles >0.4 mm, while fibres remain in the smaller particles and are recovered after calcinations. Two different arrangements for recycling disassembled PCBs are proposed by Zhou and coworkers: in the first, centrifugal separation of solder (240 °C) was followed by vacuum pyrolysis of the residue (600 °C) (Zhou and Quj, 2010); in the second, vacuum pyrolysis (600 °C) was followed by centrifugal separation of the residue at 400 °C in order to collect solder ready for reuse. Pyrolysis oil and gases were collected from the pyrolysis reactor for further refining (Zhou *et al.*, 2010).

11.4 Pyrolysis of plastics

Apart from PCBs, which are separated from the WEEE mainstream, the majority of plastics coming from housing, keyboards, etc. are mainly styrene-based polymers such as PS, HIPS and ABS. A number of these plastics in WEEE are flame retarded by BFRs, typically decabromodiphenyl oxide (DBDE) in HIPS and tetrabromo bisphenol A (TBBA) in ABS, often in conjunction with antimony trioxide as synergistic additive. In pyrolysis either bromine or antimony are distributed in pyrolysis gases, oil and residue in amount and form depending on the feed composition and on the pyrolysis conditions. A huge amount of research has been carried out on model flame retarded polymers and mixtures of polymers representative of real WEEE (Jakab *et al.*, 2003; Hall and Williams, 2006; Hall *et al.*, 2007a; Miskolczi *et al.*, 2008).

The expected pyrolysis products from styrene-based plastics are monomers and oligomers (mainly dimers and trimers); those from ABS will also contain nitrogen, and these are collected in the oil fraction. In these polymers char is missing or present in very low amounts. However brominated flame retarded HIPS (Br-HIPS) exhibits a different behaviour: BFRs evaporate under a vacuum but interact with the polymer under normal pressure operation. As a consequence Br-HIPS exhibits a lower thermal stability. With an earlier evolution of antimony tribromide ($SbBr_3$) and water, the oil fraction contains more mono-ring-aromatics (benzene, toluene, ethylbenzene, styrene) and some less brominated compounds from the dehalogenation of the flame retardant; in addition a small amount of char is also formed (Jakab *et al.*, 2003).

Under slow pyrolysis conditions at 430 °C in a fixed bed reactor Br-HIPS, not containing antimony trioxide, pyrolyses, forming large quantities of HBr, owing to the decomposition of the brominated flame retardants. Antimony trioxide alters the pyrolysis of the styrenic polymers so that more char and less oil is produced during the pyrolysis process and the bromine is converted to $SbBr_3$, rather than to HBr (Hall *et al.*, 2007a).

Flash pyrolysis of Br-HIPS in a fluidized bed reactor leads to the formation of greater amounts of pyrolysis oil (90% instead of 78%) and less char (5% instead of 16%) than in slow pyrolysis, and the amount of oil increases with the pyrolysis temperature. The majority of the bromine is found in the oils as $SbBr_3$, contextually reducing the amount of styrene in oil in favour of cumene and ethylbenzene; antimony is found in the oil as well as in the char (Hall and Williams, 2006).

Both in slow and in flash pyrolysis a small amount of organic brominated compound remains in the oil in a concentration which also depends on the type of BFRs used: Decabromodiphenyl ethane (DBDE) seems to interact more with $SbBr_3$ than decabromodiphenyl oxide (DBDO) and therefore the former is less prone to leave brominated compounds in the oil. The presence of benzenebutanenitrile might cause some problems if Br-ABS oil is combusted, due to the possible formation of nitrogen oxides (Miskolczi *et al.*, 2008).

11.4.1 Copyrolysis

Copyrolysis of Br-HIPS with a variety of plastics common in packaging waste has been investigated widely (Bhaskar *et al.*, 2004a, 2004b, 2007; Hall *et al.*, 2007a; Mitan *et al.*, 2008). The oil composition changes profoundly in copyrolysis of Br-HIPS with other plastics such as polyolefins or PET because of the degradation products of the blended plastics but other significant alterations also occur in some mixtures. Copyrolysis with PS shows basically the same effects already noticed for Br-HIPS on its own, with only minor changes in the composition of light hydrocarbons in the gases.

The copyrolysis of Br-HIPS and polyolefins leads to increased concentrations of vinyl and alkyl aromatics in the pyrolysis oil compared with the pyrolysis of Br-HIPS on its own. Br-HIPS also affects the pyrolysis products of the polyolefins, especially PE, by converting the unsaturated compounds to saturated compounds (Hall *et al.*, 2007a). Concerning the halogenated compounds in the pyrolysis oils, the GC/ECD chromatograms for Br-HIPS and polyolefins are similar to that of Br-HIPS pyrolysed on its own. However when DBDE is used as the flame retardant instead of DBDO, many fewer compounds are detected by GC/ECD, especially when antimony trioxide is present in the plastic mixture (Hall *et al.*, 2007b).

In two step pyrolysis of mixed polyolefins and Br-HIPS (330 and 430 °C) brominated compounds are found in the oil of the first step, whereas that of the second step is nearly bromine-free. The major portion of antimony is found in the oil of the first step as $SbBr_3$ and partially in the residue (Bhaskar *et al.*, 2007; Mitan *et al.*, 2008).

When pyrolysed with 20% of PET, nearly 50% of bromine is confined in gases as inorganic bromide (Bhaskar *et al.*, 2004a). If PVC is added to polyolefins and PET mixture, formation of $SbBr_3$ is prevented and a large amount of organic bromine/chlorine is found in the oil (Bhaskar *et al.*, 2004b).

11.4.2 Pyrolysis of real WEEE

Despite the huge amount of work on pyrolysis of model WEEE, there are few studies dealing with the product characteristics from the pyrolysis process of real WEEE plastics (Hall and Williams, 2007b; Vasile *et al.*, 2007; de Marco *et al.*, 2008; Achilias *et al.*, 2009; Moltó *et al.*, 2009). The WEEE stream is characterized by a large variance in the composition of the feed coming from different appliances. Therefore a first obstacle in bench-scale pyrolysis is the selection of the waste representative of the whole waste stream; secondly, the composition of the waste in terms of polymers and flame retardant packaging is mostly unknown.

Vasile *et al.*, studied the pyrolysis in a batch reactor at 430–460 °C of WEEE coming from the casing of monitors, computers, printers and mice, from keyboards, from PCBs and from a mixture 60/10/30 in weight of the preceding wastes. Casing and keyboards give a large amount of oil (71–51%); in contrast a huge amount of residue, mostly metals, is found in PCBs (70%); a mixture of phenols is found in the oil of PCBs whereas aromatics prevail in that of casing and keyboards, reflecting the different polymers they have been made with. A larger number of gases come from keyboards (19%) in comparison to casing and PCBs (7–8%). In comparison to PCB oil, casing and keyboards oils contain a lower amount of organic halogen (both bromine and chlorine) and of aliphatic and aromatic compounds. Mixed wastes exhibit a somewhat intermediate behaviour, so that pyrolysis of WEEE is a viable option provided that the pyrolysis oil is upgraded (Vasile *et al.*, 2007).

Hall and Williams investigated pyrolysis in a fixed bed reactor at 600 °C of housing of cathode ray tube equipments, of fridges/freezers after removal of refrigeration liquids and metals and of a mixed standard WEEE fraction. Chlorine was present in a relatively high concentration in original fridge/freezers and housing fractions, possibly due to the presence of PVC. On the other hand bromine was quite low in any original fraction. All samples produce a high amount of oil (70–83%) containing a relatively low concentration of halogenated organics and a low amount of gases (1–3% in refrigeration and equipments and housing, 8% in mixed WEEE). Pyrolysis oil of mixed WEEE contains a relatively high amount of phenols, indicating the presence of epoxy resins or PC in the original scraps used as a feeding; oils from other samples contain mostly aromatics indicating the presence of styrene-based polymer in the feeding. Chlorine is found in the gases, char and oils of refrigeration equipment but bromine remains only in char. Mixed WEEE char, oil and gases were relatively free from halogens (Hall and Williams, 2007b).

De Marco *et al.*, pyrolysed PE wires, table telephones, portable phones and PCBs at 500 °C in an autoclave which was not stirred. The oil yield is 16% in PCBs and 44–57% in the other samples which showed a lower amount of residue (30–34% instead of 76%). The inorganic parts prevail in residues of all fractions (66–97%) and is chiefly aluminium and copper in PE wires with a somewhat significant proportion of lead and tin in PCBs coming from the solder. Gases are higher for PE wires (23%) than for phones (12%) and PCB (7%). All pyrolysis oils contain aromatics but that from PCBs and mobile phones also contains a range of phenols and that from PE wires waxy hydrocarbons (de Marco *et al.*, 2008).

Achilias *et al.* compared results on pyrolysis in a fixed bed reactor at 550 °C of PC model polymer and of compact disc wastes (made with PC) from which the aluminium layer was removed. Results on the two fractions were comparable but in the compact disc pyrolysis the residue is higher (30% instead of 11%) and the oil lower (63% compared with 80%); the oil composition is similar in both cases with only a small difference in the phenols/bisphenols balance (Achilias *et al.*, 2009).

Eventually Moltó *et al.*, pyrolysed whole mobile phones and their circuit boards. They found that bromophenols, a possible precursor of PBDD/F (not determined there), are detectable only in the pyrolysis oil of PCB and that PCCD/F are found in both samples and they are different from those in the original feed. However the level of toxicity as far as PCDD/F and PCB is concerned, is kept to a relatively low value (24–27 pg WHO-TEQ/g) (Moltó *et al.*, 2009). The Enviromental Protection Agency (EPA) has established 90 pg TEQ/g as being an acceptable limit for residential soil contamination.

11.5 Environmental concerns about the products of pyrolysis of WEEE

As previously stated, EEEs make use of BFR plastics to reduce their potential flammability. Solid polymer materials do not burn directly, but they are first thermally degraded into smaller molecules to release flammable gases: a visible flame appears when these flammable gases burn with the oxygen and the flame is maintained by highly exothermic reactions in the gas phase. In the presence of halogenated flame retardants, hydrogen halide is released in the flame where it captures the active radicals substituting them with less active halogen radicals and regenerating hydrogen halides. Antimony trioxide is used as a synergic agent because of the evolution in the flame of antimony trihalide followed by hydrogen halide formation and radical recombination (Fig. 11.4). In addition to this 'gas phase' action a 'condensed phase' sometimes occurs which promotes the charring of the polymer reducing the fuel supply to the flame.

$? \longrightarrow H^{\bullet} + OH^{\bullet} \xrightarrow{\text{Flammable gases}} \text{Heat}$

$\text{Halogenated fire retardant} \xrightarrow{D} HX_g$ X = Br, Cl

$HX + H^{\bullet} \longrightarrow H_2 + {}^{\bullet}X$ } Flame poisoning

$HX + OH^{\bullet} \longrightarrow H_2O + {}^{\bullet}X$

$RH + X^{\bullet} \longrightarrow R^{\bullet} + HX$ HX regeneration

Sb_2O_3 synergism

$Sb_2O_3 + 6\,HX \longrightarrow SbX_3 + H_2O$ SBX_3 formation

$SbX_3 + H^{\bullet} \longrightarrow SbX_2 + HX$ } HX formation; H° capture

$SbX_2 + H^{\bullet} \longrightarrow SbX + HX$

$SbX + H^{\bullet} \longrightarrow Sb + HX$

$Sb + O \longrightarrow SbO$ } Radical recombination

$SbO + H^{\bullet} \longrightarrow SbOH$

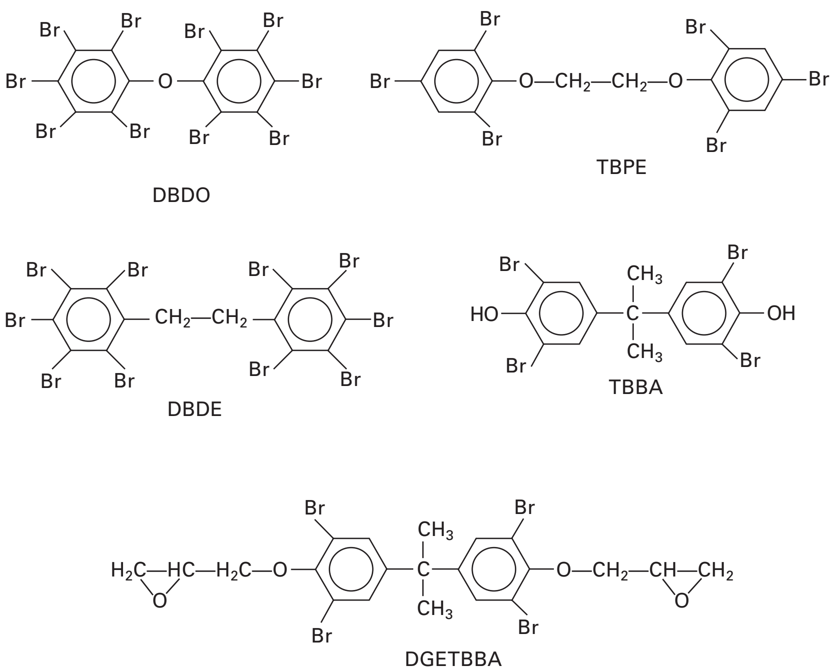
$SbOH + H^{\bullet} \longrightarrow SbO + H_2$

11.4 Mechanism of action of halogenated fire retardant.

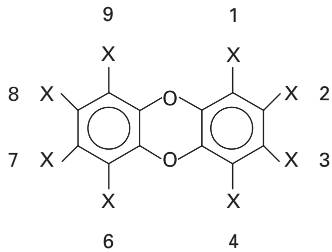
There are many different halogenated flame retardants, brominated being the preferred because of higher effectiveness and good stability during processing. Some flame retardants most used in WEEE are presented in Fig. 11.5. Two categories of BFRs can be envisaged: additive or 'matrix' brominated flame retardants and reactive or 'backbone' flame retardants.

The former category includes the polybrominated diphenyl ethers, DBPE and TBPE. Because of their high potential toxicity, penta- or octa-bromodiphenyl ethers have now been phased out of production and are found only in aged wastes. Additive BFRs reside in the polymer matrix as free molecules and, being not chemically bound to the polymer, can diffuse out of the polymer matrix under the right conditions. The second category includes flame retardants bonded chemically with the polymer, such as brominated glycydil TBBA derivatives (DGETBBA). Circuit board matrices are often DGETBBA hardened with a suitable counterpart. TBBA can either be an additive or a reactive BFR depending on its ability to react with the substrate: it is reactive in PC and additive in styrenic polymers.

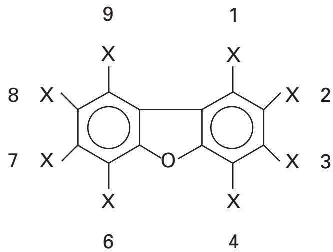
One of the primary environmental concerns regarding the polybrominated diphenyl ethers and some of the other brominated flame retardants is their potential to form PBDD/F (Fig. 11.6) when they are subjected to heat during recycling processes as well as compounding, extrusion, moulding. These compounds are of concern because there is evidence of human toxicity



11.5 Main brominated flame retardants used in WEEE.



Polychlorinated dibenzodioxins (PCDD) X = H, Cl PCDD
Polybrominated dibenzodioxins (PBDD) X = H, Br PBDD



Polychlorinated dibenzofurans (PCDF) X = H, Cl PCDF
Polybrominated dibenzofurans (PBDF) X = H, Br PBDF

11.6 PCDD/F and PBDD/F.

(Schlummer *et al.*, 2007; Herat, 2008). There are a huge number of congeners depending on the halogen substitution pattern; however, the toxicity is about a hundred times higher for those substituted in 2,3,7,8 positions.

Environmental problems have caused the plastic and additives industries to take steps to minimize BFR contents or to substitute DBDO with TBBA, which has a lower dioxin generation potential. Only a fraction of the plastics in WEEE are flame retarded; in contrast, the matrix in PCBs is often a bromine-containing flame retarded matrix likely to contain 15% of Br due to the risk of ignition during soldering of the components on the platform or impact with electric current.

During pyrolysis bromine and antimony are split in the gases, oil and residue phase depending on the substrate and on pyrolysis conditions. HBr can easily be recovered from the pyrolysis gases and reused. Inorganic halides condensed in the oil are water-soluble and therefore can be extracted from the oil by washing.

Contamination of oil by harmful compounds remains a severe issue with a strong impact on material and thermal recycling: next to halogenated dioxins, bromine-containing phenols contaminate pyrolysis products because they are potentially hazardous compounds, likely form PBDD/F through Ullmann condensation when fuel is used as a combustible. Thus reduction of the amount of brominated phenols in the pyrolysis oil in favour of less toxic substances is a way to add value to the whole recycling process.

Dehalogenation attempts have been carried out either directly in the pyrolysis of WEEE scraps or on refining the oil collected in the pyrolysis.

11.5.1 Dehalogenation during pyrolysis

Copyrolysis of brominated plastics of WEEE with other polymers is the first strategy investigated to check the effect on brominated compounds evolution and fate, however the effects depend on the polymers copyrolysed. As previously described (see Section 11.4.1) polyolefins have nearly no effect on debromination of Br-HIPS or Br-ABS whereas PET is much more effective. However a two-step pyrolysis of Br-HIPS/polyolefins makes the debromination occur in the first step, leaving the oil of the second step nearly halogen-free. The presence of PVC in the mixture prevents the formation of $SbBr_3$ and enables the formation of toxic chlorinated organics. However, the use of a solid catalyst based on a carbon–calcium composite acting in a gas phase over the pyrolysing feed removes the majority of organic bromide and chloride from oil (Bhaskar *et al.*, 2004b). A successful approach to debrominate PCB scraps is attained by microscale pyrolysis in the presence of sodium hydroxide (NaOH) or sodium-containing silicates, resulting in an enhanced bromomethane evolution and depression of the formation of brominated phenols (Blazsó *et al.*, 2002).

PBDD/F is formed during PCB pyrolysis at 850–1200 °C, the total content decreases by approximately 50% increasing the pyrolysis temperature from 850 to 1200 °C but they can be destroyed under controlled combustion conditions (1200 °C): if calcium oxide is added in the feed, inhibition of 90% PBDD/F occurs, restraining the evolution of HCl and HBr as well corroding the equipment (Lai *et al.*, 2007).

11.5.2 Depolymerization in supercritical fluids

Supercritical methanol and water have been tested to depolymerize plastics in WEEE for recycling purposes: a lower critical temperature and pressure of methanol (T_c: 240 °C, P_c: 8.09 MPa) than of water (T_c: 374 °C, P_c: 22.1 MPa) allows milder conditions. At 350 °C the oils of PCBs treated with supercritical methanol include phenol of relative purity (58%) and no brominated compounds. Large amount of HBr in the gaseous products could be recovered effectively by simple distillation (Xiu and Zhang, 2010). Br-ABS or Br-HIPS have been treated in supercritical water at 450 °C and 31 MPa of pressure. Carbon dioxide is evolved with ABS resulting from hydrolytic decomposition of acrylonitrile moieties. The oils contain brominated compounds in a low amount, and this level further decreases if plastics are treated in the presence of NaOH or calcium hydroxide in stoichiometric amount with bromine. The majority of bromine is found in the form of HBr (Br-HIPS) or ammonium bromide (Br-ABS). The antimony in the plastic remains almost entirely in the solid residue in metallic, oxide and oxybromide form (Onwudili and Williams, 2009).

11.5.3 Upgrading of the pyrolysis oil

Liquid products obtained from pyrolysis of general WEEE, PCB and their mixture are upgraded by thermal and catalytic hydrogenation using catalysts such as commercial hydrogenation catalyst DHC-8 and metal loaded activated carbon. The upgraded degradation products are separated in residue, liquids and gases; in upgraded pyrolysis oils liquids with a high amount of aromatics are found and bromine containing compounds are not obtained. The effect of thermal hydrogenation is improved by the catalysts: hazardous toxic compounds are eliminated after hydrogenation by converting them into gaseous HBr (Vasile *et al.*, 2007).

Hydrodehalogenation with hydrogen-donating media is a promising option for the destruction of halogen-containing aromatics in the pyrolysis oil, converting them into non-halogenated aromatics and valuable hydrogen halide. PP has been found to be an effective hydrodehalogenating agent in upgrading PCB pyrolysis oil from PCB scraps (Balabanovich *et al.*, 2005).

11.6 Future trends

Concern about the environment prompts many governments to issue specific legislation on WEEE recycling; however, many countries seem to be slow in initiating and adopting WEEE regulations. In both developed and developing nations, the landfilling of WEEE is still a concern and accumulation of unwanted electrical and electronic products is common in both the USA and less developed economies. Furthermore, handling of WEEE in developing countries shows a high rate of repair and reuse within a largely informal recycling sector (Ongondo *et al.* 2011).

The EU issued specific legislation about WEEE management stating recycling quotas ranging from 50% to 75% and recovery rates from 70% to 80%. The WEEE Directive (European Union, 2003b, 2003c), aimed to prevent the generation of WEEE, promotes reuse, recycling and other forms of recovery so as to reduce the disposal of waste. Similarly the Electrical Appliance Recycling Law states the principles of WEEE management in Japan.

To preserve and improve the quality of the environment, BFRs are now limited in Europe by the RoHS Directive on the restriction of hazardous substances (European Union 2003a, 2005a, 2005b) that names six substances of immediate concern: lead, mercury, cadmium, hexavalent chromium, polybrominated diphenyl ethers (penta-BDE and octa-BDE) and polybrominated biphenyls. The maximum tolerated value in homogeneous materials is 0.1% by weight for lead, mercury, hexavalent chromium, polybrominated diphenyl ethers and polybrominated biphenyls and 0.01% by weight for cadmium.

Hence, in most developed countries WEEE management options are subjected to political decisions introduced on an ideological basis with limited attention to their economic costs. However, the market cannot leave economic revenue out of consideration which, for pyrolysis processes, comes from the value of the output products (fuel or raw materials) whose standard specifications are fixed by law (and can be different from country to country). In turn the WEEE value increases if they can generate high value pyrolysis products as intended in the current legislation (Harder and Forton, 2007). The development of WEEE recycling technologies in one direction or in another is subject to these economic variables.

Although pyrolysis has been proved to be technically feasible in small-scale laboratory plants, scale up to pilot or industrial plant suffers from limitations in part due to the lack of a collection and supply guarantee. Hence large facilities in comparison to smaller factories compensate for constant costs but need continuous availability of feed and delivery of the produced feedstock. They need tremendous financial investment which can be undertaken if marketability of high value output products is assured. In contrast, the development of smaller facilities next to WEEE sorting points, which separate PCBs from the remaining fractions of WEEE, quite disseminated in developed countries, can be encouraged if WEEE value increases. In order to guarantee the maximum degree of recycling of environmentally problematic wastes and make recycling economically more attractive, pyrolysis of mixed low- and high-valued waste is an interesting option.

The value of PCBs is in the precious and semiprecious metals they contain. Some recycling processes in which PCBs are treated together with other metal scraps are available such as pyrometallurgical processes in Canada (Noranda process), at the Boliden in Sweden, at Umicore in Belgium. Here the used electronics recycled represent 10–14% of total throughput, the balance being mostly mined copper concentrates at Noranda, lead concentrates at Boliden, various industrial wastes and by-products from other non-ferrous industries at Umicore.

Mandatory recycling quotas force the technical community to consider options for the most problematic flame retarded plastics WEEE fraction, among which pyrolysis is attractive. Only a few polymers can be recycled by pyrolysis under economically favourable conditions (monomer production) and unfortunately not those common in WEEE. A few industrial or pilot initiatives of pyrolysis have started throughout Europe but are now in stand-by for some technical unresolved problem and because pyrolysis outputs as composition and purity still have to be improved to find an appropriate market. The Haloclean process, a rotary kiln process for pyrolysis developed in Germany, neatly turning brominated scrap plastics into recyclable copper and methanol feedstock while removing the halogens, is now utilized also for biomass management.

Next to WEEE, shredded residue coming from end- of-life vehicles (ELV), called automotive shredded residue (ASR), are another example of problematic wastes whose recycling is still a challenge. ASR is the remaining shredded waste after ELV dismantling (draining of fluids and wheels removal) and shredding (iron and non ferrous metals extraction). They are typically around 20–25% of the weight of ELV and constitute the most difficult ELV fraction to be recycled, being an agglomerate of plastics contaminated by metals and other substances, some of which may be hazardous (Srogi, 2008).

Similarly to WEEE, ELV are subjected to mandatory recycling schemes (European Union 2000, 2003b), forcing the reduction of disposal in landfill and searching for alternative recycling processes. Targets for recycling (including thermal recovery) of ELV correspond to an overall recycling rate of about 95% by 2015. Pyrolysis offers an environmentally nice-looking method for the treatment of ASR; however, there are only few pyrolysis processes semi- or fully commercial which clearly specify that they can handle ASR as a feed.

ASR possess a high calorific value (20–30 MJ/kg) which makes them suitable for a valuable pyrolysis oil. Despite this, the main technical problems in ASR pyrolysis primarily arise from their high amount of PVC and chlorinated rubbers they contain, secondarily from the high amount of heavy metal that can contaminate the residue. So ASR have often to be pre-treated in order to reduce the content of chorine and limit evolution of corrosive HCl even under moderate heating. On the other hand the carbon in the charred residue (33–68%) can be considered as a substitute fuel or raw material but for these purposes it is important to know what the level of remaining metals is in the char. Finally ASR, containing a limited amount of copper and practically without precious metals, scarcely interests recycling technologies mainly devoted to metals recovery (Jalkanen, 2006).

The few pyrolysis processes which have survived the last few years have all dealt with mixing ASR feed with other wastes (municipal solid waste, WEEE scraps, biomass, etc.) to regulate the energy content and material variation. They also all make significant use of the gases given off, and obtain significant material recovery by post-processing the char (Vermeulen *et al.*, 2011). Some plants for ASR treatment are adapted for WEEE pyrolysis, mainly from white goods, in Japan. An interesting alternative for recycling of problematic wastes such as ASR and WEEE are the pyrometallurgic treatments: in order to be of economic interest for copper smelters, the waste feed should contain over 5 wt% of copper, which is in general not the case for ASR; the co-smelting of ASR and shredded WEEE results in a waste stream with sufficient concentrations of copper (mainly due to the WEEE) and with an elevated heat content (mainly due to the ASR) (Jalkanen, 2006).

While pyrolysis is attractive for problematic waste to be recycled such as WEEE and ASR, even in mixtures there are technical, legislative, commercial and financial drivers affecting the landscape of options, and all of these interact. Any potential pyrolysis feed for shredder residue is a heterogeneous mixture of all the materials found in cars, EEE, etc., and this heterogeneity needs to be taken into account when designing fuels from it. The heterogeneity of WEEE and ASR implies that small-scale processes suitable for local requirements could be able to optimize a process sufficiently to make it as viable as large-scale systems which would have to deal with much more variation in shredded residue characteristics.

In addition, different or ambiguous specifications for the potential pyrolysis products affects their marketability and so the overall convenience of developing commercial and semi-commercial stages of the process, preventing investment in larger facilities. Luckily, the major directives will have to be implemented giving a clear indication of design parameters and merits of various solutions (Harder and Forton, 2007).

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12
Chemical or feedstock recycling of WEEE products

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Abstract: This chapter reviews initiatives with regard to chemical or feedstock recycling of plastics waste from electrical and electronic products. Eurostat estimates the amount of waste from electrical and electronic products that is collected is 2.2 million tonnes. Roughly 20% of this waste consists of plastics. These plastics are difficult to recycle since after separation from the main waste product, a contaminated flow of mixed plastics is usually obtained. In the 1990s, various firms took initiatives to set up dedicated plants capable of breaking the plastics waste down to a hydrocarbon feedstock via processes such as cracking, liquefaction and gasification. Examples include plants set up by BASF and VEBA in Germany, and plans developed by, among others, Texaco and BP in the Netherlands and the UK. These dedicated initiatives, however, proved not to be commercially viable. The feedstock recycling plants still operational today are in use as reducing agent in blast furnaces and the SVZ process in Germany. Although these plants were built for other purposes, plastics can be applied with minor pre-treatment, leading to the important advantage that no capital investment is needed for the recycling process.

Key words: feedstock recycling, chemical recycling, waste from electrical and electronic plastics, cracking, liquefaction, gasification.

12.1 Introduction

Electrical and electronic equipment (EEE) forms a significant and growing material flow. For the EU15, the volume grew from 5.76 Mt per year in 1980 to 11.15 Mt in 1995 (EBFIP, 1999). Recent Eurostat statistics suggest that around 9.5 million tonnes of EEE was put on the market in 2007 (Eurostat, 2011). Most EEE has a long lifetime, and in a given year the new production is added to the product stock in use. Equipment that has become obsolete or damaged after use is discarded as waste. The total EEE waste flow was 4.4 Mt in 1995. Eurostat figures for 2007 suggest a total (separate) collected amount of waste of EEE (WEEE) of 2.2 Mt (Eurostat, 2011). Note that there may be definition differences between the Eurostat data and those of earlier studies.

Plastics form an important part of EEE and are fast growing. Around 20% of EEE consisted of plastics in 2000 (EBFIB, 1999). This amount of plastics forms a problem in the waste stage, particularly in view of the policy trend to stimulate re-use and recycling rather than incineration or landfill. First, it consists of many different plastic types. Second, except for, e.g., TV or computer casing, it consists in part of small and difficult to separate elements (e.g. insulation of wires). This all makes re-use and recycling of EEE plastics waste (WEEE plastics) difficult. Re-use of product components is hardly an option given innovations and design changes in the years that it takes before EEE becomes waste. The most common type of recycling, i.e. mechanical recycling, needs a clean, uniform and hence well-sorted plastics waste flow which could be expected only from bulk elements of EEE (see Table 12.1), and even these are costly to separate. We see hence that EEE are usually shredded, followed by a separation step, in order to get the individual components available. The plastic residues are often too mixed and too polluted to make direct form of recycling possible. Or, as formulated in a study on composition of WEEE plastics by Mark (2006: 22):

> The product quality of the refined plastics can become borderline with respect to meeting the German Chemical Banning Ordinance on dioxins/furans and heavy metals such as Cd, Pb, Cr (VI) and Hg which are restricted as a consequence of the European Directives: RoHS, the Penta and Octa-PBDEs and ELV. The final product quality produced from commercial recyclate has therefore to be assessed by the producer/compounder to ensure it does not exceed the limit values of PBDD/Fs and penta- and octa-PBDE concentrations. In view of the challenge to mechanically

Table 12.1 Specification items for plastics recycling (with modifications taken from: Mark, 2006: 17)

Content (wt%)	Product use	Fuel use	Feedstock use
Minimum plastics	>98%	>50%	>80%
Maximum inert	<2%	<50%	<20%
Maximum metal	<1%	tba	tba
Maximum heavy metal	RoHS Directive*	tba	tba
Maximum halogen	n.a.	May be limited due to corrosion	tba
Maximum regulated organic	EU Directives RoHS* + 2003/11*	n.a.	n.a.

Note: n.a. = not applicable for the use considered, tba = to be agreed.
* The Restriction on Hazardous Substances (RoHS) Directive applies only to the electrical and electronic sectors covered under the WEEE Directive.
Other sectors are currently not regulated except for the penta and octa PDBE restriction according to EC 2003/11 which applies for all market sectors.

remove metals, heavy metals and halogens from E&E plastics to comply with legislation, it is prudent to explore the benefits of other EoL options such as chemical feedstock recycling and energy recovery.

Chemical or feedstock recycling hence probably has an important role to play in management of WEEE plastics. These terms are often used as synonyms, though sometimes the following differentiation is made:

- Chemical recycling implies a change of the chemical structure of the material, but in such a way that the resulting chemicals can be used to produce the original material again.
- Feedstock recycling implies a change of the chemical structure of the material, whereas the resulting chemicals are used for another purpose than producing the original material.

Particularly for WEEE plastics, chemical recycling as defined here is unlikely. This would require – again – a quite pure waste stream with just a single plastic. In this chapter we will concentrate on feedstock recycling but in this 'broad' definition we will include chemical recycling as well where relevant.

In this chapter we will first describe in somewhat more detail the volumes and composition of WEEE plastics that are generated in Europe (Section 12.2). We then will describe some historical initiatives to set up feedstock recycling plants, using a variety of technologies (Section 12.3). It has to be noted that most of these initiatives were taken in the 1990s and early 2000s related to packaging plastics waste, and that relatively few of them became operational. Section 12.4 concludes with the potential for these technologies for the treatment of WEEE plastics and ends with conclusions and an outlook. The chapter is largely based on technology descriptions by Tukker *et al.* (1999) and Buekens (2006).

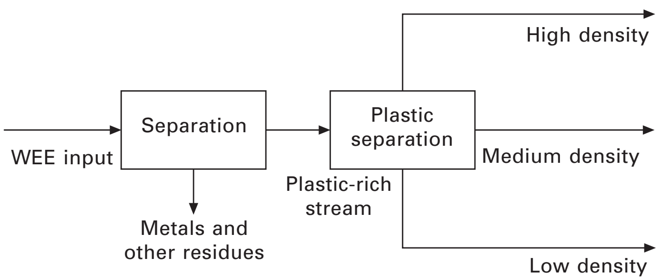
12.2 Characteristics of WEEE plastics

Chemical and feedstock recycling plants are, compared with, for example, incineration plants, relatively critical with regard to their acceptance criteria. Processes may have limited tolerance for halogens (e.g. from polyvinyl chloride, PVC) and certain metals, or such components may give difficulty in handling waste streams from such processes. It is therefore interesting to have insight in the composition of WEEE (see Table 12.2; Boerrigter, 2000).

As indicated, recycling of EEE is often started with a shredding step that breaks down the product into small parts, followed by separation. The plastics fraction is then further separated (see Fig. 12.1). In practice, this does not free the plastics fraction that needs to be recycled from the metals part of

Table 12.2 WEEE material breakdown by sector (source: EBFIB, 1999)

	Brown goods (%)	Data processing & office equip. (%)	White goods (%)	Printed circuit boards (%)
Plastics	26	13	7	30
Ferrous	35	40	44	
Non-ferrous	26	30	32	30
Glass	4	5	4.5	30
Wood	1	1	1	
Other	8	11	11.5	10
Total	**100**	**100**	**100**	**100**



12.1 Typical separation steps for WEEE plastics (WEEP; adapted from Mark, 2006).

EEE, mainly due to a limited level of metal separation (compare Table 12.3; Vehlow and Mark, 1997).

The problem of recycling of WEEE plastics is in that sense similar to that of plastics from automotive shredder residue (ASR) – there, plastics are also made available after separation from a shredded product with high metal content. With the practical experiences of feedstock recycling of WEEE plastics being limited, experiences with ASR can give valuable information about viability. For comparison, Table 12.3 gives the composition of ASR plastics (Boerrigter, 2000). Table 12.3. suggests that bromine and chlorine (from flame retardants and PVC) as well as certain heavy metals may be problematic. Table 12.4 and 12.5 give some other data about WEEE plastics composition.

12.3 European feedstock recycling initiatives since the 1990s

12.3.1 Introduction

Around 2000, the following feedstock recycling of mixed plastic waste (MPW) with a low chlorine content looked most promising. It concerned technologies that had been tested and operated in the past, or had even proven commercial

Table 12.3 Typical WEEE elemental composition by sector (EBFIB, 1999; ECN, undated)

	Brown goods (wt%)		Data processing & office equipment (wt%)		White goods (wt%)		Printed circuit boards (wt%)		Automotive shredder residue
	Plastics	Total	Plastics	Total	Plastics	Total	Plastics	Total	
Calorific value	*		*		*		*		~18 MJ/kg
Percentage composition									
C	79	20.6	65.8	8.6	46.4	3.2	27	8.1	37
O	3.4	1	7.7	1	20	1.4	30	9	13
H	6.8	1.8	5.9	0.8	5.6	0.4	2.3	0.7	4.5
N	0.8	0.2	3.7	0.5	5.3	0.4	0.55	0.17	1.9
S	0	0	0	0	0	0	0	0	0.11
P	0.01	0	0.14	0.02	0	0	0	0	–
Br	4.4	1	5.3	0.6	5.1	0.36	9	2.7	0.1
Cl	1	0.3	1.2	0.2	0	0	0	0	1.6
Sb	1.3	0.3	1.9	0.19	0.4	0.03	0	0	–
B	0.02	0.01	0.14	0.02	0.6	0.04	1	0.3	0.03
Ferrous metals	0	35	0	40	0	44	0	0	9.7
Non-ferrous	1.3	26.4	4.2	31	14.2	33	30	40	2.0
Glass	0.7	4.8	1.6	4.6	2.2	4.6	0	30	–
Others	0.35	8.6	2.2	11.6	0.2	11.5	0	10	30
Total	100	100	100	100	100	100	100	100	100

Table 12.4 Typical composition of WEEE plastics (taken with minor changes from Mark, 2006: 14)

Plastics (wt%)	Heavy metal (wt%)	Metals (wt%)	Halogens (wt%)	Inert, other (wt%)
95	5.0	0.08	1.4	3.2
95	4.0	0.25	1.8	3.1
90	0.6	8.5	6.8	Not measured
	0.3	0.5	6.8	8.2
92	0.32	0.23	0.4	Not measured
97	<2.5	0.023	5.5	<1.0
97	<1.5	0.02	3.0	1.2
51	n.a.	~0.02	n.a.	48*
99	~2.0	<1	n.a.	After separation of no-plastics
90	0.7	3	4.1	6

Note: *mainly wood. The table figures do not add up to 100% as other compounds, chemical species or metals/heavy metals can be in the WEEP. These have not been analysed. The fact that Cu, Pb are separated out from the heavy metals group is due to the fact that they are valuable for the N–Fe industry from a recovery standpoint. The heavy metals characterised in column 2 and legislated are: Hg, Sb, As, Pb, Cr (total), Cr, Co, Mn, Ni, V, Sn, Zn, Tl.
The caloric value of WEEE plastics typically is 22–24 MJ/kg.

Table 12.5 Composition of some medium density fractions waste from electrical and electronic products plastics (WEEP) from different recyclers (Mark, 2006: 19)

		WEEP from ESR 8	WEEP pellet from ESR 8	WEEP from ESR 9 <1.12 kg/l	WEEP from ESR 9 1.12–1.22 kg/l	WEEP from ESR 9 > 1.22 kg/l	WEEP housing
Ash content	(wt%)	5.58	2.2	3.7	5.1	19.5	2.3
Halogen (total Cl, Br, F)	(wt%)	3.53	0.24	2.0	4.5	10.5	6.2
Heavy metals	(wt%)	0.59	0.073	<0.14	<0.12	0.54	0.20
Metals (Cu, Pb, Zn)	(wt%)	0.16	0.04	<0.012	0.175	0.48	0.05

viability and remain on the market today. It must be stated that the techniques have mainly been developed with the idea of treating MPW from packaging rather than WEEE plastics. It concerns (Tukker *et al.*, 1999):

- Texaco gasification process (Netherlands, pilot in the US);
- polymer cracking process (consortium project, pilot);
- BASF conversion process (Germany, pilot but on hold);
- use as reduction agent in blast furnaces (Germany, operational) (In this process MPW is used as a reducing agent, and hence generally seen as a

form of chemical recycling. For instance, in Germany this is one of the most important technologies by which the ambitious German recycling target for plastic packaging waste is met (DKR/DSD, 1999);
- Veba combi cracking process (Germany, operational until 2000);
- pressurized fixed bed gasification of SVZ (Germany, operational).

These processes are discussed below.

12.3.2 Texaco gasification process

Background and current status

For regular feedstock, Texaco has operated gasification plants for over 40 years. Their reliability, flexibility and commercial viability has been proven in over 100 plants globally. In view of the more stringent demands to waste management, Texaco started to consider plastic waste as feedstock in the 1990s. To test the suitability of their technology for waste plastics, Texaco started pilot plant experiments with mixed plastic waste (10 t/day) in its plant in Montebello, California, USA (Weissman, 1997).

Commercialization to a full-scale plant was most seriously considered by a Dutch-oriented consortium comprising Texaco, Air Products, Roteb and VAM (the latter two being Dutch waste management companies). VAM would provide plastics from a municipal waste separation process and the Texaco process seemed a way to meeting the ambitious Dutch recycling quota for plastics waste. Ultimately the initiative was shelved since VAM found other, apparently more cost-effective, outlets (e.g. cement kilns and energy power plants).

Description of the process

Texaco gasification combines a liquefaction step and an entrained bed gasifier. The liquefaction step cracks the plastic waste under relatively mild thermal conditions. The result is depolymerisation to a synthetic heavy oil and a gas fraction, which in part is condensable. The non-condensable fraction is used as a fuel in the process. The process is comparable to the cracking of vacuum residues that originate from oil recycling processes.

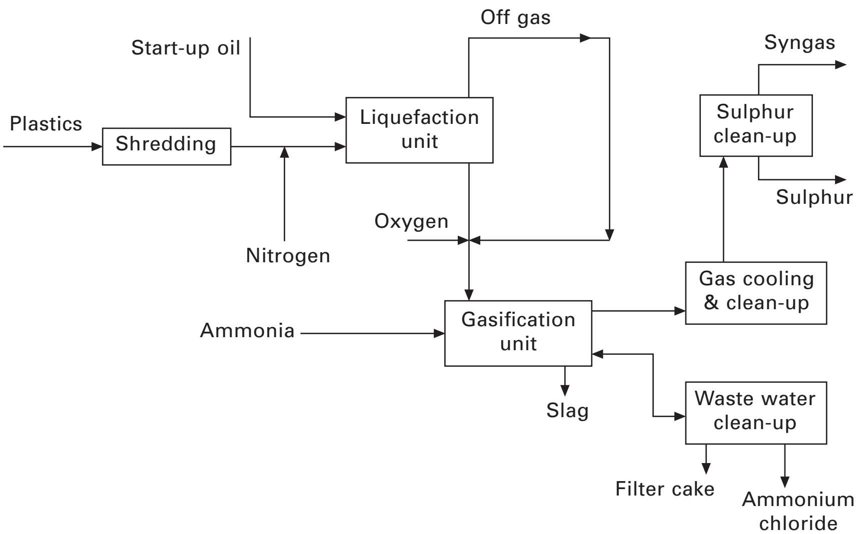
Particles are removed from the heavy fraction by filtration. The condensed gas fraction and the filtered heavy oil then are fed into the gasifier. The gasification takes places between 1200 and 1500 °C. under presence of steam and oxygen. Impurities like HCl and HF in the synthesis gas produced (in short: syngas) are removed in a number of cleaning steps – the washing of syngas with NH_3 results in saleable NH_4Cl (Croezen and Sas, 1997). Sulphur from MPW is won back in a pure, saleable form. The clean syngas, CO and H_2, contains smaller amounts of CH_4, CO_2, H_2O and some inert gases and is ready for use in other processes. Metals in the feedstock end up in slag and fines. The slag meets the quality standards of the Dutch Building decree, and the fines have a comparable quality to municipal solid waste incinerator (MSWI) fly-ash (Croezen and Sas, 1997).

Treatment of mixed plastics waste results in the following products. Roughly 350 000 N m^3 clean syngas can be produced from 150 t of mixed plastic waste daily. Next to this, pure sulphur and saleable NH_4Cl is produced. The process also produces vitrified slag and fines that meet the requirements of Dutch legislation for secondary building materials (Fig. 12.2).

Acceptance criteria for the input material

For an EU study by Tukker *et al.* (1999) Texaco communicated the acceptance criteria for its process. Reputedly, the Texaco process could handle up to 10% PVC in its feedstock. The tolerance to non-plastic materials like inorganics and paper is thought to be around 10%. Other acceptance criteria include:

- Material texture – dry to the touch, not sticky, free flowing
- Physical description – shredded or chipped
- Size – less than 10 cm
- Physical fines content – less than 1% under 250 mm
- Bulk density – > 100 g/litre
- Form at delivery – baled or agglomerated
- Plastics content – > 90 wt%



12.2 A schematic representation of the Texaco process (Tukker *et al.*, 1999).

- Free metals – < 1 wt%
- PVC content – < 10 wt%
- Ash content – < 6 wt%
- Residual moisture – < 5 wt%
- Paper content – < 10 wt%.

Environmental and cost performance

An extensive life-cycle assessment (LCA) for treatment of MPW was published by Croezen and Sas (1997). No specific problems with emissions control were mentioned by these authors. As for most other techniques discussed here, Texaco did not make public a cost structure or required gate fee. Figures circulating for potential gate fees are €90–135 per tonne for a 50 kt/year plant, decreasing to €50/t for a 200 kt/year plant (Tukker *et al.*, 1999). Since, as discussed, the plans to realize this plant have been abandoned, no more recent cost figures have become available. Since the plans were dropped for commercial reasons it seems unlikely that the current cost structure would be much lower.

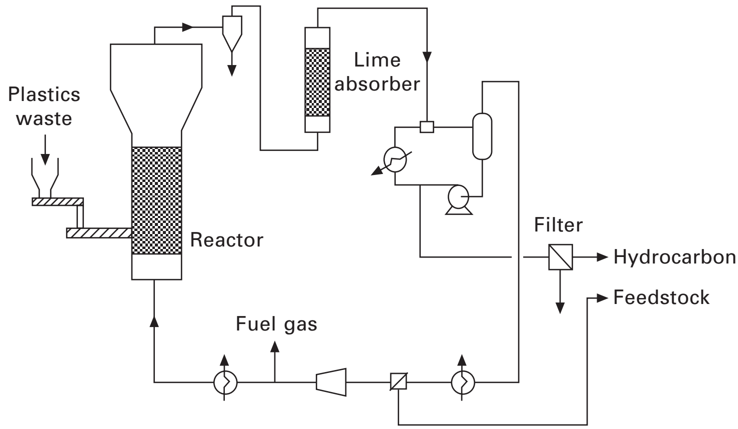
12.3.3 The polymer cracking process (consortium project)

Background and current status

BP Chemicals has a cracking process available that could be used for feedstock recycling of plastics waste. As for Texaco, stringent demand with regard to plastics recycling lead to tests by a consortium of BP Chemicals, Elf Atochem, EniChem, DSM, CREED and the APME if the process could be used for recycling of MPW. The 'polymer cracking process' is a fluid bed cracking process. After lab-scale tests, a continuous pilot plant for MPW treatment with a capacity of 400 tpa was built on BP's Grangemouth site. It has done test runs at 50 kg/h scale as it has limited product storage. Until now, conditions have not been right for scaling up to a full commercial plant.

Description of the process

First, a basic separation of the non-plastic fraction and size reduction of MPW is needed. The prepared MPW is then fed into a heated fluidised bed reactor, which operates at approximately 500 °C in the absence of air (Fig. 12.3). The MPW is thermally cracked. The resulting hydrocarbons vaporise and leave the bed with the fluidising gas. A solid fraction and coke fraction accumulate in the bed. Another fraction is blown out with the hot gas and captured in a cyclone. Halogens in the feedstock (e.g. chlorine from PVC) are converted into the corresponding acid (e.g. HCl) and removed with



12.3 A schematic representation of the BP process (Tukker *et al.*, 1999).

lime by the gas fraction. The resulting $CaCl_2$ fraction has to be landfilled. A cooling step condenses the gas and makes it available as hydrocarbon feedstock for other processes (some 85% of the MPW input). After cooling a light hydrocarbon gas fraction remains (15% of the MPW input) that is compressed, reheated and returned to the reactor as fluidising gas. It can also be used as a fuel for the cracking process.

A chlorine concentration of 1% of chlorine in the MPW input (2% PVC) will lead to 10 ppm Cl in products, which is somewhat higher than the specifications of 5 ppm typical for refinery use. Given the high dilution taking place in any refinery or petrochemical application, BP assumes that this is acceptable (Brophy *et al.*, 1997). Metals like Pb, Cd and Sb can be removed to very low levels in the products. Tests have shown that all the hydrocarbon products can be used for further treatment in refineries.

Acceptance criteria for the input material

Input specifications for BP's Grangemouth pilot plant are (Tukker *et al.*, 1999):

- Polyolefins: 80 (min. 70) wt%
- Polystyrene: 15 (max. 30) wt%
- Polyethylene terephthalate (PET): 3 (max. 5) wt%
- PVC: 2 (max. 4) wt%
- Total plastic content: 95 (min. 90) wt%
- Ash: 2 (max. 5) wt%
- Moisture: 0.5 (max. 1) wt%
- Metal pieces: max. 1 wt%

- Size: 1–20 mm
- Fines sub-250 **m**m: max. 1 wt%
- Bulk density: 400 (min 300) kg/m^3.

Environmental and economic performance

Emissions from the process will be low, complying with local regulations. Waste products are about 0.2 kg/kg of total solids feed (a combination of solids in the feed plastics and used as make-up in the process). As for costs, BP estimated that for a 25 000 t/year plant in Western Europe an investment of £15 to 20 million (1998 prices), would be needed. This would lead to a gate fee of around £172 per tonne (some €250). For a plant double this size the gate fee could be £100 per tonne (some €150). All figures exclude collection costs but take into account receipts from products. Like the case of Texaco, with the plans for this plant shelved, no more recent price estimates are available.

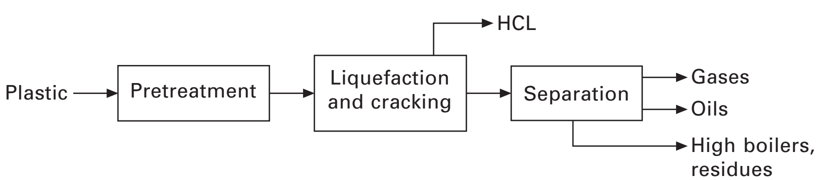
12.3.4 The BASF conversion process

Background and current status

In the 1990s, Germany introduced one of the most ambitious packaging recycling schemes in Europe (the Duales System Deutschland (DSD)). This stimulated a lot of MPW recycling initiatives in Germany, among them the BASF feedstock recycling process. A 15 000 t/year pilot plant was operational in Ludwigshafen in 1994. In 1996 BASF announced closure of its pilot plant after consultation with DSD and the Deutsche Kunststof Recycling AG (DKR). Reputedly uncertainty about waste volumes and prices made it too risky for BASF to scale its plant up.

Description of the process

In a pretreatment step, plastics are separated from non-plastics, ground and agglommerated (Fig. 12.4). The agglomerate is fed into the process. The plastic is melted and dehalogenated as a first step. Dehalogenation is needed



12.4 Schematic representation of the BASF pyrolysis process (Tukker *et al.*, 1999).

to prevent corrosion in the process. Most chlorine is recovered as HCl, that can be re-used; as small fraction of the chlorine ends up as NaCl or $CaCl_2$ in an aqueous effluent (Heyde and Kremer, 1999). Output from the process are liquefied plastics and gaseous fraction. After decompression, the gaseous fraction is used as feedstock in a cracker.

The liquefied plastic fraction is heated to over 400 °C in a cracker, resulting in 20–30% gas and 60–70% oils. These are separated by distillation. Any naphtha from this process is fed into a steam cracker, resulting in ethylene, propylene and other monomers. The heavy fractions are processed to syngas or converted to coke. Around 5% of the input, mainly the inorganic additives in plastics, is converted into a mineral fraction.

To sum up, the process leads to naphtha that is treated in a steam cracker, various monomers, that can be used for plastic production, high boiling oils, that can be converted to syngas or coke, inert residues, and a HCL fraction.

Environmental and economic performance

The process is fairly robust. The pilot plant handled MPW with PVC contents of 4–5% (or 2.5% clorine). Emissions and resource use are described extensively by Heyde and Kremer (1999). All emissions will comply with local regulations.

Reputedly, the BASF process would require a gate fee of (€160) per tonne for a 300 000 t/yr plant and a fee of €250 per tonne for a 150 000 t/yr plant. To our knowledge BASF has not disclosed a more detailed cost structure. Again, since the plant was closed in the 1990s, no more recent cost data are available.

12.3.5 Use of mixed plastic waste in blast furnaces

Background and current status

In blast furnaces iron ore (Fe_2O_3) is reduced to metallic iron (Fe). Regular reduction agents are materials like coke, coal and/or heavy oil. Yet, steel producers such as British Steel (UK) and Stahlwerke Bremen (Germany) sought alternative agents, such as plastics waste. Stahlwerke Bremen (in the mean time known as ArcelorMittal Bremen) is using this source on a regular basis and others, such as VoestAlpine in Austria, want to implement this practice (Plastics Europe, undated). ArcelorMittal Bremen operates two blast furnaces to produce over 7000 t/day, or some 3 Mt/year pig iron. In various steps they increased capacity to 162 500 t/year MPW in 1998, which was some 25% of the recycling capacity for MPW in Germany (DKR/DSD, 1999). With SVZ (see Section 12.3.7) feedstock recycling in blast furnaces is the only operational full-scale treatment option for MPW via feedstock recycling in the EU. The potential to use this technique in the EU is huge. The total pig iron production in the EU is some 90 Mt, or some 30 times the capacity of Bremen Stahlwerke. With 162 500 t/year treated in Bremen, this would imply a capacity of 5 Mt MPW per year for all European steelworks.

Description of the process

In essence MPW is used as a substitute for heavy oil. In the same way as coal powder or heavy oil plastic granulates are injected into the blast furnace. The plastic has to go to a separation step first. Large particles are separated via a screen of >18 mm. The smaller plastic waste particles (<18 mm) go to the injection vessel. An injection pressure of about 5 bar is built up. Via a pneumatic process the plastics can be dosed and discharged into the blast furnace. The bulk density of the plastics has to be $0.3\,t/m^3$. Input has to be controlled stringently. MPW contains relatively low amount of sulphur, but the chlorine content has to be limited. Dioxin emissions seem less of a problem, as shown via measurements during experiments. Dioxin emissions with or without plastic input appeared to be about a factor 100 below the standard of $0.1\,ng/N\,m^3$ TEQ TCCD (Janz and Weiss, 1996). However, the PVC throughput in the blast furnace kiln is just a fraction of the total material throughput. This is comparable to MSWIs, where PVC in general forms less than 1% of the input. Under such circumstances, the relation between PVC input and dioxin formation appears quite difficult to assess. For MSWIs, this controversy is greatest. Most research reports claim that there is no clear relation (e.g. Rigo *et al.*, 1995; Rijpkema and Zeevalking, 1997). However Greenpeace has published a number of reports that suggest otherwise (e.g. Costner, 1997). Furthermore, it has to be noted that the off-gas of blast furnaces is generally used as an energy carrier in other processes. Checks on dioxin formation are desirable there as well. On top of this, PVC is by no means the only chlorine source. Other raw materials and (particularly for blast furnaces close to sea) even the air used in incineration processes may have siginificant contributions to the chlorine throughput too.

Acceptance criteria for the input material

ArcelorMittal has a permit that allows using MPW with a chlorine content of up to 1.5% (= ca. 3% PVC) on a daily average. This balances the need to allow for a reasonable PVC tolerance in MPW (lower values are rare in MPW), and the desire to have materials as ‘free’ of impurities as possible. Chlorine has no added value in the process, and may only contribute to such problems as corrosion in the blast furnace, etc.

Environmental and economic performance

The earlier mentioned study of Heyde and Kremer (1999) gives an extensive review of emissions and resource use. One could assume that the emissions from using plastics as reducing agent will be more or less equal to the emissions that would occur if another reduction agent would be used, so that the net emissions of this form of feedstock recycling would be zero.

There is no public information on the gate fee that is obtained. Various sources suggest that DSD would pay €100 per tonne around 2000. Since some pretreatment and trials were needed a certain gate fee seems logical, but it is also clear that this process has a major advantage over any purpose-built feedstock recycling plant: capital investment to be allocated to waste recycling is negligible. It could even be that for the company there is a net gain, since costs for primary energy carriers can be avoided. The actual gate fee thus will mainly depend on the availability and the price of competing technologies for the treatment of plastic waste. Unfortunately for commercial reasons companies do not disclose detailed insights in costs and benefits of their operations – this is why the gate fee figures in this chapter are indicative and mainly based on 'hear-say' type of evidence.

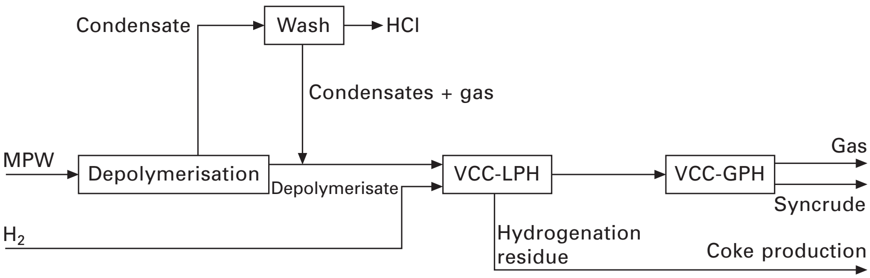
12.3.6 Veba combi cracking process

Introduction

In 1981 Veba Oel started a hydrogenation plant for coal, which produced naphtha and gas oil. The plant is known as the Kohleöl Anlage Bottrop (KAB) in Germany. After a modification in 1987 with the Veba combi cracking (VCC) technology, vacuum distillation residues of crude oil could be transformed into synthetic crude containing naphtha, gas oil and heavy distillates. Later, Veba started to substitute its normal feedstocks by waste, and added in 1992/1993 depolymerisation unit at the front of the process to allow for processing MPW collected via the DSD system. The capacity is about 10 t/h. MPW treatment peaked in 1998, but then DSD and Veba agreed to terminate the original contract for MPW treatment by the end of 1999 (whereas it was meant to continue to 2003). Since in the mean time the plant processed only DSD waste, Veba decided to close down the plant entirely. Reputedly, the Veba technology could not compete on costs with the SVZ (see next section) and blast furrnace processes.

Description of the process

The plant consists of a VCC part and a depolymerisation part (Fig. 12.5). Depolymerisation allows for further processing of the residues in the VCC section. The depolymerisation takes place between 350 and 400 °C. Here,



12.5 Schematic representation of the Veba Oel process (Tukker *et al.*, 1999).

at the same time chlorine is released. Over 80% of the chlorine input will become available as HCl in the light fraction and washed out in a purification process, yielding technical HCl. The overhead product of the depolymerisation is partially condensed. The condensate, containing 18% of the chlorine input, is fed into a hydrotreater. The HCl is eliminated with the formation water. The resulting Cl-free condensate and gas are mixed with the depolymerisate for treatment in the VCC section. Under high pressure (100 bar), the depolymerisate is hydrogenated in the VCC section at 400–450 °C. After separation and treatment in a fixed-bed hydrotreater a synthetic crude oil comes available, next to a hydrogenated residue stream that contains the heavy hydrocarbons contaminated with ashes, metals and inert salts (from inorganic materials in the input). This 'hydrogenation bitumen' is blended with the coal for coke production (2 wt%). The gaseous light cracking produces are cleaned from H_2S, HCl and ammonia. Just 2% of the chlorine input is bound to $CaCl_2$, the rest becomes useful HCl (Sas, 1994; Heyde and Kremer, 1999).

In sum, the Veba process converts MPW into HCl, syncrude (free of chlorine and low in oxygen and nitrogen), a hydrogenated solid residue, which can be blended with the coal for coke production, and off-gas.

Acceptance criteria for the input material

When Veba was operational, the following input specifications for the depolymerisation section applied:

- particle size < 1.0 cm;
- bulk density ≥ 300 kg/m^3
- water content < 1.0 wt%;
- PVC < 4% (**£** 2 wt% chlorine);
- inerts < 4.5 wt% at 650 °C;
- metal content < 1.0 wt%;
- content of plastic ≥ 90.0 wt%.

Interestingly, the plant did successful tests with electrical and electronic waste plastics. In the test, some 50 t of E&E waste were mixed with some 250 t of DSD waste (HCL, 1998).

Environmental and economic performance

LCAs were performed by Sas (1994) and Heyde and Kremer (1999). The studies of Sas in particular suggested that the Veba process was a bit less advantageous than the Texaco process, mainly because the Texaco process does not need agglomeration of MPW as pretreatment, whereas the Veba process apparently does. As is the case for most other processes reviewed here, no detailed cost data are given by the firm that operates the process. It seems that the gate fee is around €250 per tonne (compare also Pohle, 1997: 120) which could explain the closure of the plant, giving competition of a factor 2 lower prices from blast furnaces and SVZ (see below).

12.3.7 The Sekundärrohstoff Verwertungs Zentrum (SVZ) gasification process

Background and current status

The Sekundärrohstoff Verwertungs Zentrum (SVZ) (informally named 'Schwarze Pumpe') operates a plant that converts several feedstocks into synthesis gas, methanol and electricity. It was originally coal gasification plant, which after major investment also could handle waste materials, including plastics, as an input. The plant is currently fully operational. The range of waste treated is large, including contaminated wood, waste water purification sludge (including industrial sludges), waste-derived fuel from MSW, paper fractions, plastic fractions, the light fraction of shredder waste, and liquid organic waste that arises from SVZ-related plants. The plant can treat about 410 000 t/year solid and 50 000 t/year liquid material.

Description of the process

Lignite, waste oil and MPW is fed into a reactor (a solid bed gasification kiln), where a gasification reaction takes place supported with oxygen and steam. Like many processes discussed before, this results in hydrogen and CO (synthesis gas), liquid hydrocarbons, and effluent. The liquid hydrocarbons are gasified. The resulting gases and the gases from the fluidised bed reactor are purified by the rectisol process, which removes components like H_2S and organic sulphur compounds.

The syngas is used for the production of methanol (70%) and electricity (20%) and some other purposes. Waste gas products are incinerated; the fate of any chlorine is not clear from the various descriptions available. Inorganic materials in the input end up in the slag, which seems to have rather good elution characteristics (landfill class 1 according to the German TA Siedlungsabfall).

Acceptance criteria for the input material

The plant is fairly robust in terms of acceptance criteria. Experience has been developed with treating mixed plastics waste, waste-derived fuel (a mixture of plastics, wood and paper), the shredder light fraction of car wrecks, and the plastic fraction from shredded white goods and electronics. SVZ can handle on average 2% chlorine in MPW, with short-term excursions to 6%, although high levels are not welcomed – it gives problems like a higher risk of corrrosion, and the need for neutralisation, leading to a salt that has to be landfilled at high cost. Key acceptance criteria are:

- particle size: > 20 to 80 mm;
- chlorine content: 2% as default, though higher concentrations are tolerable;
- ash content: up to 10% or more;
- caloric value: not critical.

Environmental and economic performance

Heyde and Kremer (1999) have provided a quite detailed insight in the input–output balance of the plant (see Table 12.6). No public insight is available in the gate fee. However, indirectly one can deduce that SVZ's position is rather competitive. It is from all initiatives in Germany (that included BASF and Veba) the only one that survived competition with options such as treatment in steelworks. Hence, it seems unlikely that SVZ's gate fee will be much higher than the €100 per tonne of MPW that seems to be valid for steelworks.

Table 12.6 Inputs and outputs of the SVZ process (based on Heyde and Kremer, 1999)

Inputs		Outputs	
MPW agglomerate	763 g	Methanol	712 g
Waste oil	256 g	Synthesis gas	204 g
Lignite	1.25 kg	Electricity	2.28 MJ
Water	7.9 l	CO_2	6.32 kg
Oxygen	1.47 kg	Water vapour	9.9 kg
Natural gas	0.1 m^2	Gypsum	0.1 kg
		Slag	0.9 g

12.4 Conclusions and future trends

In this concluding section we want to address the following issues. First, is it conceivable that WEEE plastic waste can be treated via feedstock recycling, and if yes, which processes are suitable? Second, what are the prospects for commercial scaling up of feedstock recycling plants?

As for the first question, it is striking to see that most if not all initiatives in the field of feedstock recycling have been focused on mixed plastics waste (MPW), particularly packaging waste. This is probably a cleaner waste stream less polluted with additives and sorting residues as shredded and separated WEEE plastics. At the same time, some plants have done successful tests of full scale operations with WEEE plastics (Veba, SVZ) or similar wastes such as Automotive Shredder Residue. So it seems that with the right equipment feedstock recycling of WEEE plastics is certainly possible. The commercial reality and experiences from the last decades however show that one should be careful with thinking that what is technically possible can also be realised. For MPW we have seen the following (see Table 12.7):

- Feedstock recycling of MPW has only been realised in practice in Germany, where some 360 t/year MPW were treated in 1998. Waste

Table 12.7 A review of options for chemical recycling of MPW, including cement kilns

Technology	Status	Capacity	Indicative gate fee per tonne (end 1990s)	Future potential
Texaco (NL)	Pilot/on hold	–	€90/135	Uncertain
Polymer cracking (UK)	Pilot/on hold	–	€150	Uncertain
BASF (D)	Closed in 1996	15 kt/year before 1996	€160–250	–
Veba (D)	Closed by 1 January 2000	87 kt/year before 2000	€250	–
Blast furnaces	Operational (D)	162.5 kt/year in 1998	<€100 ?*	5 Mt/year in the EU
SVZ (D)	Operational	110 kt/year in 1998	?*	
Cement kilns	Operational		?*	3 Mt/year in the EU

* Blast furnaces, the SVZ process and cement kilns are not built for treatment of plastics waste but other purposes. Capital costs hence do not need to be allocated to the waste treatment operations. They can treat plastics waste with minor pretreatment, replacing primary energy and feedstock carriers in the process. It is likely that they still can work with gate fees that are close to €0, since they save on energy and feedstock costs. It is likely that they will ask for the highest gate fee possible given the price of alternative feedstock recycling options.

supply and funding were guaranteed due to the existence of the DSD system.

- Of the three purpose-built chemical recycling plants in Germany, two have in the meantime been shut down (BASF and Veba). Use of plastics as a reducing agent in blast furnaces is in terms of volume the most important technology.
- Two initiatives outside Germany have, to date, not been able to arrange waste supply at a sufficient gate fee that allowed for investment in a full-scale plant (Texaco and the consortium initiative). With the long time elapsed, it seems illusive that scaling up to full scale plants will be done soon.

Of the two operational feedstock recycling options at SVZ and in blast furnaces, it is obvious that the last one has relatively critical input parameters. The damage that can be caused if the wrong impurities end up in the process can be high (both for equipment and the product, i.e. steel). To our knowledge no testing with WEEE plastics or ASR has been performed here. The SVZ process seems much more robust in this respect and has in practice already treated WEEE plastics. It seems, however, inevitable that with competition of robust and cheap options like energy recovery in, for example, cement kilns available, even a technology such as managed by SVZ needs legal steering mechanisms to ensure waste is recycled rather than incinerated. Even under beneficial conditions such as the German DSD financial system, most feedstock recycling initiatives failed and only the most cost-effective ones survived. These were the ones that used plants that were primarily built for other purposes: SVZ and blast furnaces. Unlike e.g. Veba, BASF and Texaco these plants only needed to do a very limited capital investment to make their plant suitable for treating plastics waste. This gives them a significant competitive advantage over any purpose-built feedstock recycling facility. For WEEE plastics waste, the situation will probably not be different.

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13
Recycling printed circuit boards

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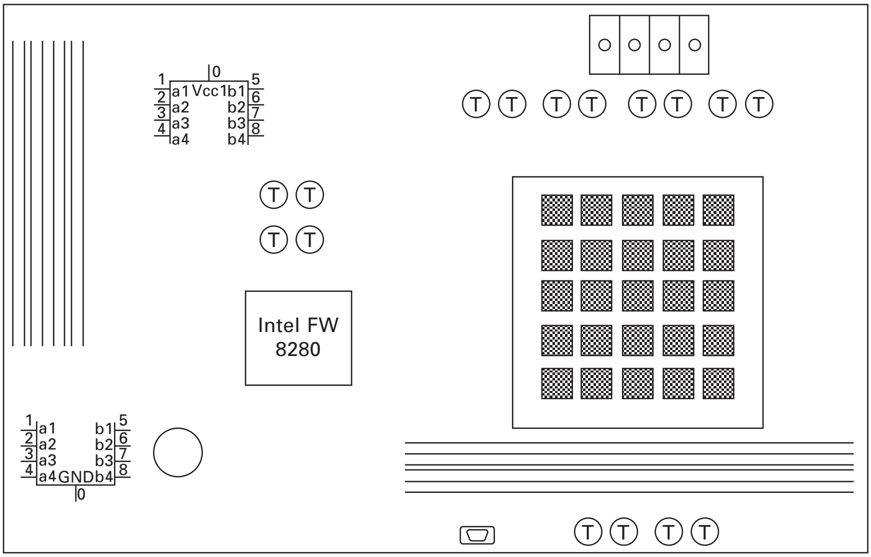
Abstract: The chapter illustrates how to recycle and recover printed circuit boards (PCBs). First the definition, source and mass fraction of PCBs from electronic and electrical equipment is analyzed and the quantity of waste PCBs is extrapolated according to the generation of e-waste. Secondly, the categories of PCBs is discussed, including FR-4, FR-2, FR-1, CEM-1 and CEM-3 along with their application to electronics and electrics. The categories of electronic components mounted to bare board are illustrated, and their function, materials, packaging and possibilities for reuse and recycling are discussed. Thirdly, the history of flame retardants is introduced. Then, the categorization and physical/chemical properties are discussed, including brominated flame retardants (BFRs), non-halogenated phosphorus, inorganic and nitrogen flame retardants. Fourthly, the technology used to dismantle and recycle PCBs is reviewed. The costs and benefits of recycling technology are compared in detail. The best available technology used in developed and less-developed countries is recommended, based on the recent development of e-waste management. Finally future trends and challenges of recycling PCBs are indicated such as improving the recycling efficiency, and minimize the environmental risk.

Key words: printed circuit boards, recycling, life cycle, composition, cost, benefit.

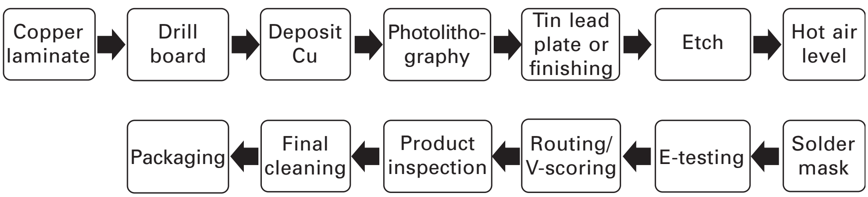
13.1 Introduction

Printed circuit boards (PCBs) are used to mechanically support and electrically connect electronic components using conductive pathways, tracks or signal traces etched from copper sheets laminated onto a non-conductive substrate, employed in the manufacturing of business machines and computers, as well as communication, control and home entertainment equipment. PCBs are an essential part of almost all electric and electronic equipment, and have revolutionized the electronics industry. The creation of circuit patterns is accomplished using both additive and subtractive methods. The conductive circuit is generally copper, although aluminum, nickel, chrome and other metals are sometimes used. PCBs are the platform upon which microelectronic components such as semiconductor chips and capacitors are mounted. A typical basic PCB for an electronic component is shown in Fig. 13.1, and its fabrication process is illustrated in Fig. 13.2.

PCBs are crucial to the manufacture and sales of about $1 trillion of



13.1 Schematic of typical printed circuit board.

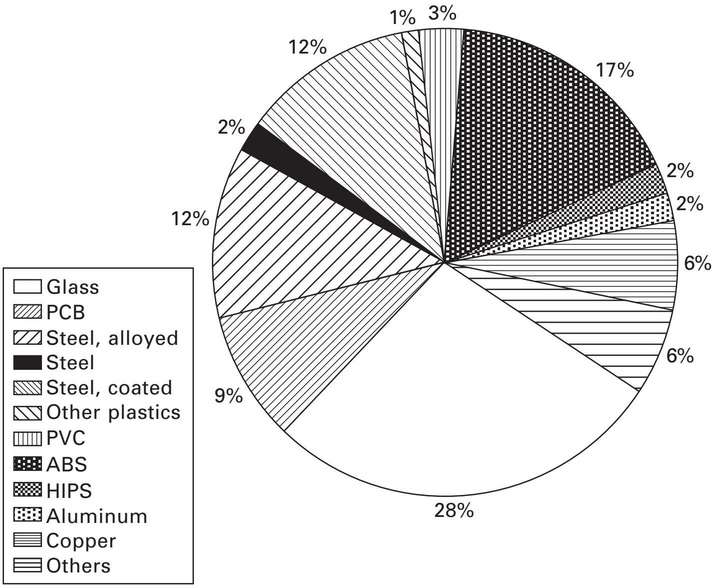


13.2 Fabrication process of PCB.

electrical and electric equipment (EEE) each year (LaDou, 2006). For instance, personal computers (PCs) are presently some of the most popular EEE based on PCBs. The main composition of a PC is shown in Fig. 13.3, indicating that:

- the first part including copper, aluminum, high impact polystyrene (HIPS), acrylonitrile-butadiene-styrene (ABS), poly (vinyl chloride) (PVC), and other plastics is easier to recycle, accounting for 31%;
- The second part including all the steels and glass can be recycled by simple treatment, accounting for 54%; and
- The final part including PCB and others is difficult to directly recycle, accounting for 15%.

PCBs usually contain epoxy resin, fiberglass, copper, nickel, iron, aluminum and a certain amount of precious metals such as gold and silver; those materials and metals along with electronic parts are attached to the



13.3 Composition of personal computer (wt%) (Source: Atlantic Consulting, Presentation at EGG 2004+, Berlin).

board by a solder containing lead and tin. The main material composition of PCBs was determined and is shown in Table 13.1. From the table, the composition of metals, ceramic and plastics could reach 40%, 30% and 30%, respectively. Further, the concentrations of precious metals in waste PCBs are richer than in natural ores, which makes their recycling important from both economic and environmental perspectives. Table 13.2 shows the average content and value ratio of different metals in PCBs. One can see that Au, Cu, Pd and Ag account for nearly all of the economic material value in waste PCBs. Therefore, PCB recycling focuses on recovering these metals above all else.

For the technology and engineering of very complex boards, the United States, the United Kingdom, Germany and France still have a competitive advantage. There is every reason to believe that the advantage will soon be lost to Asia. Asia produces three-fourths of the world's PCBs, with over 1000 manufacturers in China alone. The PCB industry, like the larger electronics industry, has always had a global component. Only in the past four years, however, has the US manufacturing base faced a serious decline. In 2003, the United States produced 15% of the world's PCBs, trailing Japan, the largest producer at 29%, and China, the second largest at 17%. Taiwan was the fourth largest producer at 13%. Europe produced only 10%, and South Korea 8%. No American company is now among the top ten manufacturers of PCBs. China has overtaken Japan as the leader in PCB production and

Table 13.1 Representative material composition of printed circuit boards (wt%)

Materials	%[a]	%[b]	%[c]	%[d]	%[e]	%[f]	%[g]
Metals (max. 40%)							
Cu	20	26.8	10	15.6	22	17.85	23.47
Al	2	4.7	7	–	–	4.78	1.33
Pb	2	–	1.2	1.35	1.55	4.19	0.99
Zn	1	1.5	1.6	0.16	–	2.17	1.51
Ni	2	0.47	0.85	0.28	0.32	1.63	2.35
Fe	8	5.3	–	1.4	3.6	2.0	1.22
Sn	4	1.0	–	3.24	2.6	5.28	1.54
Sb	0.4	0.06	–	–	–	–	–
Au/ppm	1000	80	280	420	350	350	570
Pt/ppm	–	–	–	–	–	4.6	30
Ag/ppm	2000	3300	110	1240	–	1300	3301
Pd/ppm	50	–	–	10	–	250	294
Ceramic (max. 30%)							
SiO_2	15	15		41.86	30	–	–
Al_2O_3	6	–	–	6.97	–		
Alkaline and alkaline earth oxides	6	–	–	CaO: 9.95; MgO: 0.48	–		
Titanates, mica, etc.	3	–	–		–	–	–
Plastics (max. 30%)							
Polyethylene	9.9	–	–		16	–	–
Polypropylene	4.8						
Polyesters	4.8						
Epoxides	4.8						
Poly(vinylchloride)	2.4						
Poly(tetrafluroethane)	2.4						
Nylon	0.9						

[a] Shuey *et al.* (2006); [b] Zhao *et al.* (2004); [c] Zhang and Forssberg (1997); [d] Kim *et al.* (2004); [e] Lji and Yokoyama (1997); [f] Kogan (2006); [g] Ogunniyi *et al.* (2009).

Table 13.2 Metal content and economic value of waste PC boards (per tonne)

Metals	Content (%)*	Metal price ($/kg)**	Potential value ($)	Value ratio (%)
Cu	9.7	3.6	349.2	4.8
Al	5.8	1.7	98.6	1.35
Fe	9.2	0.4	36.8	0.51
Ni	0.69	10.5	72.5	0.99
Pb	2.24	1.2	27	0.37
Sn	2.15	13	279.5	3.84
Ag	0.06	315	189	2.6
Au	0.023	24 434	5620	77.17
Pd	0.01	6100	610	8.38
Total	29.87	–	7282	–

* Chris *et al.* (2007)
** London Metal Exchange, Nov., 2008

is forecast to produce $10.6 billion worth of PCBs, accounting for 25% of the world total (LaDou, 2006).

13.2 Materials

PCBs are now increasingly complex: many of them are multilayer, high-speed products that are beginning to compete with the technology of the semiconductor industry. The choice of manufacturing materials used for PCBs depends on the application, for example, difunctional epoxy resins are adequate for simple two-sided circuit boards but more sophisticated multifunctional epoxy resins or cyanate esters are required for thick multi-layered boards.

Raw PCB stock is graded in flammability ratings (FR) from 1 to 5, with 1 being the most flammable and 5 being the least. Of the several materials used for the boards, six are the most widely manufactured: FR-1, FR-2, FR-3, FR-4, CEM-1 and CEM-3. FR 1, 2 and 3 are essentially the same, with only minor differences in properties. They are not suited for building multilayer boards. The same is true for CEM-1. FR-4 and CEM-3 are two laminates that can be used for multilayer boards. Of the two, FR-4 is more widely manufactured, and hence is cheaper. FR-4 is commonly used in industrial quality equipment such as high-value EEE, while FR-2 is used in high-volume consumer applications such as TVs and home electronics. Although there are no set rules for this, it appears to be an industry 'standard'. Deviating from it without good reason can limit the number of suppliers of raw board material and the number of PCB houses that can fabricate the board, since their tooling is already set up for these materials.

The basic building blocks of a PCB are composites of resin and reinforcement. A wide variety of resin and reinforcement types that are commonly used in the PCB industry are listed in Table 13.3. The thickness of the PCB can be 1.0, 1.2 or 1.6 mm. The PCB can be single sided or double sided with copper clad of 1 oz (28 g) (0.036 mm) or 2 oz (56 g) (0.072 mm).

FR-4 PCB is a composite of epoxy resin with woven fiberglass reinforcement and it is the most widely used PCB material. The steps involved

Table 13.3 Common PCB material types (Coombs, 2001)

Nomenclature	Reinforcement	Resin	Flame retardant
FR-2	Cotton paper	Phenolic	Yes
FR-3	Cotton paper	Epoxy	Yes
FR-4	Woven glass	Epoxy	Yes
CEM-1	Cotton paper/woven glass	Epoxy	Yes
CEM-2	Cotton paper/woven glass	Epoxy	No
CEM-3	Woven glass /matte glass	Epoxy	Yes

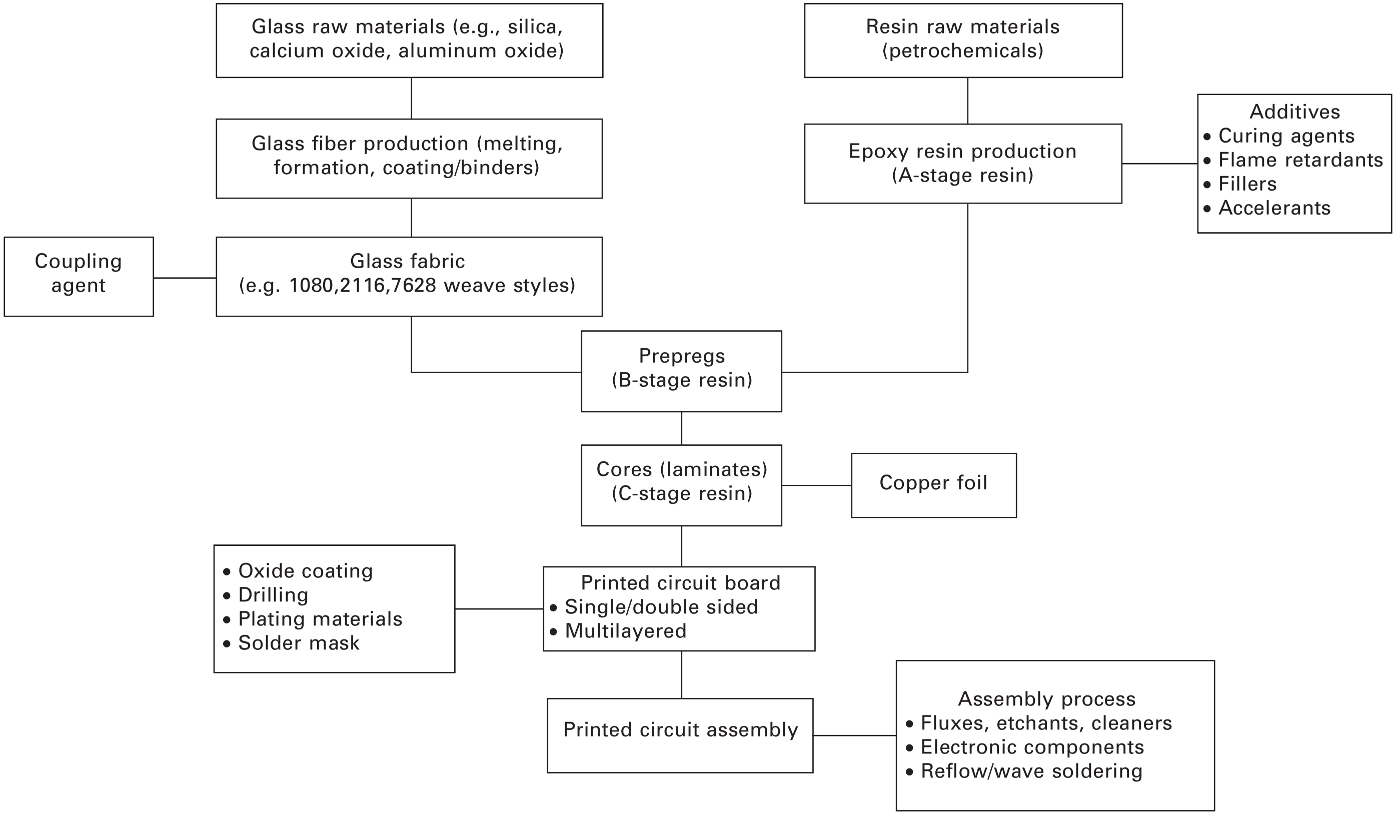
in the fabrication of FR-4 printed circuit assembly (PCA) are shown in Fig. 13.4.

Glass raw materials are melted in a furnace and extruded to form fiberglass filaments that are combined into strands of multiple fiber yarn. Yarns are then woven to form fiberglass cloth. A coupling agent, typically an organosilane, is coated onto the fabric to improve the adhesion between organic resin and inorganic glass. Resin is obtained from processing the petrochemicals and in its pure (uncured) form is called A-stage resin. Additives such as curing agents, flame retardants, fillers and accelerators are added to the resin to tailor the performance of the board.

A prepreg is fabricated from a glass fabric impregnated with the semi-cured (B-stage) epoxy resin. Multiple prepregs are thermally pressed to obtain a core or laminate (C-stage resin). Copper foil is then typically electrodeposited to obtain a copper clad laminate. Several prepregs and cores (with copper cladding etched as per the circuit requirements) are stacked together under temperature and pressure conditions to fabricate a multilayered PCB. Through-holes and micro-via interconnects are drilled in the PCB as per the application specific design data and then plated with copper. Solder mask is applied on the board surface exposing the areas to be soldered. Flux is applied at regions where the electronic components are to be soldered. The boards are then subjected to reflow and/or wave soldering process depending upon the type of components (surface mount or through-hole) to obtain the printed circuit assembly.

There are three major types of PCB construction: single-sided, double-sided and multilayered. Single-sided boards have the components on one side of the substrate. When the number of components becomes too much for a single-sided board, a double-sided board may be used. Electrical connections between the circuits on each side are made by drilling holes through the substrate in appropriate locations and plating the inside of the holes with a conducting material. The third type, a multilayered board, has a substrate made up of layers of printed circuits separated by layers of insulation. The components on the surface connect through plated holes drilled down to the appropriate circuit layer. This greatly simplifies the circuit pattern.

Copper is the most commonly used material for traces. Simple methods involve plating the entire board with copper, and then etching away unnecessary areas through a mask (stencil) to leave the required traces. More complex methods allow traces to be added on to a bare board. Each approach has associated pros and cons. Some boards require the use of gold for sensitive, low-voltage applications or lead-free Restriction on Hazardous Substances, (RoHS) compliance. Copper traces usually demand the use of a nickel barrier layer before gold-plating. This is to prevent gold from migrating into the copper. Indiscriminate use of nickel can result in huge losses to impedance.



13.4 Typical steps involved in FR-4 PCA fabrication.

Almost every piece of electronic equipment has its electronic components mounted by soldering onto a fiber-based epoxy PCB or similar with the interconnecting wiring provided by tracks of copper on that board. A typical circuit board module includes a PCB and a variety of circuit board components soldered to the PCB. The PCB is generally a laminated board with circuit traces on external surfaces of the board or at interlayer levels within the board, and the electrical components are typically light-emitting diodes (LEDs), processors, memory devices, clock generators, resistors, cooling units, capacitors and virtually any other type of electrical components. PCBs generally comprise a composite of organic and inorganic materials with external and internal metal traces, permitting assembled electronic components to be mechanically supported and electrically connected. The components themselves are a mixture of often quite sophisticated construction and include the components listed in Table 13.4. Additionally, the typical constituents of a FR-4 laminate are listed in Table 13.5. Each of these constituents is important on its own, and in combination they determine the properties of the laminates.

13.3 Flame retardants

13.3.1 History of flame retardants

Flame retardants (FR) are used to protect the public from accidental fires, by reducing the flammability of combustible materials such as plastics and synthetic polymers. Since the 1960s, FRs have been used in polymers to reduce the flammability of household products made from these materials. Fire codes dictate the use of FRs in such products as insulating materials, electronic and electrical goods, upholstered furniture, and carpets. The most frequently used organic FRs are the polybrominated flame retardants (BFR) and organophosphoric compounds. The main advantage of FRs, reduction of risk of fire, is offset by possible risks from the toxicity and eco-toxicity of FRs (Kemmlein *et al.*, 2003).

Table 13.4 Typical PCB components and their major compositional components

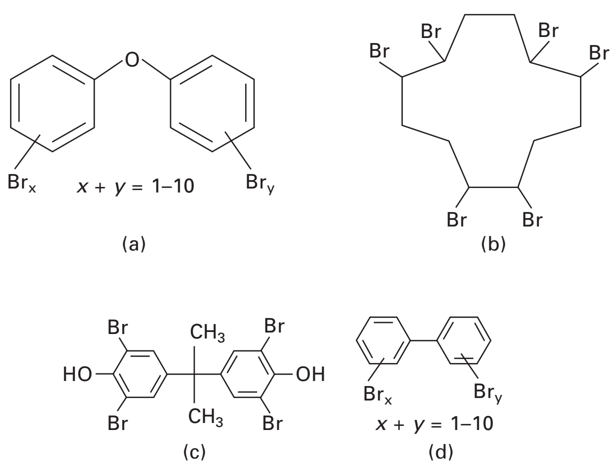
Electronic component	Majority composition or materials
Resistors	Ceramic, carbon
Capacitors	Aluminum, electrolyte, plastics etc., copper leads
Inductors, transformers	Steel, copper
Integrated circuits	Plastic cases, copper leads, silicon
Transistors, diodes	Plastic cases, copper leads, silicon
Connectors	Copper, plastic
Mounting brackets	Aluminum, steel
Heat sinks	Aluminum

Table 13.5 Typical constituents of FR-4 laminates

Constituent	Major function(s)	Example material(s)
Reinforcement	Provides mechanical strength and electrical properties	Woven glass (E-grade) fiber
Coupling agent	Bonds inorganic glass with organic resin and transfers stresses across the matrix	Organosilanes
Resin	Acts as a binder and load transferring agent	Epoxy (DGEBA)
Curing agent	Enhances linear/cross-polymerization in the resin	Dicyandiamide (DICY), phenol novolac (phenolic)
Flame retardant	Reduces flammability of the material	Halogenated (TBBPA) or Halogen-free (phosphorus compounds)
Fillers	Reduces thermal expansion	Silica
Accelerators	Increases reaction rate, reduces curing temperature, controls cross-link density	Imidazole, organophosphine

13.3.2 Category, physical/chemical properties

Flame retardants are substances used in plastics, textiles, electronic circuitry and other materials to prevent fires. Some of the technical flame retardant products contain brominated organic compounds including polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), tetrabromobisphenol A (TBBPA) and polybrominated biphenyls (PBBs). The structures for these are shown in Fig. 13.5. Many of these substances are persistent and lipophilic and have been shown to bioaccumulate.



13.5 The chemical structures of (a) PBDEs, (b) HBCD, (c) TBBPA and (d) PBBs.

PBDEs have low vapour pressures and are very lipophilic, with log K_{ow} values (octanol–water partitioning coeffcients) in the range 5.9–6.2 for TeBDEs, 6.5–7.0 for PeBDEs, 8.4–8.9 for OcBDEs and 10 for DeBDE. Experimentally determined subcooled vapor pressures for several BDE congeners were found to be lower than for comparably chlorinated PCBs, and decreased with increasing number of bromines. Halogen substitution pattern influences vapor pressure such that congeners with bromine substitution in the *ortho* positions to the ether bond have higher vapor pressures. TBBPA has a log K_{ow} of 4.5. The dimethylated derivative of TBBPA (MeTA) has a log K_{ow} of 6.4, making it more lipophilic than the parent compound. The log K_{ow} for HBCD is 5.8. PBDEs are persistent, have low water solubility, high binding affnity to particles and a tendency to accumulate in sediments. HBCD also has low water solubility, and probably also has an affnity for particles and sediments.

Flame retardants are added to polymers used in electrical and electronic products to ensure that they meet international standards. Typical applications and polymers used in the electronics industry are summarized in Table 13.6. Traditionally, the electronics industry has preferred to use BFRs such as TBBPA. However, a number of halogen-free flame retardants are now commercially available. Some of the main alternatives which are applicable to different polymer types used in the electronics industry are summarized in Table 13.7. To give an indication of the relative popularity of these flame retardants, Fig 13.6 analyzes the commonest types of flame retardant used in Swedish-made products in 1999.

13.3.3 Toxicity and hazards of brominated flame retardants (BFRs)

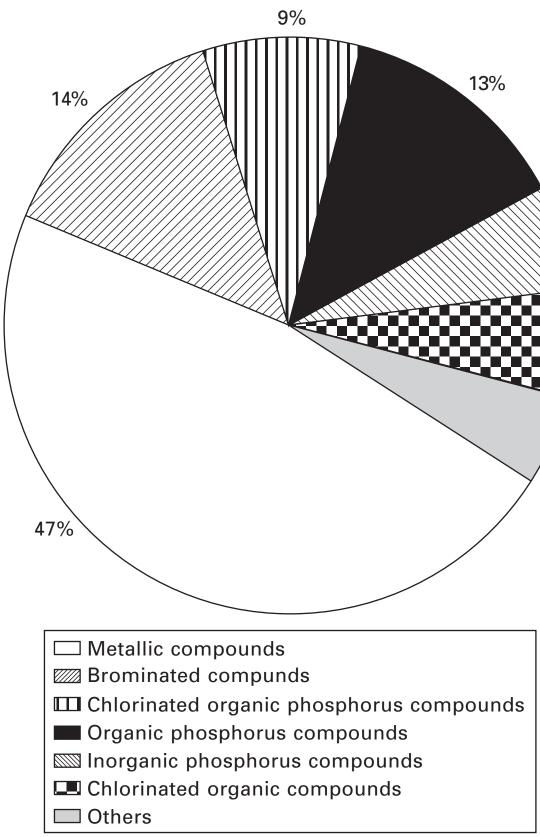
A schematic representing the environmental behaviour of BFRs is given in Fig. 13.7 (Watanabe and Sakai, 2003). Briefly, almost all BFRs used are the higher brominated compounds. The higher brominated compounds are less mobile in the environment, possibly because of their low volatility,

Table 13.6 Applications and polymers used in the electronics industry

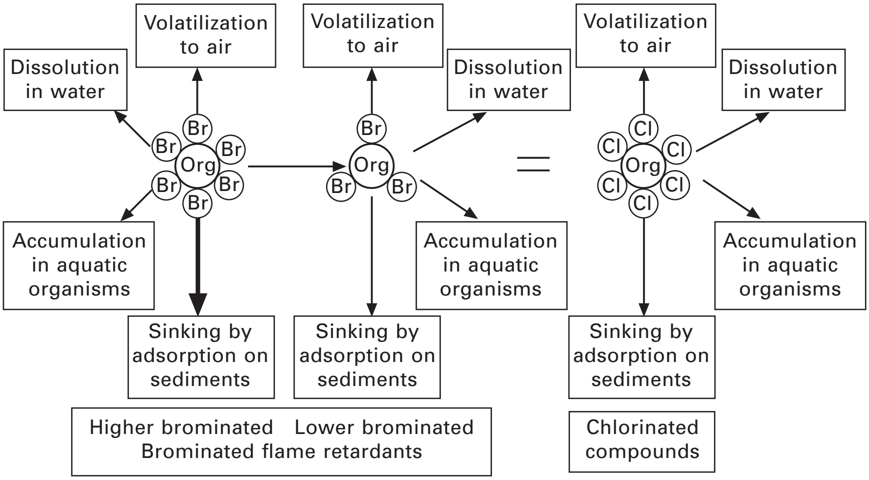
Application	Polymers used
Laminated PCBs	Epoxy, phenolic, polyamides
Encapsulants for electronic components	Epoxy
Housing for electrical and electronic equipment	ABS, HIPS, PC, nylons
Switches, sockets and connectors	PET, PBT, polyamides
Wire and cable insulation	PVC, ethylene-vinyl acetate (EVA), cross-linked polyethylene (XLPE)

Table 13.7 Halogen-free flame retardants applicable to different polymer types

Halogen-free flame retardant	Applicable polymer types
Aluminum trioxide	Epoxy, ABS, HIPS, PC, EVA, XLPE
Magnesium hydroxide	Epoxy, ABS, HIPS, PC, nylons, PVC, EVA, XLPE
Magnesium carbonate	ABS, HIPS, PC, PVC, EVA, XLPE
Zinc borate	Epoxy, nylons, PVC, EVA
Zinc hydroxystannate	PVC, EVA
Zinc stannate	Epoxy, nylons, PVC
Red phosphorus	Epoxy, phenolic, nylons
Ammonium polyphosphate	Epoxy
Phosphate esters	Phenolic, ABS, HIPS, PC, PVC, EVA
Melamine derivatives	ABS, HIPS, PC, nylons
Reactive P-N	Epoxy



13.6 Flame retardants used in Swedish-made products in 1999 (Source: www.kemi.se).



13.7 Schematic representation of environmental behaviour of brominated flame retardants.

water solubility, bioaccumulation and strong adsorption on sediments. The higher brominated compounds therefore tend to end up in sediments, at high residue levels, near their emission sources, rather than in marine organisms or humans. On the other hand, the lower brominated compounds, including environmental decomposition products of BFRs, are predicted to be more volatile, water soluble and bioaccumulative than the higher brominated compounds. The environmental behavior and fate of lower brominated compounds are thus thought to be similar to those of chlorinated pollutants, such as polychlorinated biphenyls (PCBs) and PCDDs/DFs.

13.4 Costs and benefits of recycling printed circuit boards (PCBs)

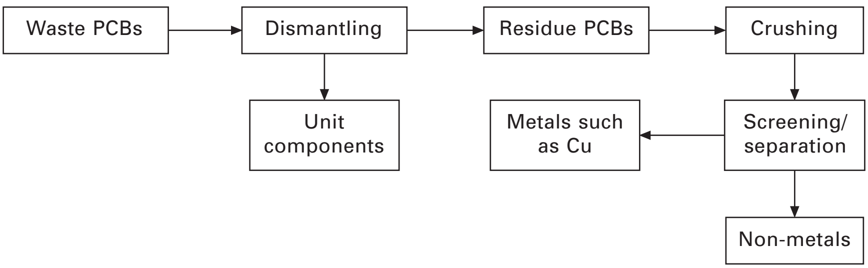
Waste PCBs form about 3% by weight of the total amount of waste electrical and electronic equipment. The economics of recycling for waste PCBs results in quite a large variety of materials being part of the whole assembly, with the possibility of significant environmental impacts arising from both the material resources use and the effects of disposal. Specifically, a significant proportion of the embodied materials are metals which are worth recycling as shown by the data in Table 13.8.

Regarding waste PCBs, highly available value and potential risk to environment and human health have determined that waste PCBs should be treated in environmentally sound manner. However, the recycling of waste PCBs is a huge challenge, because of the diversity and complexity of materials, components and manufacturing processes.

Table 13.8 The energy benefits of recycling materials commonly found in printed circuit boards

Material	Energy savings over virgin materials (%)	Material	Energy savings over virgin materials (%)
Aluminum	95	Zinc	60
Copper	85	Paper	64
Iron and steel	74	Plastics	>80
Lead	65		

Source: Cui and Forssberg (2004).



13.8 Mechanical processes for the recycling of waste PCBs.

13.4.1 Mechanical recycling process of printed circuit boards (PCBs)

PCB mechanical recycling can be broadly divided into two major steps (Fig. 13.8). The first is the disassembly and/or separation of different components and materials, generally using mechanical or metallurgical processing to upgrade the desirable material content. Shredding, electrostatic separation, supercritical extraction and pyrolysis are the main technologies employed in this step. The second step is the further separation or screening and processing of metal streams; this is probably the most important step from economic and environmental viewpoints. Many methods are available to extract metals from post-processing PCBs. These technologies are very different in terms of economic feasibility, recovery efficiency and environmental impact.

The most attractive research on dismantling process is the use of robots. Unfortunately, full (semi) application of automated dismantling for recycling of PCBs is greatly frustrating. In the practice of recycling of PCBs, selective dismantling is an indispensable process since: (1) the reuse of components has first priority, (2) dismantling the hazardous components is essential, and (3) it is also common to dismantle highly valuable components and high grade materials such as batteries in order to simplify the subsequent recovery of materials.

Most recycling plants utilize manual dismantling. A typical dismantling process is operated at Ragn-Sells Elektronikåtervinning AB in Sweden (Cui and Forssberg, 2004). A variety of tools is involved in the dismantling process for removing hazardous components and recovery of reusable or valuable components and materials.

The purpose of crushing is to strip metals from the base plates of waste PCBs. Crushing technology is intimately related not only to the energy consumption of crushing equipment, but also to further selective efficiency. Waste PCBs comprise reinforced resin and metal parts such as wires and joints. They have a high hardness and tenacity. Comminution of waste PCBs and high effective liberation of the metal composition from non-metals is a prerequisite of the following separation sequence for better recovery of waste PCBs. More often, two-step crushing is necessary for proper screening, as shown in Fig. 13.8 (Wen *et al.*, 2005).

Screening has not only been utilized to prepare a uniformly sized feed to certain mechanical process, but also to upgrade metals contents. Screening is necessary because the particle size and shape properties of metals are different from those of plastics and ceramics. The primary method of screening in metals recovery uses the rotating screen, or trammel, a unit which is widely used in both automobile scrap and municipal solid waste processing.

Shape separation techniques have been mainly developed to control properties of particles in the powder industry. The principles underlying this process make use of the differences between (1) the particle velocity on a tilted solid wall, (2) the time the particles take to pass through a mesh aperture, (3) the particle's cohesive force to a solid wall, and (4) the particle settling velocity in a liquid.

Magnetic separators, in particular, low-intensity drum separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Over the past decade, there have been many advances in the design and operation of high-intensity magnetic separators, mainly as a result of the introduction of rare earth alloy permanent magnets capable of providing very high field strengths and gradients.

Electric conductivity-based separation separates materials of different electric conductivity (or resistivity). There are three typical electric conductivity-based separation techniques: (1) eddy current separation, (2) corona electrostatic separation and (3) triboelectric separation. Corona electrostatic separation is an important technique feasible for fine particles with a size range of 0.6–1.2 mm. In corona electrostatic separation, the electrode system, rotor speed, moisture content and particle size have the greatest effect in determining the separation results (Ma *et al.*, 2006; Li *et al.*, 2007).

13.4.2 Costs and benefits of recycling technology/equipment

Along the life cycle of waste PCBs, costs and benefits of recycling technology are evaluated to cater for different countries. In order to assess the PCB recycling process, PCBs were assessed as around 1000 t per year (Xiang *et al.*, 2007).

Resource consumption

In this PCB recycling process, the electric energy consumption is about 140 kW per hour, which is the main cause of environmental impact. According to the structure of energy resources in Beijing (seen in Table 13.9) and emissions from energy formation processes (seen in Table 13.10), we can assess the environmental impact caused by energy consumption with Eq. (13.1). The results of environmental impact assessments are illustrated in Fig. 13.9.

$$EI(j)_i - \sum_{i-1}^{n} EI(j)_i - \sum_{i-1}^{n} Q_i \cdot EF(j)_i \qquad [13.1]$$

where Q_i is the emission of substance i; $EF(j)_i$ is the substance (i)'s equivalency factor for the environmental impact category j; $EI(j)_i$ is the emission's contribution to the environmental impact j.

The main environmental impacts are illustrated in Fig. 13.9. From Fig. 13.9, we can determine the environmental impacts caused by energy formation mainly include global warming potential, ozone-depletion potential, acidification and eutrophication.

Environmental impact of wastewater

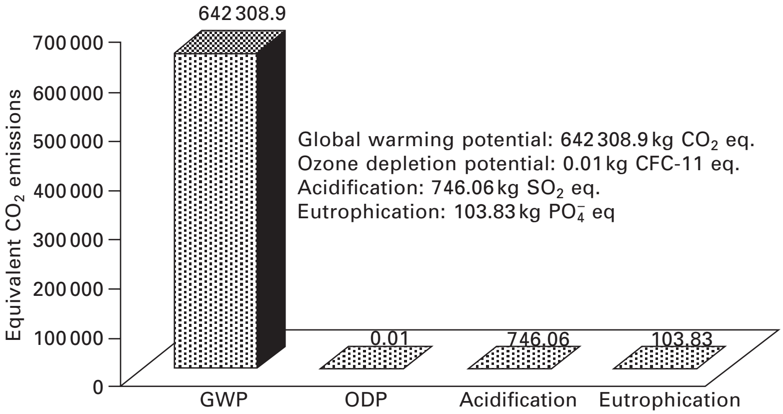
In the PCB recycling processes, the particles in the water will be separated with a shaking table. The metal particles can be collected directly. The non-metal particles are filtered with a microstrainer. The filtered water will be reused in smashing PCB chops and separating metal and non-metal particles, so only a little wastewater is emitted to the environment. Table 13.11 gives the metal ion contents in the wastewater. Obviously, the contents are much less

Table 13.9 The structure of energy resources in Beijing

Electric-power output (billion kW h)			Fuel used generating electric energy		
Hydro-electricity	Thermal power	Nuclear electricity	Raw coal (10^4 t)	Fuel oil (10^4 t)	Fuel gas (10^4 m^3)
9.49	162.57	0	628.64	40.69	33 285

Table 13.10 The emissions of the different styles for generating electric energy (1 TJ)

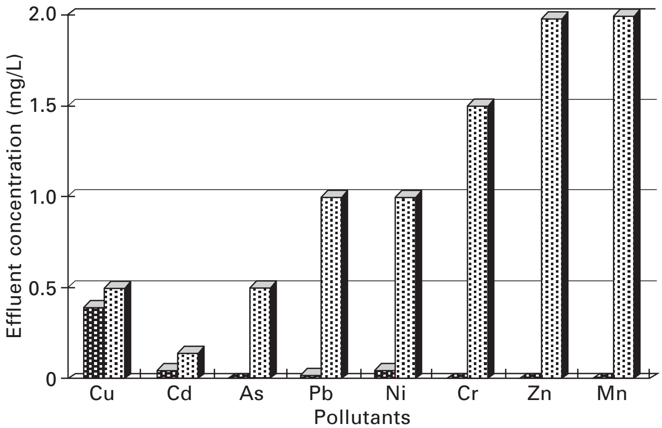
Style for generating electric energy	Emissions (kg)	Discharge amount
Electricity by fuel gas	CO_2	208 705
	Dinitrogen oxide	419
	HALON-1301	0.000438
	Methane	496
	Nitrogen oxides (as NO_2)	418.17
	Sulfur dioxide	91.5655
Electricity by raw coal	CO_2	270 413
	Dinitrogen oxide	703
	HALON-1301	0.000655
	Methane	1169
	Sulfur dioxide	1107.87
	Nitrogen oxides (as NO_2)	702.048
	Nitrate	6.43825
Electricity by fuel oil	CO_2	242 085
	Dinitrogen oxide	548
	HALON-1301	0.01794
	Methane	308
	Sulfur dioxide	2542.58
	Nitrogen oxides (as NO_2)	543.756
Hydro-electricity	CO_2	1108
	Dinitrogen oxide	0.016
	HALON-1301	0.0000185
	Methane	2.45
	Nitrogen oxides (as NO_2)	4.25727
	Sulfur dioxide	3.06571



13.9 The environmental impacts of energy consumption of PCBs.

Table 13.11 Metal ions content of 1 liter wastewater (mg/L)

Metal ion	Content	Metal ion	Content
Cu	0.42	Pb	0.02
Au	0.02	Sn	0.05
Cd	0.015	Ni	0.04
Pd	0.14		



13.10 Comparison between emissions to wastewater and the emission standard.

than the city pollution exhausts criteria of China. Figure 13.10 illustrates the comparison between wastewater and Chinese pollution exhaust criteria.

According to every metal amount in wastewater in Table 13.11 and the equivalency factor in Table 13.12, the environmental impacts of wastewater can be estimated with Eq. (13.1). The results are: environmental impact on freshwater aquatic ecotoxicity = 655.2 mg 1,4-dichlorobenzene eq., and environmental impact on freshwater sedimental ecotoxicity = 1609.3 mg 1,4-dichlorobenzene eq.

Human health damage caused by physical process of PCB recycling

Because of the adoption of the spray water process and the sound insulation measures, there is little human health damage resulting from industrial dust and noise from the above analysis. Thus we mainly analyzed the damage from the metal ions in wastewater. According to Table 13.11, the main metal ions in wastewater are Cu, Au, Cd, Pd, Pb, Sn, Ni and Ag. However, there are five substances which cause damage to human health, viz. Cu, Cd, Pb, Sn, and Ni. With Eq. (13.1) and the equivalency factor for human toxicity in Table 13.13, we can get the emission's contribution to human toxicity, which is shown in Table 13.13.

Table 13.12 The environmental impacts of metal in wastewater (mg 1,4-dichlorobenzene eq)

Metal ion	Cu	Cd	Pb	Sn	Ni
Equivalency factor for freshwater aquatic ecotoxicity	1.2E3	1.5E3	9.6	1.0	3.2E3
Environmental impact on freshwater aquatic ecotoxicity	504	22.5	0.192	0.5	128
Total of environmental impact on freshwater aquatic ecotoxicity			655.2		
Equivalency factor for freshwater sedimental ecotoxicity	2.9E3	3.9E3	2.5	5.2	8.3E3
Environmental impact on freshwater sedimental ecotoxicity	1218	58.5	0.5	0.208	332
Total of environmental impact on freshwater sedimental ecotoxicity			1609.3		

Table 13.13 The human toxicity of metal in wastewater (mg 1,4-dichlorobenzene eq)

Metal ion	Cu	Cd	Pb	Sn	Ni
The equivalency factor for human toxicity	1.3	2.3	1.2	1.7E-2	3.3E2
Environmental impact on human toxicity	0.546	0.345	0.24	8.5E-4	13.2
Total of environmental impact on human toxicity			14.3		

The best available technology used in developed and less-developed countries will be separately recommended.

Primitive open-soldering methods used in less developed countries

In China, immature technologies are the main obstacle to the recycling of waste PCB assemblies. During the manual dismantling process in informal dismantling and recycling sites, e-recyclers use chisels, hammers and cutting torches to open solder connections and separate various types of metals and components. PCB assemblies, which are more complicated and difficult to process, are simply cooked on a coal-heated plate and melted (on the iron plate or flat wok) in order to resell the chips and other recovered components to acid strippers for further processing. A pungent smell permeates workshops, accompanied by black fumes rising from the cooked scraps (Liu *et al.*, 2006; Huang *et al.*, 2009). Such a manual dismantling process was applied in China more than 10 years ago, but it has been prohibited according to Chinese law recently. In fact, the said technology is still employed with simple improvement by using electric heating plate, which is semi-enclosed, temperature-controllable, and comprised exhausted gases collector.

The fact that the PCB assembly is one of the fastest growing sources of waste in many developing countries has focused attention on the need to recycle, recover and reuse materials that have been consigned to informal dismantling sites. In India or Nigeria, the above mentioned methods have been widely used as well. The major common point of these disassembling technologies is the recovery of the solder remaining on the board by subjecting it to a temperature greatly higher than the molten point of the solder. In these processes of PCB assembly dismantling, pyrolysis under high temperature heating, during which the toxic products from resins and adhesives are decomposed, is common (Williams *et al*., 2008).

Intelligent and automatic approaches and their application

A flexible automated cell for PCB assemblies dismantling has been proposed and described in several publications (Brandstotter *et al*., 2004; Yi *et al*., 2007). First, the PCB assemblies are fixed on frames and fed into the dismantling cell. Next, a recognition system with an image-processing 'Vision System' identifies reusable parts and toxic components on the PCB assemblies, by comparing the shape and labels of the parts with a database containing information from manufacturers and information from the reuse market. The dismantling cell removes reusable and hazardous components from various PCB assemblies and produces PCB assemblies which are less environmentally hazardous and electronic components suitable for reuse.

Legarth *et al*. (1995) reported another automated method for disassembling PCB assemblies as follows. The first step in the selective dismantling is to identify and obtain information about the PCB assembly via three-dimensional pictures. Picture-processing algorithms give statements about components of interest and extract data on how to disassemble them, such as coordinates and rotation angles. Only sockets and solder joints are separated. Application of small amounts of force and heat such as hot air and a vacuum gripper may be used. Surface-mounted device (SMD) components, hot liquid and a parallel-jaw gripper are employed to disassemble through-hole device (THD) components. The task of the simultaneous dismantling module is to evacuate the entire PCB.

Another automatic disassembly system has been developed by NEC Corporation (Li *et al*., 2006). The system comprises two heating units and two removal units. The first removal unit is equipped with impacting propellers and PCB assembly reversing arms. The second removal unit is equipped with shearing propellers. The PCB assemblies are fixed to a holder in either a vertical or a horizontal configuration. There is no identification module in this system; however, before the disassembly process, the forces required to remove components are calculated according to the connection type and direction configuration. Actually, owing to the complexity and high cost of equipment, such automated methods can rarely be practiced, particularly in China.

Semi-automatic approaches and their application

Compared with automated approaches, a semi-automated method is flexible. A more practical technology, known as a semi-automated approach, has been developed for the recycling of PCB assembly. The electrical connectors (ECs) on the PCB assemblies are removed by a combination of heating them to above the melting point of solder and applying such external forces as impact, shearing and vibration. The recycling ratio of useful materials recovered from a test PCB assembly using this method was 65%, compared with 23% using a traditional method of refining useful metals from PCB assemblies.

In order to control appointed temperature and heating rate during the dismantling process, an updated semi-automated PCB assembly dismantling cell has been developed by Chinese researchers, which is commercially applied. It includes the following subsystems or units: sequential heating units; a part-removal unit; a PCB assembly transport system; a solder-removal unit; and a component-collection unit. This system controls the PCB assembly's heating rate effectively by matching the temperatures of the six heating units and the velocity of the PCB assembly's progress through the dismantling cell. The heating technology, which could be called a semi-automatic approach, has been successfully used by an e-waste recycling company in China. In the case of Beijing, the equipment, which comprises a heating system (electric resistant tube, exposed to air) at a temperature of 250°C, exhausted gas controlling stall, and conveyor belt to collect bare board, has been used, and the capacity is 800 kg per day (Ding *et al*., 2008; Gao *et al*., 2008).

13.5 Challenges and future trends

13.5.1 Dismantling

Dismantled PCB assemblies have a significant environmental impact because they contain heavy metals and halogen-containing flame retardant, such as lead (soldering tin), mercury (switches, round cell batteries), cadmium (pins), brominates and mixed plastics that can seep into the environment if not properly managed. Cell batteries may ignite or leak potentially hazardous organic vapors if exposed to excessive heat or fire. An explosion may result if a capacitor is subjected to high currents and heating. Thus, in this process, round cell batteries and capacitors that are large or that contain polychlorinated biphenyl should be manually removed and separately disposed of in an appropriate way. The circuit boards can then be sent to a facility for further dismantling (for reuse or reclamation from integrated circuits (ICs) which contained precious substances or soldering tin) and copper recovery (from bare board) works. Hg switches are being phased out. The main sources of Hg and Cd are accumulators on PCB assembly. Substitutes for lead in solders are currently being developed, but are not yet in production (Duan *et al.*, 2011).

While the melting of soldering tin could lead to the separation and recycling of electronic components, in addition to the melting of soldering tin, the mechanical strength of the pin which is packaged to the through hole is another key factor in separating the components. The strength required to dismantle electronic components depends on the number of pins, their arrangement and mass. For through-hole device (THD) packaging, the strength needed to successfully disassemble components is dependent on: liquid adhesion of the solder tin, mass/gravity of components (in favor), and bending resistance of the pin inserted in the through-hole. The resistant strength against dismantling is influenced by the adhesion force of the liquid solder tin (if heated) and the mechanics of the bend of the pin. When heating soldering tin, the strength induced by the superimposed layer consisting of compounds having certain copper/tin ratios is transferred into adhesion strength located in welding sites.

To open soldered connections, it is recommended that a solder bath temperature between 40 and 50 °C higher than the melting temperature of the solder is used for effective dismantling. The surface-mounted components hanging down or on the surface are removed due to their own gravity or vibration, whereas the components with through-hole mounting are removed with the help of a brush or rotary steering.

13.5.2 Recovery of copper and precious metals

In developing new technology for waste PCBs, most researchers have focused on the technology by which the valuable metals in PCBs can be separated and recovered. For a long time, the major economic driver for recycling of waste PCBs has been the recovery of metals. Initially, the simple incineration (uncontrollable incineration, open burning, etc.) was adopted to recover metals from waste PCBs. As this process lacked effective environmental protection and posed a threat to human health, it was banned in China. Consequently, pyrometallurgy and pyrolysis were developed based on this thermal process (Quan *et al.*, 2010).

Pyrometallurgy is a traditional technology for recovery of non-ferrous metals as well as precious metals from waste PCBs. Pyrometallurgy includes incineration, smelting in a plasma arc furnace or blast furnace, drossing, sintering, melting and reactions in a gas phase at high temperature. Pyrolysis is the chemical decomposition of organic materials by heating in the absence of oxygen or any other reagents. Pyrolysis of organic materials contained in waste PCBs leads to the formation of gases, oils and chars which can be used as chemical feedstocks or fuels. At present, there are some pilot-scale studies on the recovery of metals from waste PCBs by pyrolysis in China (Li *et al.*, 2010). A new process of 'centrifugal separation + vacuum pyrolysis' for recovery of solder and organic materials from waste PCBs was studied and developed (Zhou and Qiu, 2010).

Hydrometallurgy is another traditional technology for the recovery of precious metals from waste PCBs. The main steps in hydrometallurgy consist of a series of acid or caustic leaches (cyanide leaching, halide leaching, thiourea leaching, and thiosulfate leaching, etc.) of solid materials. The solutions are then subjected to separation and purification procedures such as precipitation of impurities, solvent extraction, adsorption and ion-exchange to isolate and concentrate the metals of interest. Consequently, the solutions are treated by electrorefining process, chemical reduction or crystallization for metal recovery.

The mechanical-physical recycling process for waste PCBs is based on the differences of materials in physical characteristics (including density, magnetic susceptibilities, electric conductivity, etc.). Owing to its improved environmental properties (such as less wastewater), high efficiency and easier operability, additionally non-ferrous metals and precious metals contents have gradually decreased in concentration in PCBs. In the above integrated recycling process for waste PCBs, the materials coming out of separators are metallic and non-metallic. There are about 30% metallic materials after separation. These metallic materials are hard to recover, because the fractions concentrated on metallic materials obtained from these processes are still a mixture of various metals (copper, aluminum, lead, zinc, etc.) (Yoo *et al.*, 2009). Until now, there have been no proper methods to separate the various metals or recover them. The existing mechanical technologies (pneumatic separation, electrostatic concentration, etc.) focus on recover the copper, but the studies on further separation of the mixed metals are relatively fewer in China (Wu *et al.*, 2009). In order to further separate the concentrated fraction in metals and increase the copper content in the metallic mixture, vacuum metallurgy separation method was presented in some studies (Huang *et al.*, 2009).

13.5.3 Recycling and recovery of the non-metallic materials

According to their applications and properties, synthetic polymers can be classified as plastic, rubber, fiber, adhesive, etc. Plastics include thermoplastic plastics and thermoset plastics. Plastics consist of resin, filler and addition agents. In general, the fillers for polymers have two functions: one is to reduce the cost of the products, and the other is to enhance the performance of the products. Sometimes the properties of fillers are crucial to the performance of polymer products, especially for composites. The invention of glass fiber reinforced composites has great influence on space aeronautical industry and other industries. Nowadays, superior performance fillers play a key role in high-tech material areas. Therefore, how to take advantage of filler for polymer products is a significant topic.

Zheng *et al*. (2009a,b) studied a novel fluidized bed process technology for recycling glass fibers for non-metallic materials. This process can produce a clean flue gas without violating environmental regulations. Physical recycling of the non-metallic fractions is a promising recycling method without environmental pollution and with reasonable equipment investment and low energy cost. More work should be done to develop comprehensive and industrialized usage of the non-metallic fractions recycled by physical methods. The trend in chemical recycling of the non-metallic fractions from waste PCBs is to make the most of advantages over physical recycling of the non-metallic fractions to compensate the higher cost of chemical recycling methods. Removing and treating hazardous substances contained in the non-metallic fractions is an ultimate method to eliminate the pollution. However, research on this topic is just in its infancy and the challenges caused by technical and economic feasibility should not be underestimated. To obtain a clean separation between the metallic fractions and the non-metallic fractions from waste PCBs is a way of reducing the contents of heavy metals in the non-metallic fractions and thus a way of reducing the potential environmental risk for the recycling of the non-metallic fractions. Catalytic hydrogenation can be an effective method to eliminate the most of hazardous toxic compounds in the oil produced by chemical recycling of the non-metallic fractions from waste PCBs (Guo *et al*., 2009).

Except for recycling of non-metallic materials, recovery using a thermal method is traditionally important for organic waste such as waste plastic to achieve high quality energy. It is estimated that if all of Europe's waste plastic which it is not feasible to recycle were turned to energy, it would be equivalent to at least 17 Mt of coal. Additionally, plastics can also be co-incinerated with other combustible products from the waste stream, which will contribute even more to the reduction of greenhouse gases through prevention of the emission of methane gas from landfill (Tange and Drohmann, 2005). And besides, the WEEE Directive in Europe has adopted for many years a collection target of 4 kg of WEEE. Now most of the countries have overpassed the target and the directive is proposed to revise (Ongondo *et al*., 2011). Therefore, a large amount of WEEE has improved the probability for non-metallic materials to recover energy by thermal process.

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14
Recycling liquid crystal displays

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Abstract: The WEEE Directive states that mercury-containing backlights used in liquid crystal display (LCD) panels, are hazardous and must be removed. With little data available on the recycling techniques required for LCDs, the electronic waste management industry is uncertain as to the best practical environmental options for their treatment. The most appropriate process for the waste industry will be based on the following: (i) composition, (ii) treatment processes, (iii) material recovery and (iv) environmental protection. These challenges are now facing the recycling industry in their endeavour to process LCDs and to be prepared for their successor technologies. This chapter will outline the important issues to consider when recycling display equipment.

Key words: LCD, WEEE, mercury, electronics, displays, televisions, monitors.

14.1 Introduction

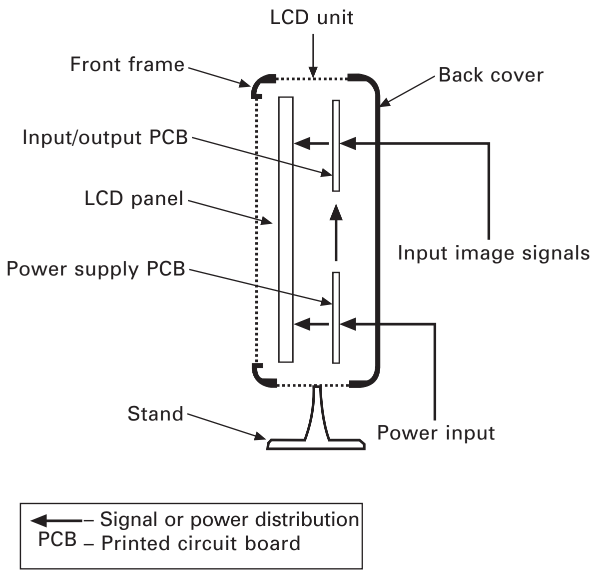
Liquid crystal displays (LCD) have become the dominant technology in televisions and monitors in our homes and offices (Torii, 2009). This has led to LCDs displacing traditional cathode ray tube (CRT) equipment within the display waste stream (Armishaw *et al*., 2007). However, as yet the electronic recycling industry has only received low volumes of LCDs into their waste stream. This is because the majority of LCDs are still in their working phase. The longevity of CRT in the marketplace has seen the development of specific recycling techniques to process this technology (Menad, 1999). In contrast, the rapid emergence of LCDs onto the market has meant that little is known about their composition (McDonnell and Williams, 2010a) and how to process them. Under the EU Waste Electrical and Electronic (WEEE) Directive both CRT and LCD technologies are classed as hazardous waste, requiring the selective removal of components and substances of concern (EU Commission, 2003a). This chapter discusses the treatment of waste LCD from a recycling perspective. It includes not only legislation and technology but also the many environmental challenges faced by the industry.

When one considers any recycling processes for LCD, the most important factors are: (i) the material composition and (ii) the location of any hazardous components within the equipment. The removal of the hazardous components and the associated environmental protection requirements are intrinsic to the recycling process (European Parliament, 2008). As a direct result, increasing legislative controls and best practice standards will eventually be applied to the waste management industry that recycles LCD (McDonnell, 2011; WEEE Forum, 2011). The recovery of valuable materials is paramount to the viability of any recycling operation. Changes in technology and costs of repair and refurbishment are all factors which will either promote or act as barriers to re-use. Current industrial processes that have been developed and are under development are discussed. The future trends in LCD technology and their eventual succession by new technologies are reviewed.

14.2 Liquid crystal displays (LCDs)

14.2.1 Composition and characterisation of LCDs

A typical construction of LCD monitors and televisions consists of a front frame surrounding a flat display panel revealing the screen. The LCD panel is secured to the front frame and the removable back cover is attached to the front frame by an array of screws. Figure 14.1 is an exploded side view schematic showing the front frame, back cover and typical components in LCD equipment. Display image signals and power connections are introduced through rear panel electrical connectors to electronic printed circuit boards (PCB) servicing the LCD panel.



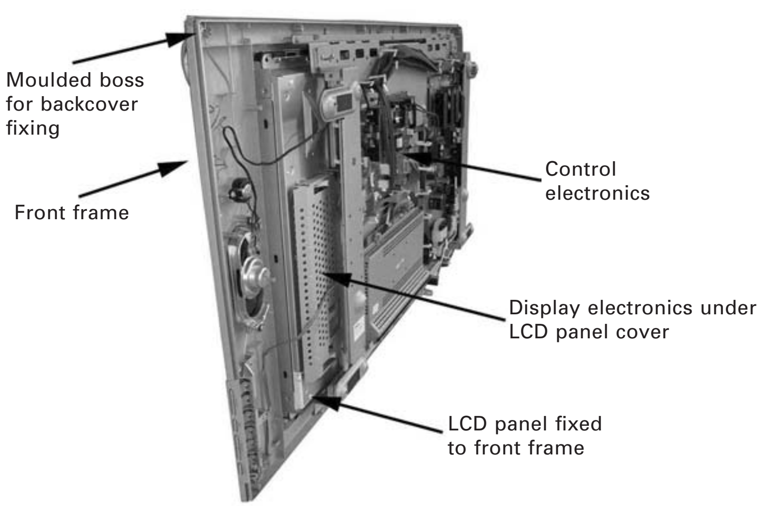
14.1 Exploded schematic of typical components contained in LCD equipment.

Figure 14.2 shows a typical construction of an LCD television with the back cover removed. Front frame and back covers are manufactured from injection moulded plastic with integral fixing bosses. These bosses provide anchor points for: (i) metal brackets to secure the LCD panel in the front frame; (ii) locating structural steelwork to provide unit rigidity; (iii) attaching loudspeakers; and (iv) securing the back cover.

The LCD panel is a self-contained unit fitted with all the necessary electronics to form images on the screen (Fujitsu, 2006). An LCD television or monitor can therefore be conveniently divided into two areas: (i) support components and (ii) the LCD panel (Williams and McDonnell, 2010). However, the LCD panel is not a suitably rigid structure to carry all the support components. Therefore, increasing quantities of pressed steel supports and frameworks are used in LCDs to provide rigidity and anchor points. In LCD monitors, it is usual to find a pressed steel frame to: (i) carry the LCD panel; (ii) provide an anchor for the equipment stand; and (iii) provide fixing points for electronic boards. In contrast, for LCD televisions an interlinking set of pressed steel supports are used to: (i) connect together the front frame, the LCD panel and the electronic boards and (ii) provide an anchor point for the stand.

As the LCD equipment screen size increases the steel content also rises. Tables 14.1 and 14.2 show the typical material composition of a 15″ screen size LCD monitor and a 37″ screen television. It is clear from Tables 14.1 and 14.2 that the highest material weight is that of steel followed by plastics contained in the support components (front frame and back cover) and finally the LCD panel.

Composition of the monitor and television shows that the LCD panel



14.2 Typical LCD panel mounted in front frame of 37″ television.

Table 14.1 Compositional analysis of a 15″ LCD monitor (adapted from McDonnell, 2011)

Support components	kg	LCD panel	kg
Internal steel	1.14	Aluminium back and frame	0.11
Plastics ABS/HIPS	0.79	Plastics	0.44
Electronics	0.30	LCD screen and electronics	0.30
Cables	0.20	Backlights	0.03
Others	0.08	Cables and others	0.01
Total for components	2.51	Total for LCD panel	0.89

ABS/HIPS = acrylonitrile-butadiene-styrene/high impact polystyrene.

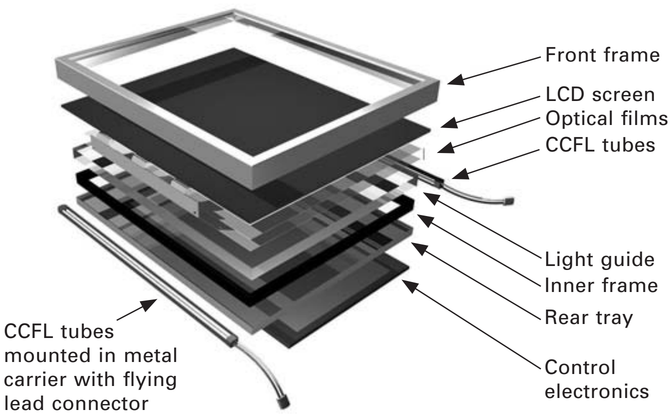
Table 14.2 Compositional analysis of a 37″ LCD television (adapted from McDonnell, 2011)

Support components	kg	LCD panel	kg
Internal steel	4.94	Steel frame and back	6.07
Plastics ABS/HIPS	3.40	Plastics	1.57
Electronics	1.47	LCD screen and electronics	1.95
Cables	0.28	Backlights	0.24
Others	0.33	Cables and others	0.41
Total for components	10.42	Total for LCD panel	10.24

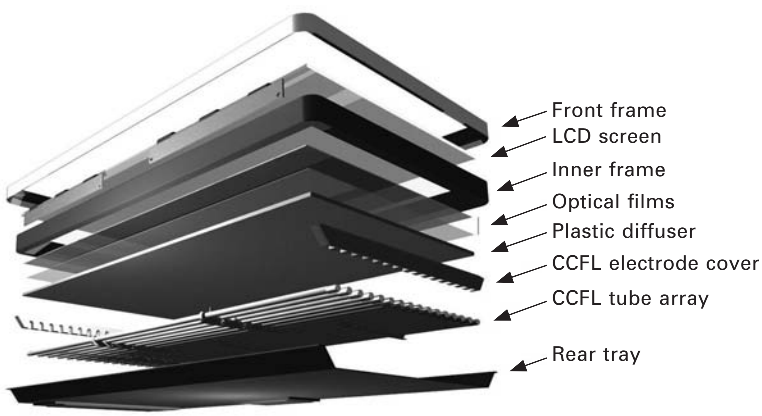
represents 26% and 49% of the unit weight respectively. To achieve the WEEE Directive material recovery targets of 75% of the monitor or television, the LCD panel must be disassembled for material recycling (EU Commission, 2003b). The disassembly and separation of the support components only would be insufficient to meet the Directive's material recovery targets.

The LCD panels are self-contained units, fitted with all the necessary electronics to process images on the screen. Liquid crystal screens are light transmissive with images formed by arrays of primary colour filters arranged as pixels. The unique properties of liquid crystal allows light to be twisted by the alignment of liquid crystal molecules to form a prismatic effect. The use of light polarisation filters orientated at different angles provides a method of creating a light shutter when the crystal is subject to an electric field. By controlling the time the light shutter is operative in the three colour pixel determines the shade of colour at that point. The combination of thousands of these controllable pixels allows the formation of colour images on the screen. The light sources used to create bright screen images in the majority of LCDs are compact tubular fluorescent lamps known as cold cathode fluorescent lamps (CCFL) (Fujitsu, 2006). These lamps contain small amounts of mercury to create vapour discharge during operation. The discharge of ultraviolet radiation excites a mix of phosphors lining the tube, creating a high intensity white light source (Kahl, 1998). The CCFLs are arranged to provide rear screen illumination. It should be noted that there are different lamp configurations in monitors and television displays. In monitors there are typically one to three lamps mounted in carriers at the top and bottom of the screen edges. These lamps light a polymethylmethacrylate (PMMA) light guide to create screen illumination; see Fig. 14.3. This is in contrast to televisions where the CCFLs are arranged in arrays across a rear light tray behind the screen; see Fig. 14.4 (McDonnell and Williams, 2010a). The number of lamps used in the television array increases as a function of screen size. Figure 14.5 shows the average number of lamps used with the varying screen sizes of LCD monitors and televisions (McDonnell and Williams, 2010b).

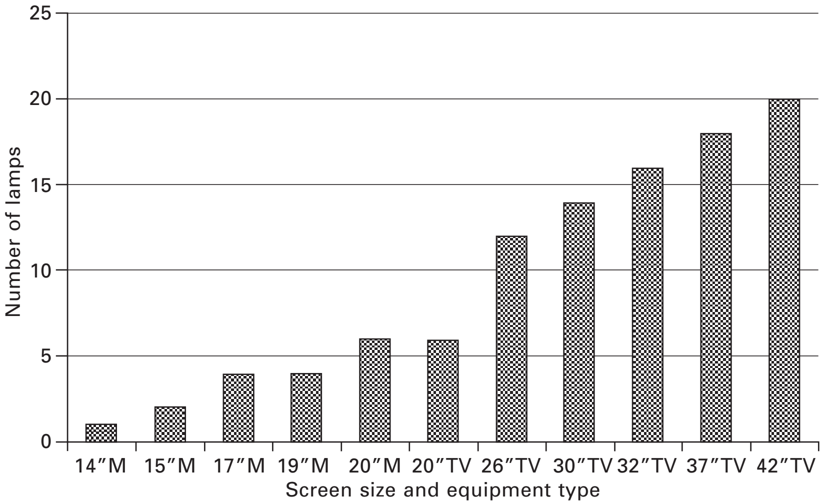
The construction used by manufacturers of monitor display panels for locating and electrically connecting lamps is common across the industry.



14.3 Typical construction of a 15″ screen LCD panel.



14.4 Typical construction of a 37″ television panel.



14.5 Number of CCFL lamps contained in LCD monitors and televisions (M = monitor, TV = television).

The majority of lamps are mounted in 'U'-shaped channel metal carriers. These lamps are connected to the control electronics by electrical flying leads terminated in plug style connectors, illustrated in Fig. 14.3. The CCFL carriers are usually retained in position with a single screw fixing. However in contrast, the method of fixing and electrically connecting lamps in television panels varies with LCD panel manufacturer. The most widely used configuration is a series of lamps mounted in a distributed array as shown in Fig. 14.4. The number of CCFL lamps used in LCD monitors and televisions increases with screen size as shown in Fig. 14.5. It should be noted that television screen sizes >20″ contain more lamps due to the change from lamp carriers (used in monitors) to lamp arrays in televisions (Figs 14.3 and 14.4).

In the majority of television panels straight lamps are held in place using a variety of methods such as crimping, rubber mounts or solder jointed at either end. In contrast to the monitors, where CCFLs can be easily removed from the panel, the removal of lamps from televisions requires full panel disassembly.

14.2.2 Barriers to recycling of LCDs

LCDs in common with CRTs are classed as hazardous waste under the WEEE Directive (EU Commission, 2003b). The Directive requires that this form of WEEE must be separately collected and that hazardous components listed in the Directive's Annex II must be removed during treatment. The principal components in the LCD panels of concern are the LCDs and the mercury-containing backlights. However, the hazardous nature of liquid crystal has been changed on the release of a briefing note from the UK Environment Agency in 2010 stating 'liquid crystal displays which do not contain mercury backlights or where these have been removed are classed as non-hazardous' (Environment Agency, 2010). This leaves the mercury-containing backlights as the only key hazardous component contained in the majority of LCD monitors and televisions in this particular waste stream. The rapid emergence of LCD onto the multimedia display market has meant that relatively few have entered the electrical waste stream. Consequently the recycling industry's focus so far has been solely on the CRT waste stream, treating LCD as more of annoyance than a serious waste stream (Allen, 2008; McDonnell and Williams, 2010b). The industrial focus on CRTs was confirmed by research in 2009 which showed that LCDs represented only 2% of the display waste stream (McDonnell and Williams, 2010a). This was also supported by another independent European study (Krukenberg, 2010). In 2010, a follow-up study showed that this percentage had risen to 3.6% (McDonnell, 2011) and this trend is set to increase.

The rising volume of this waste stream has understandably turned the attention of the display recycling industry to the challenges that LCDs pose. A far too common criticism from the recycling industry has been the lack of data available on the construction and the material content of this equipment (Lim and Schoenung, 2010; Rifer *et al*., 2009). This has meant that recycling techniques for LCD have remained underdeveloped (Eastern Research Group Inc., 2007). The lack of techniques to effectively deal with LCD has been highlighted in the EU WEEE Review report conducted by Huisman *et al*. (2007) who concluded that the environmental risk from mercury escape during treatment was a key issue. The report suggested that the environmental protection regarding the mercury recovery had priority over the economic costs of developing the processes (Huisman *et al*., 2007). From a recycling perspective this means the removal of the mercury for recovery is the priority in the treatment process (McDonnell, 2011). The lack of familiarity with LCD in the industry has left the development of recycling techniques for this equipment as a 'wait and see' policy leaving a few companies to 'trail blaze' new technologies. However, it is clear that the volumes of waste LCD are rising and WEEE display recyclers will have to tackle LCD as the traditional CRT volumes diminish. The reluctance of some sections of the display recycling industry to become 'LCD prepared' could be a false economy as environmental mis-management of this waste stream could ultimately be a costly mistake in prosecutions and reputation loss.

14.3 Recycling processes for liquid crystal displays (LCDs)

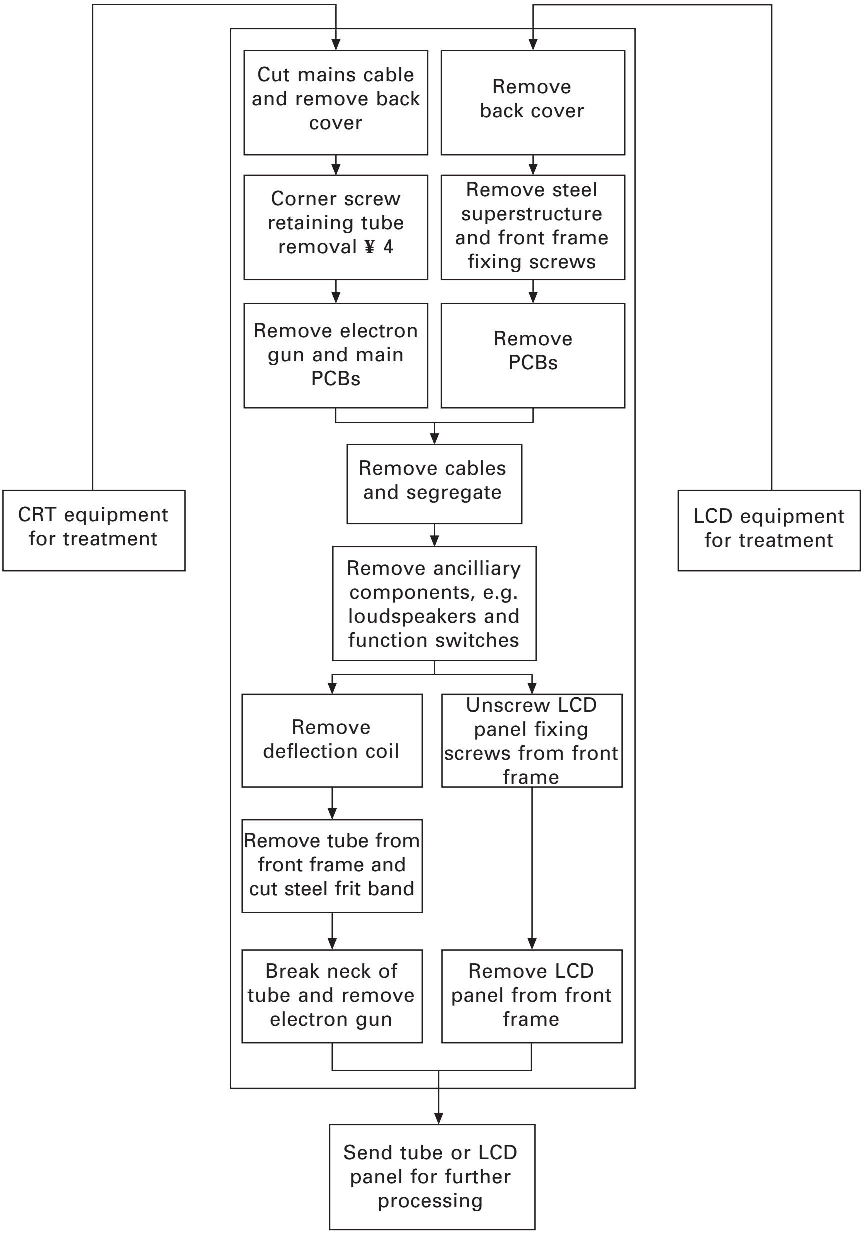
14.3.1 Manual disassembly

As the LCD waste stream develops, display recycling facilities will have to turn their attention to developing suitable disassembly lines for LCD. The current techniques for manual disassembly of CRTs require the removal of the tube from the equipment for separation and removal of leaded glass and screen phosphors. The robust nature of the CRT tube means that the equipment casing, electronic control and image display PCBs are arranged around this central structure. More importantly, from a disassembly perspective, the low number of fasteners (<25) and the strength of the tube means that removal of components can be a mix of fastener removal and destructive techniques to recover the tube. However, in the case of LCDs the fragile nature of the display requires the extensive use of metal support structures connected to the display panel and the plastic framework (Fig. 14.2). Consequently, the number of screw fasteners requiring removal during the disassembly of typical 37″ LCD television is 154 (McDonnell and Williams, 2010a). From a recycling perspective this will increase the labour content of manual disassembly of LCD.

The manual disassembly processes of LCD and CRT displays are similar with the initial objective to remove the display medium (display panel in LCD and the tube in CRT). The flow diagram for the disassembly of both types of equipment to recover the display medium is illustrated in Fig. 14.6.

In the case of LCD the removal of the support components around the display panel is the first stage of the disassembly. Once the LCD panel is removed, the second stage is to recover the mercury-containing backlights. This now presents a challenge to the recycler as the configuration of CCFL backlights differs between LCD monitors and televisions (Figs 14.3 and 14.4). As previously discussed the CCFL in LCD monitors are arranged in metal carriers fitted at the top and bottom of the screen. Typical screen panel sizes range from 15″ to 20″ and are typically fitted with two to six lamps. Some lamps are easy to remove by manually withdrawing the metal lamp carrier after releasing a securing screw as illustrated in Fig. 14.7.

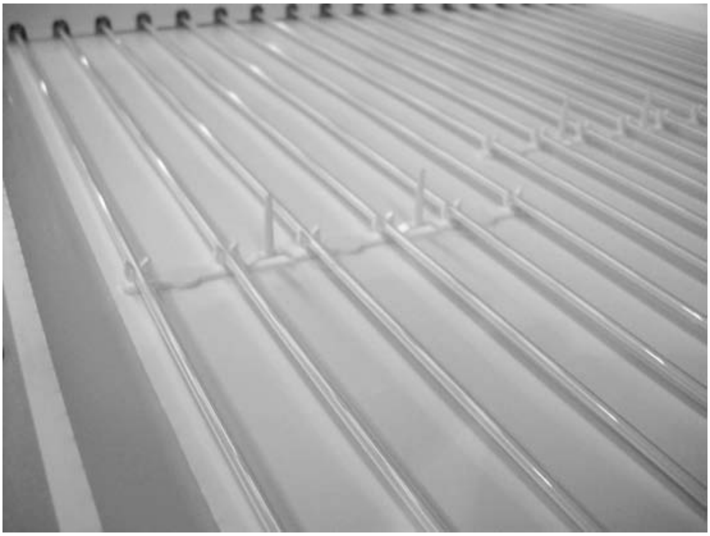
However, with many screen panels this is not the case. The varying amount of difficulty means many will require full panel disassembly. From a recycler's perspective this makes the removal of the lamps more difficult and thereby increases the chance of breakage and mercury release. LCD televisions with screen sizes over 20″ use arrays of backlights mounted in a pressed metal tray behind the screen. Invariably these trays have no access to the backlights from the rear of the display. Therefore, their recovery will always require full panel disassembly. The construction of LCD panels in the majority of equipment are designed for manufacturing assembly with



14.6 Manual disassembly flow diagram for LCD and CRT equipment.

little regard for end-of-life dismantling (McDonnell, 2011; Rifer *et al.*, 2009). This is demonstrated by the use of the following: (i) barbed clips; (ii) assemblies designed for component insertion/retention; and (iii) large numbers of screw fasteners. This necessitates a sequence for the removal of

14.7 Removal of CCFL in metal carrier from a 15″ monitor LCD panel.



14.8 CCFL backlight array in the rear tray of an LCD television panel.

components which would be: (i) the front frame; (ii) liquid crystal screen; (iii) inner frame; (iv) optical films; and (v) plastic light diffuser to finally reveal the arrays of CCFL backlights (Fig. 14.8).

Figure 14.8 shows a typical arrangement of conical plastic spacers to support the following parts: (i) plastic light diffuser; (ii) optical films; and (iii) liquid crystal screen. As part of their construction they also serve to securely locate the glass tube of the long CCFL backlights. The barbed cradles securing the CCFL tubes are designed for insertion and retention of the tube on panel assembly. The ends of the tubes are fixed under polycarbonate end covers with manufacturers using a variety of fixing methods. The most common are:

- mounting the tube in an elastomeric moulded rubber fixing with electrical connection by insulated flying lead;
- insertion of the tube wire end into a PCB-mounted crimp connector;
- direct soldering of the wire end of the tube into a strip PCB mounted in the polycarbonate tube cover.

The difficulty in dismantling LCD panels is an issue that has been addressed by the EU in establishing revised ecological criteria for the award of Community Eco-Label to televisions (EU Commission, 2009a). This Commission Decision clarifies the requirements manufacturers must meet for design for disassembly (DfD) in the product. The significant (DfD) requirements (adapted from EU Commission, 2009a) from a recycling perspective in facilitating dismantling are:

- fixtures within the television shall allow for its disassembly, e.g. screws, snap-fixes, especially for parts containing hazardous substances;
- plastic parts shall be of one polymer or be of compatible polymers for recycling and have the relevant ISO11469 marking if greater than 25 g in mass (ISO, 2000);
- metal inlays that cannot be separated shall not be used;
- data on the nature and amount of hazardous substances in the television shall be gathered in accordance with Council Directive 2006/121/EC (1) and the Globally Harmonised System of Classification and Labelling of Chemicals (EU Commission, 2007; United Nations, 2009).

However, the adoption of eco-labelling by manufacturers is a voluntary process but the DfD requirements listed above would be an advantage to display recyclers and manufacturing producers in reducing the dismantling time in the manual disassembly of LCD televisions (McDonnell, 2011).

Manual disassembly processing for LCDs

The release of mercury from lamp breakage is a primary environmental concern for approved authorised treatment facilities (AATF) engaged in LCD recycling (Environment Agency, 2011). With little data on the fate of mercury released from CCFL lamps available to the recycling industry, it has been reluctant to tackle end-of-life LCD disassembly, preferring in many instances to stockpile waste LCDs pending a recycling solution (Rifer *et al.*, 2009). In 2011, Recycling Lives Ltd, an AATF based in the UK, announced the development and installation of a dedicated disassembly line for LCD treatment (Lockerbie, 2011). The key factor in the development of this process was the requirement for environmental protection from mercury which was released during treatment (McDonnell and Williams, 2011).

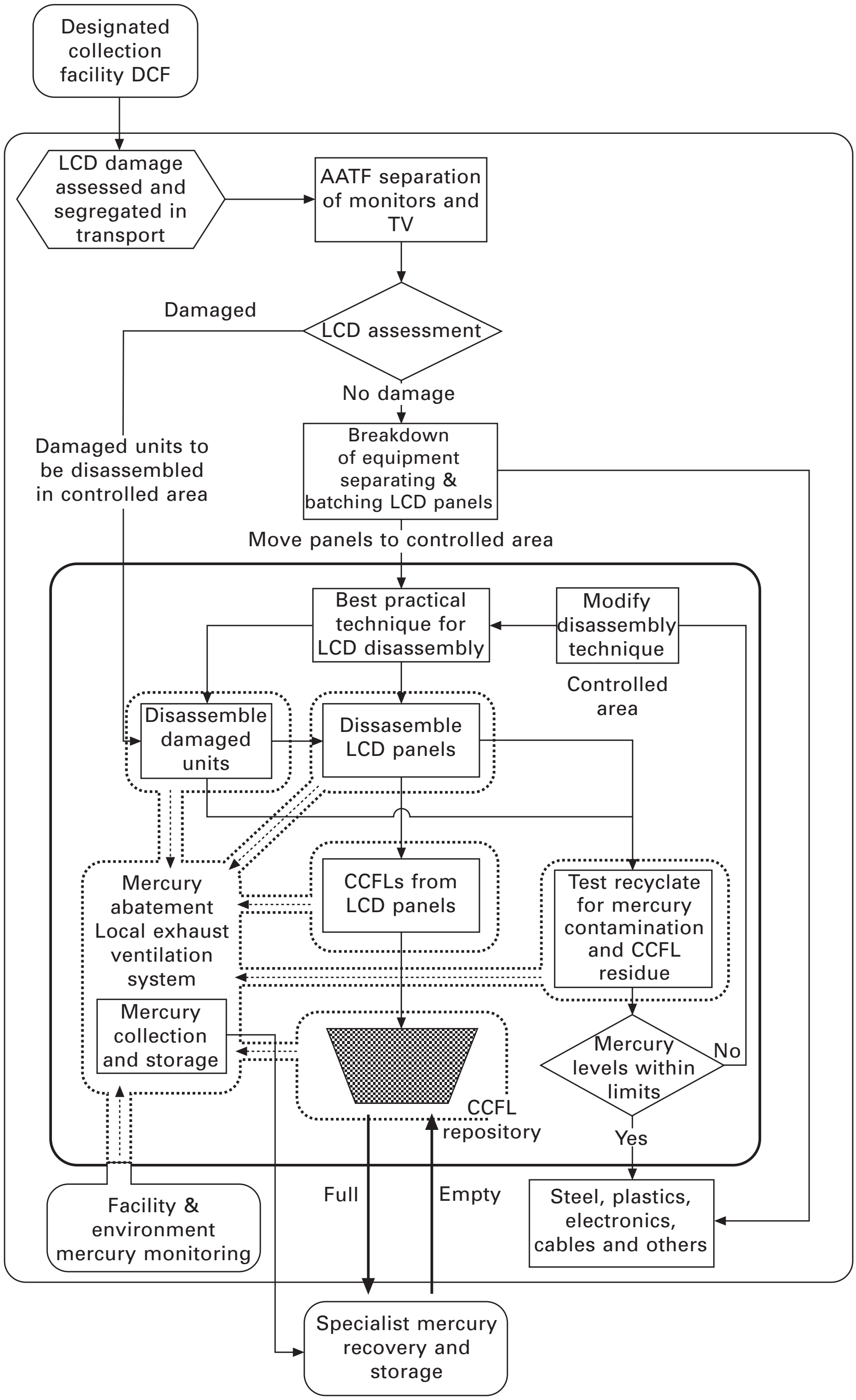
The need for mercury protection is not limited solely to the disassembly process of LCDs but extends in both directions (from the AATF) in the waste hierarchy from upstream LCD collection to downstream final recovery or disposal of components. The collection of damaged equipment with broken backlights from a designated collection facility to the delivery of mercury bearing lamp waste for specialist mercury recovery are potential mercury release issues for the industry AATF. The development of an environmental management protocol (EMP) extending from the AATF to include all stakeholders involved in the logistics of waste LCD recycling is therefore a key factor in mitigating mercury release (McDonnell, 2011; WEEE Forum, 2011).

A typical flow diagram for a manual disassembly facility is illustrated in Fig. 14.9. It should be noted that the flow diagram shown is concerned only with the end-of-life recycling of LCD. In reality, the process would include an equipment assessment providing a route for the function test, re-use and refurbishment of serviceable equipment (BSI, 2011; EU Commission, 2009c).

Figure 14.9 shows that, central to any facility, is the controlled area, where disassembly of damaged equipment and LCD panels takes place. The potential for mercury escape to the wider environment is limited by the confines of the controlled area. The installation of local exhaust ventilation (LEV), with mercury abatement and air monitoring, provides protection for disassembly operators from mercury vapour. This ensures that airborne mercury levels are below the indicative occupational exposure limit values (IOELV) of $20\,\mathrm{mg}\,\mathrm{m}^{-3}$ time weighted average for handlers and disassembly operators (EU Commission, 2009b). However, it is still a mandatory requirement for disassembly operatives to use personal protective equipment (Lockerbie, 2011). The controlled area processing removes mercury-containing backlights (CCFLs) from the LCD panels which are stored in suitable sealed repositories for transfer to specialist mercury recovery operations. The potential for mercury release from broken backlights is high. Consequently, this means that suitable procedures are needed to remove any mercury residues from both the recyclate and environment within the controlled area.

14.3.2 Automated processes for LCD recycling

In Western Europe, the high cost of labour has influenced the treatment and processing of WEEE. Consequently, recovery by automated mechanical



14.9 Flow diagram for a manual end-of-life LCD recycling facility.

disassembly has been the preferred option (Dalrymple *et al.*, 2007). This has usually been in the form of shredding and mechanical recovery of components. However, for LCDs the presence of mercury backlights and the liquid crystal screen in the panel has meant that this approach is restricted. This is because CCFL lamps and liquid crystals are both classed as hazardous, requiring removal under Annex II of the WEEE Directive (EU Commission, 2003b) In 2010, the UK Environment Agency (Environment Agency, 2010) issued a briefing note to AATFs recycling LCD displays. This re-evaluated liquid crystals as a low hazard risk to the environment which effectively removed the requirement for their selective removal (ibid.). This means that LCD panels with the mercury-containing backlights removed are classed as non-hazardous waste. In 2011, the inter-institutional consultation document on the recast of the WEEE Directive (EU Commission, 2009c) clarified the term 'removal'. The interpretation of this term by the recycling industry had been one of the stumbling blocks to motivating the industry to look for automated solutions. The recast document unequivocally stated that removal of mercury backlights was no longer solely a pre-treatment process but could now take place during mechanical processing. However, any mercury released during this processing had to be removed as a separate measurable waste stream (EU Commission, 2009c).

Currently there are no commercial automated recycling solutions for the disassembly of LCD containing mercury (Cryan *et al.*, 2010). Shredding trials of LCD have been unable to quantify the amount and locations of mercury released from the lamps (Cryan *et al.*, 2010). Any such process would produce a mercury-bearing shred. Research by McDonnell (2011) suggested that the shredding process would release a combination of 'micro-balls' of mercury, mercury vapour and mercury-contaminated lamp components into the final shred material. The process of shredding LCD produces destructive turbulence within the shredder. This turbulence would promote the release of the micro-balls into the shred environment (McDonnell, 2011). Without the use of suitable local exhaust ventilation (LEV) adjacent to the shredder an increase in mercury vapour would occur. This atmosphere would inevitably become laden with both mercury micro-balls and mercury vapour (McDonnell, 2011) which would travel into the final shred. Research performed by Böni and Widmer (2011) have indicated that during LCD shredding without LEV, increased mercury concentrations levels, above the permitted IOELV Directive limits of 20 **mg** m^{-3} (EU Commission, 2009b) were measured near to the mechanical shredder. It is likely that the air, around the shredder during processing, contained not only mercury vapour but also heavier mercury 'micro-balls'.

From any shredding process, a percentage of the total mercury released would become trapped in the shred material. The shredding process produces a co-mingled material that will have to be sorted. This is in order to meet the 75% recyclate separation targets set by the WEEE Directive (EU Commission, 2003b). However, the presence of small amounts of mercury in the shred material will render the shred as hazardous unless a suitable mercury recovery technology is used. This requires the development of mercury recovery technology.

Automated disassembly processes for LCDs

Once an LCD panel has been shredded the components of the mercury backlights are effectively lost into the shred. The manual isolation and recovery of lamp components that only represent 0.02% by weight of typical 37″ television screen is unrealistic. It will therefore be necessary to develop monitored processes to remove the following components: (i) mercury amalgamated to metal lamp components; (ii) mercury bound in the fluorescent powder and (iii) elemental mercury distributed in the shred. The processes to remove mercury must also preserve the shred material in such a manner to allow the WEEE Directive recyclate recovery targets to be met. A suggested flow schematic of an automated facility for end-of-life LCD is shown in Fig. 14.10. The operating procedures that would be required for an automated process would encompass those shown Fig. 14.10. It is paramount that any mercury recovery from an automated process needs to demonstrate:

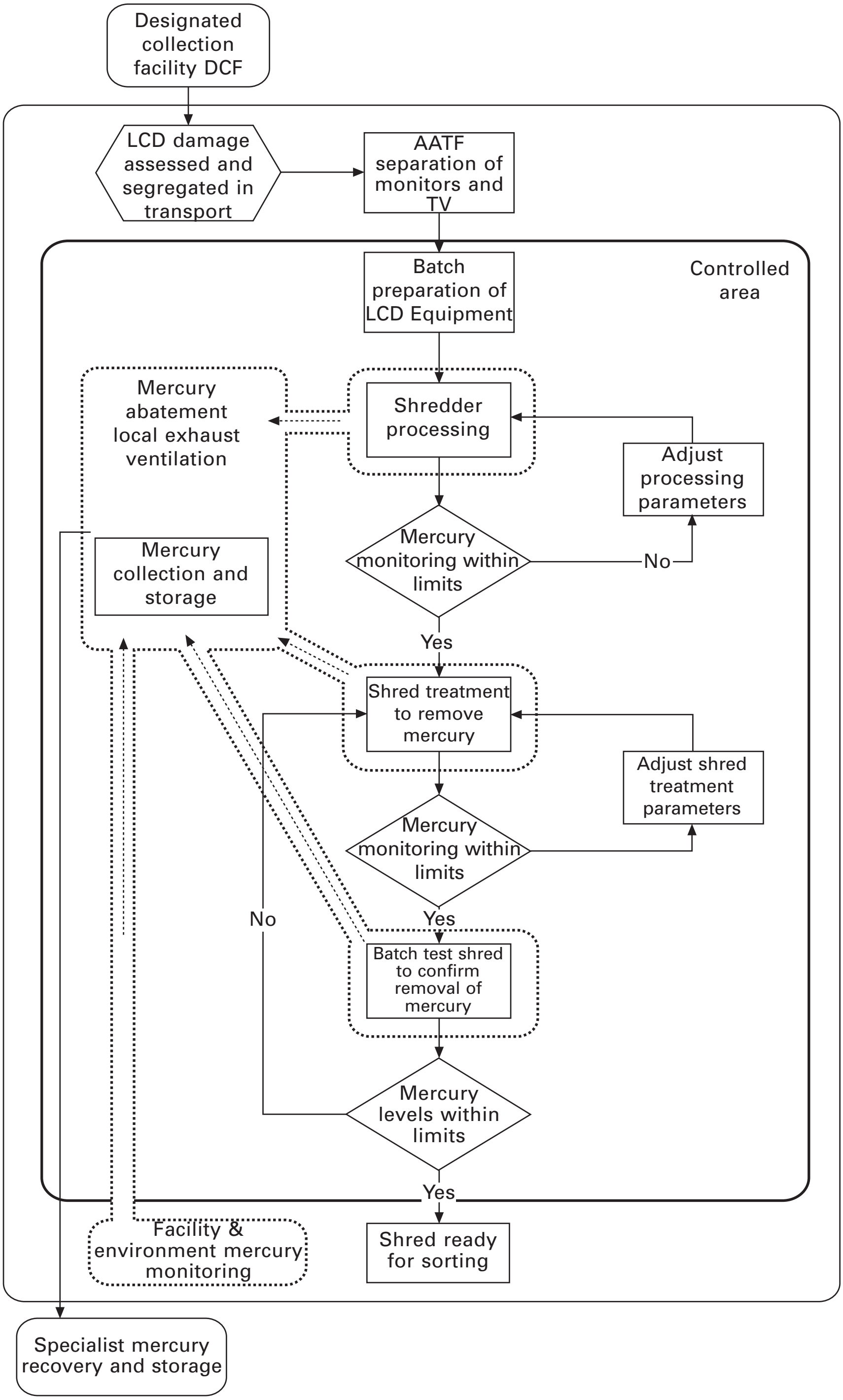
- a quantified amount of mercury collected during the shredding process;
- a quantifiable amount of mercury collected during shred treatment;
- a verifiable method to batch test shred to confirm mercury has been removed by the process.

The processing facility would require a negative pressure environment for the shredding process with local exhaust ventilation and mercury abatement. A key element in the processing of LCD by automated shredding will be the benchmarking of mercury by batch testing of the shred material to ensure that mercury has been removed effectively by the process.

14.4 Hazardous materials in liquid crystal displays (LCDs)

The EU WEEE Directive classes LCD equipment as hazardous, requiring selective removal and treatment of components listed in Annex II of the Directive (EU Commission, 2003b). These components are as follows:

- LCD panels with a surface area >100 cm^2;
- mercury-containing backlights;



14.10 Flow diagram for an automated LCD recycling facility.

- electronic PCBs;
- components containing restricted brominated flame retardants.

The first two components listed above present the WEEE recycling industry with its key challenges in developing tailored treatment techniques for LCD (Stevens and Goosey, 2009). The remaining components in the list, although important in the environmentally sound treatment of LCD, are known items present in other established electrical waste treatment techniques such as CRT recycling (Stevens and Goosey, 2009).

Two important reports have been produced. These are 'Flat Panel Displays: End-of-Life Management Report' (Eastern Research Group Inc., 2007) and the '2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE) for the EU Commission' by Huisman *et al*. (2007). They independently concluded that mercury from LCD backlights will be a primary component of concern in recycling LCD equipment. Furthermore, it can be stated that without data on the fate of mercury released from the backlights of LCD equipment during disassembly (and its subsequent recovery), the recycling industry is understandably reluctant to invest in unproven automated recycling techniques.

14.4.1 Substances of concern in LCD

Liquid crystal in screens

The majority of liquid crystals used in the screens of monitors and televisions are supplied by only a few manufacturers: Merck KGaA Germany; Dainippon Ink & Chemicals Inc. Japan and the Chisso Corporation Japan (Lee and Cooper, 2008). The quantity of liquid crystal used in a typical LCD screen is 0.5 mg cm^{-2} (Martin *et al*., 2004). They are formed from polycyclic aromatic hydrocarbons and include both biphenyls and phenylcyclohexanes (Takatsu *et al*., 2001). Modern liquid crystals for display applications are mixtures of up to 20 different chemical compounds (Matharu and Wu, 2009). The exact composition of these mixtures is proprietary information held exclusively by the manufacturers. This has led to uncertainty as to their true eco-toxic performance in the environment (Eastern Research Group Inc., 2007). The liquid crystal manufacturers have released results from studies demonstrating the low toxicology of their own liquid crystals (Martin *et al*., 2004; Takatsu *et al*., 2001).

Research by Heinze *et al*. (2000) suggests that certain liquid crystals do have negative biological impacts in water. However, it not clear whether the tested liquid crystals were used in television and monitor displays. In line with the issued EU Commission Directive (1991) on Manufacturers Safety Data Sheets for chemicals, liquid crystal manufacturers have produced such data sheets. As an example the Merck data on liquid crystal MLC-6405-100

LC for LCD states the following: (i) quantitative data on the ecological effect of this product are not available and (ii) liquid crystal material must not be allowed to enter waters, waste water or soil (Merck KGaA, 2003). This gives a very ambiguous picture of the apparent benign properties of liquid crystals.

Liquid crystal eco-toxicity tests conducted by Merck in conjunction with the German Federal Environment Agency have not resulted in the imposition of any special requirements for the disposal of liquid crystals. (Merck KGaA, 2000). In 2010 the UK Environment Agency clarified the UK position on liquid crystal in end-of-life LCD displays, stating that 'evidence on the eco-toxicity of liquid crystals from LCD posed little threat to the environment' (Environment Agency, 2010). It is the view of the UK Environment Agency that LCDs are non-hazardous components providing mercury-containing backlights are not present (Environment Agency, 2010). This effectively removes the requirement for removal of the liquid crystal screen during treatment of end-of-life LCD in either manual or automated disassembly processes.

Mercury-containing backlights

The majority of LCD monitors and televisions sold use mercury-containing fluorescent lamps (CCFL) to provide the rear screen illumination (Lim and Schoenung, 2010); see Section 14.2. These lamps operate using mercury vapour discharge to excite phosphor coatings on the tube wall to produce white light (Kahl, 1998; Mester *et al.*, 2005). The composition of CCFL comprises a hollow glass tube made of borosilicate glass with a tri-phosphor coating lining the internal wall and electrodes for electrical conduction (Kahl, 1998). The tri-phosphors contain rare earth elements which include yttrium and europium (Rabah, 2008). The standard electrodes used in CCFLs mainly consist of molybdenum or nickel with a caesium compound coated on the exterior (Sugimura *et al.*, 2009). The lamps are cylindrical in design with wires connecting the electrode to the outside of the tube through a hermetic glass seal (ibid.). The tubes range from 2.0 to 6.5 mm in diameter. Other constituents of CCFLs include: (i) Penning gases (argon and neon) and (ii) elemental mercury reservoirs (Kahl, 1998). The numbers and arrangement of lamps in LCD equipment vary and increase with larger screen area. LCD equipment can contain from 2 to 22 lamps (McDonnell and Williams, 2010b). Research by Mester *et al.* (2005) has shown that the varied locations and removal techniques of CCFL backlights in LCD notebooks makes it difficult to design simple mechanical extraction processes. Research by McDonnell and Williams (2010b) on a broader range of LCD equipment including televisions showed that the fixing methods of CCFL lamps vary among manufacturers of LCD panels. This suggests that recyclers will have to employ panel-specific techniques to remove CCFLs during manual disassembly (McDonnell and Williams 2010b). The conclusion of Mester *et al*. (2005) was that manual disassembly was not feasible, but acknowledged that there is a lack of automated processes with the required facilities to remove mercury. The study concluded that the only feasible solution to the treatment of LCD was automated shredding with a suitable mercury extraction unit. The ReLCD project conducted by Kopacek (2008) concluded that manual disassembly of LCD notebooks offered the optimum economic solution.

Disassembly studies on LCD equipment have shown that CCFL lamps are discovered broken during disassembly (McDonnell and Williams, 2010b; Mester *et al*., 2005). It is clear that the fragility of CCFL in LCD will lead to breakages during manual disassembly or automated shredding of LCD panels. For both processes the airborne release of mercury from CCFL has a significant eco-toxicity potential (Lim and Schoenung, 2010). For mechanical crushing and shredding of LCD the contamination of the shred material with mercury from the lamps and its removal is the significant challenge (Li *et al*., 2009). This is supported by Morf *et al*. (2007) who suggest that the pre-shredding separation and collection of mercury-containing components is an effective method to avoid contamination of the output fractions. Irrespective of the treatment method, the containment of mercury and its recovery is the key challenge in the safe environmental treatment of LCDs containing mercury backlights. As highlighted in the WEEE review, conducted for the EU Commission, Huisman *et al*. (2007) stated 'Due to the absence of recycling solutions for LCD, the high risk of mercury emissions from these panels points to a strict target setting for mercury removal without causing health and safety risk'. They also suggest that treatment costs per LCD unit will be high with recycling targets a secondary priority (Huisman *et al*., 2007).

14.5 Recovery of valuable materials

Previous research in recycling LCD equipment has mainly focused on the display panel and the recovery of valuable materials such as liquid crystal, plastics and precious metals (DIUS, 2009; Eastern Research Group Inc., 2007; Li *et al*., 2009; Martin *et al*., 2004). Many of these research projects have shown that the recovery of materials is possible. However, this has not been translated into a commercial disassembly recycling scenario. Typically materials recovered from LCDs with a commercial value are:

- zinc coated steel;
- aluminium;
- PMMA light diffuser;
- optical enhancement films;
- recyclable plastics ABS, HIPS and polycarbonate;
- PCBs;

- cable copper content;
- indium in the screen.

As shown in Tables 14.1 and 14.2 the large weight of steel and aluminium relative to the equipment mass has an obvious recycling value and in common with other types of WEEE, reprocessing and recovery are already established. The PMMA and optical enhancement films are of pure optical quality and will be subject to re-use and alternative applications, although as described previously the display recycling industry is just starting to explore the possibilities as the waste stream develops. PCBs recovered from LCDs vary in the complexity of the semiconductor components and other valuable metals. The main boards such as digital image processing and those associated with the LCD display panel are the highest value from a resource recovery perspective. This is because of the high use of precious metals. However, the re-use and repair market for functioning electronic boards also present the recycling industry with a potentially enhanced revenue stream above the scrap value of the circuit boards. The use of separate PCBs inside LCDs requires interconnecting cables carrying digital signals and power distribution. These cables will have a copper wire content and with recycled copper values rising on the commodity markets this provides another revenue. A rare metal targeted for resource recovery is indium. This is contained in the indium tin oxide used as a transparent electrical conductor on the inner faces of the glass screen (EU Commission, 2011). This material has been shown to be recoverable by the Sharp Corporation (2009). It is estimated that the global usage of indium in the LCD manufacturing industry is 20 t (Matharu and Wu, 2009) and with a fluctuating cost of around $800 per kg (Metal Prices, 2011) values the annual market at $16 million. New technologies in transparent electrical conductors are presenting alternatives in the form of carbon nanotube deposition. This latest 'Graphene' technology has the potential to remove the dependency of the LCD industry on indium in the future. However, it is suggested from a recycling perspective, that recovery of materials from LCD will only occur in dedicated plants incorporating a range of technologies to recover the diverse materials found in LCD. It is unlikely that manual disassembly AATFs would undertake the investment in individual recovery technologies without a clear commercial advantage.

14.6 Re-use of liquid crystal display (LCD) equipment and components

The growth in LCD screen size has been controlled by the development of factories capable of handling and cutting the larger sizes of glass for screen manufacture. These facilities are referred to as manufacturing generations and clear emergence of larger size LCD equipment can be traced from the development of larger screen size capacity factories since 2000 (Semenza, 2007).

Early development of LCD for multimedia applications drew criticism on the poor switching response time of the liquid crystal. This resulted in screen image motion blur and a narrow screen viewing angle for users. Continuous improvement in the technical performance of LCD has seen the optimisation of liquid crystals used in televisions (Pauluth and Tarumi, 2005). The earlier types of liquid crystal such as the twisted nematic have been superseded by faster response vertical alignment and inter-plane switching varieties of liquid crystal mixtures in the LC panel (Matharu and Wu, 2009).

The progress in LCD technology since 2000 has brought about advances in the LCD panel in terms of picture resolution and types of crystal employed, thus creating obsolescence in the equipment in a relatively short period of time. For older models of LCD monitors and televisions, the availability of earlier technology screens and parts is limited by the manufacturers. This leaves second user parts as the only solution to the refurbishment and re-use of older LCD equipment. The unavailability of original equipment manufacturer parts has been addressed in the Eco-label Directive for televisions which requires manufacturers to maintain a supply of parts for seven years after a product has been discontinued (EU Commission, 2009a). The emphasis on refurbishment and re-use is highlighted in the proposed recast of the WEEE Directive in which 5% of WEEE is the target for refurbishment and re-use (EU Commission, 2009c). As AATFs develop techniques for the recycling of end-of-life LCDs, the high value of second user parts and equipment will promote the refurbishment and re-use of repairable LCDs in the waste stream. The release of the publicly available specification British Standard PAS141:2011 on the procedures and regulation of refurbishment and re-use of used and waste equipment (BSI, 2011) has laid the foundations in the establishment of a confident market in re-use of electrical and electronic equipment (REEE).

14.7 Future trends

The rapidly changing technology of the display market has largely seen the CRT replaced by flat panel displays in developed regions worldwide with LCD as the dominant display equipment of choice (Torii, 2009). The latest change in display application technology is the rapid move to light emitting diode (LED) backlight units, replacing mercury-containing CCFL. With these changes in backlighting technology, a new generation of LCD high definition televisions (HDTV) equipped with LED backlighting appeared on the market in 2009. This trend is set to continue with the marketing vice-president of the Sharp Corporation announcing all Sharp HDTV will be 100% LED backlit by 2012 (Reisinger, 2009). The forecast for market penetration of

LED backlighting is estimated at 66% or more of all large screen televisions by 2014 (DisplaySearch, 2009). However, given the growing environmental issues and legislative direction this percentage may be achieved sooner as manufacturers head for the high green ground.

The drivers for the move to LED backlighting are: (i) power consumption savings; (ii) removal of toxic mercury from these products and (iii) enhancement of the contrast ratio of the screen. Manufacturers such as Apple, Dell and Samsung have committed to the introduction of LED backlit LCDs, citing the removal of mercury and environmental concerns from customers as driving policy (Apple Inc., 2009; Dell Inc., 2009; Thompson, 2009). The main barrier to universal adoption of LED backlight units (BLU) has been the higher cost (Chang, 2005). The move to LED BLU will allow manufacturers to reduce the environmental impact of LCD with lower power consumption but the other important factor is the elimination of mercury from these products.

The latest technology to threaten the dominance of the LCD is the new organic light emitting diode (OLED) array (McDonnell and Williams, 2008). The technology has been proven and a number of manufacturers have commercially available models on the market. The barriers to the wider introduction of this technology are the high production cost and affordability, but it is envisaged that this will be the successor technology to LCD (McDonnell and Williams, 2008).

The technology behind OLED displays uses luminescent inks to create images on the screen. The composition of these inks remains proprietary information. The recycling of OLED displays will result in another environmental uncertainty as to their potential negative impact. This will be a similar situation to the adoption of LCDs over CRTs.

14.8 Sources of further information and advice

Research and development organisations:

1. Centre for Waste Management, University of Central Lancashire: www.uclan.ac.uk/cwm: Research and development of recycling processes. Monitoring and evaluation.
2. C-Tech Innovation, Capenhurst, Chester, UK: http://www.ctechinnovation.com: liquid crystal recovery research.

Government and advisory bodies:

1. CIWM: Chartered Institution of Wastes Management: www.ciwm.co.uk
2. WEEE Forum: European Association of WEEE collection and recovery organisations: www.weeeforum.org
3. ENDS Report: Environment, Carbon and Sustainability journal: www.endsreport.com

4. IEMA: Institute of Environmental Management and Assessment: www.iema.net
5. JEITA: Japan Electronics and Information Technologies Industries: www.jeita.or.jp/english
6. ICER: Industry Council For Electronic Equipment Recycling (ICER) is an association of member companies dealing with the recycling or treatment of waste from all electrical and electronic equipment : www.icer.org.uk
7. EA: Environment Agency in the United Kingdom: www.environment-agency.gov.uk
8. DEFRA: UK Department for Environment, Food and Rural Affairs: www.defra.gov.uk
9. BIS: UK Department for Business, Innovation and Skills: www.bis.gov.uk
10. UNEP: United Nations Environment Programme: www.unep.org
11. European Union: Europa official website of the European Union: www.europa.eu

Commercial recycling and materials recovery organisations;

1. Recycling Lives Limited, Preston, Lancashire: Display equipment recycler (AATF) : www.recyclinglives.com
2. Mercury Recycling Ltd., Trafford Park, Manchester: Specialist mercury recovery processors (AATF) : www.mercuryrecycling.co.uk

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15
Recycling cooling and freezing appliances

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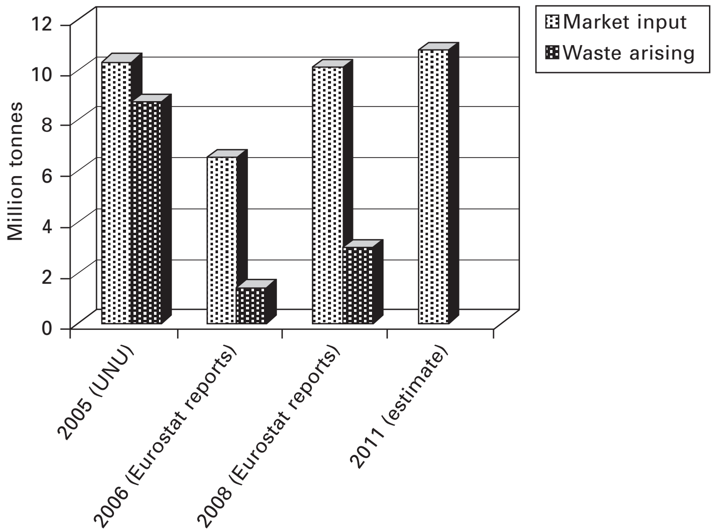
Abstract: This chapter deals with the amount of cooling and freezing appliances put on the market and arising as waste in the European Union. Furthermore it highlights the importance of collection and environmentally sound treatment due to the refrigerants and blowing agents still contained in the equipment. It gives an overview of the incorporated materials and the standard treatment technology as well as the amounts of refrigerants and blowing agents which should be recovered with the best available techniques. Based on recently published studies, future composition of waste streams are shown, which enables a forecast of the technologies and tasks recyclers will need to face in future.

Key words: refrigerators, ozone depleting substances (ODS), waste electric and electronic equipment WEEE, treatment, recovery rate of ODS.

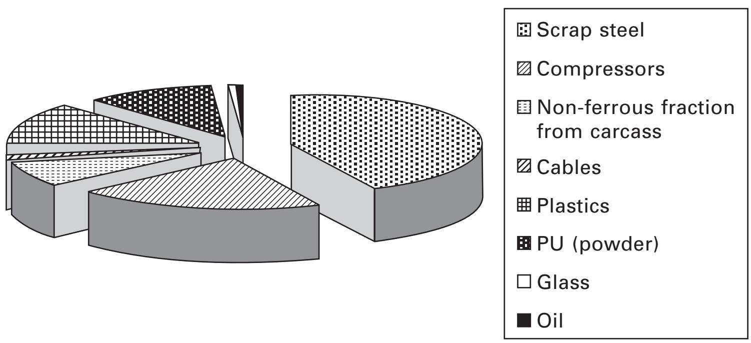
15.1 Introduction

In the impact assessment for the WEEE (waste electrical and electronic equipment) Directive recast, the predictions made during the 1990s estimated the tonnage of EEE (electric and electronic equipment) put on the EU15 market at 7 Mt. The more recent UNU study (United Nations University, 2008) estimates that the amount of new EEE put on the EU27 market in 2005 was 10.3 Mt per year due to the expansion from EU15 to EU27. The latest available figures of Eurostat show an amount of ca. 6.5 Mt for 2006 (this is comparatively low, because reports of some big member states are still missing) and 10.1 Mt for 2008. Based on current trends of a moderate yearly growth rate of 2.5%, sales of new EEE can be re-estimated to rise to 10.8 Mt per year by 2011.

In the explanatory memorandum of the WEEE Directive, the amount of EEE arising as waste (WEEE) was estimated in 1998 for the EU15 at 6 Mt. The new estimate of the UNU study for the current WEEE arising across the EU27 for 2005 is between 8.3 and 9.1 Mt per year. The actual figure based on the reports of the member states to Eurostat is ca. 1.4 Mt for 2006 and 3 Mt in 2008 (see Fig. 15.1). The increase in the WEEE arising since 1998 is due to expansion of the EU, the growth in the number of households and higher consumption per capita. The percentage of cooling and freezing appliances can be estimated to be approximately 25% of the large household appliances (Elektroaltgeräte Koordinierungsstelle Austria GmbH, 2010) and therefore they represent the second largest group.



15.1 Market input of EEE and amount of WEEE.



15.2 Average material composition of refrigerators.

15.1.1 Materials

The three main materials found in electrical and electronic scrap are metals, glass and plastics. The material composition of an average refrigerator is shown in Fig. 15.2. Ferrous metals account for more then 50%, non-ferrous metals for ca. 8% and plastics for 20–25% of waste. Other essential materials are oil and cooling agents.

15.1.2 Ozone-depleting substances (ODS), blowing agent recovery

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) were developed in the US in the early 20th century and became widely used as refrigerants and for making plastic foams producing refrigerators and freezers until the early 1990s, when it was found that these chlorinated gases damaged the ozone layer. CFCs are non-toxic, non-flammable and very stable, which makes them ideal for use in appliances in private households. However, it is their stability that creates environmental problems today.

Ozone molecules form a layer in the stratosphere, 10 to 50 km above the Earth. This layer protects us from ultraviolet (UV) radiation and, in particular, from most of the ultraviolet B radiation (UVB). UVB is the main cause of sunburn and skin damage, and a decrease in ozone levels will result in more UVB reaching the Earth's surface.

The destruction of ozone by ozone-depleting substances (ODS) has been recognised since 1974. Research has identified CFCs and HCFCs as the primary ODS (National Academy of Sciences, 1982). When CFCs are released into the atmosphere they are not broken down immediately but are transported into the stratosphere, where they are eventually broken down by UV radiation. The breakdown of CFCs releases chlorine, which then acts as a catalyst for the destruction of the ozone layer. In 1985, the first scientific evidence of the ozone hole over the Antarctic was reported (Farman *et al.*, 1985). In 1994, this hole measured round about 25 million km² (NASA, http://ozonewatch.gsfc.nasa.gov/meteorology/annual_data.html). Moreover, in addition to the hole that appears over the Antarctic each spring, there is a similar ozone hole forming over northern Europe.

While productive steps have been taken to reduce and ban the use of CFCs in manufacture processes, recent findings (Morrisette, 1989) suggest there remains an urgent need to eliminate ODS from our environment. So ozone depletion remains a current issue.

Council Regulation (EC) No. 3093/94 of 15 December 1994 on substances that deplete the ozone layer amended by Regulation 2037/2000/EU of the European Parliament and of the Council of 29 June 2000 on substances that deplete the ozone layer banned their manufacture and regulated their treatment. Owing to the long life cycle of cooling appliances, those gases still make up a significant part of today's WEEE stream. In many countries, the use of ODS has been reduced dramatically or phased out. The focus is now on the reduction of HCFC consumption, which is due to be phased out by 2015.

There are now several blowing agents that do not destroy the ozone layer. European refrigerator manufacturers nowadays use cyclopentane as a blowing agent in polyurethane foam insulation, in place of CFC, HCFC and HFC. Cyclopentane has none of the environmental dangers of CFCs or HCFCs, but it does carry potential health and safety risks. Cyclopentane has zero ozone-depletion potential and a global-warming potential that is less than one hundredth of that of CFC-11 (UNEP, 1994). But it is flammable – its flash point is below –20 °C – and it can be highly explosive when mixed with air. This has confronted the fridge recycling plants with a new set of challenges, especially those using traditional technology.

15.2 Challenges relating to WEEE refrigerators and freezers

The main climate-related impacts of WEEE derive from the release of CFCs due to inappropriate treatment or disposal of cooling and freezing appliances. Based on the latest available reports of the member states to Eurostat (http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/weee) the total market input of large household appliances in 2008 was 4.18 Mt and the total amount collected was 1.78 Mt, giving a collection rate of 37%. Derived from the Austrian figures where there are specific reports for large household appliances and refrigerators and freezers, the percentage of refrigerators can be assumed to be ca. 25% of the large household appliances category.

Based on these figures, the amount of fridges and freezers bypassing proper collection and treatment is at least 730 000 t. Assuming an average weight of 44 kg, this means up to 16.6 million refrigerators or freezers. Around 80% of these are estimated to contain ODS with an average of 0.4 kg of CFCs in the refrigerant and insulating foam per appliance. Given the fact that an average European refrigerator represents therefore a CO_2 equivalent of 2800 kg, this suggests that the greenhouse gas release from cooling and freezing appliances would be around 37 Mt of CO_2 equivalent a year. This gives a monetised value of the damage having a magnitude of more then 1 billion euro per year, declining each year to low levels by 2025. This decline comes as the CFC ban in cooling and freezing equipment results in lower numbers of appliances containing CFCs.

More than three-quarters of the ODS release from refrigerants and foams in cooling and freezing equipment due to improper treatment or disposal will most likely happen between 2017 and 2025, depending on the rate with which ODS-containing equipment enters the waste stream. With any low target regarding the collection rate of WEEE and in the absence of a specific target for the separate collection of refrigerators and freezers, a large percentage of them, between 40 and 60%, will not be subject to proper treatment. The main reasons are the relatively expensive treatment (to remove the CFCs and HCFCs) and the option to treat other more profitable appliances, in terms of the value of secondary raw materials in relation to treatment costs, to achieve the given target.

It is a well-known fact that there is an enormous quantity of refrigeration appliances containing CFCs which are still in operation in European households (about 200 million old devices). The tremendous climate relevance of this group has to be taken into consideration (more than 500 Mt of CO_2 equivalents may be emitted by these waste appliances in the oncoming years). Against this background, waste refrigeration appliances have to be considered the most hazardous group within the WEEE products. So one of the major objectives of the WEEE Directive should be the collection of all waste cooling appliances and their environmentally sound treatment but this is not explicitly stated either in the actual WEEE Directive or in the impact assessment published by the European Commission.

15.3 Requirements for de-gassing processes

Regulation 2037/2000/EC requires that ODS contained in refrigeration, air-conditioning and heat pump equipment should be recovered for destruction, recycling or reclamation during the servicing and maintenance of equipment or before the dismantling or disposal of equipment. In principle, emissions from equipment covered by the WEEE Directive should be avoided. Improving the recovery of ODS contained in fridges and freezers could be achieved by strengthening the provisions contained in the directive, notably by inserting concrete values or a minimum recovery rate for ODS contained in specific categories of fridges and freezers.

It is still a common misapprehension that the reason for the collection and treatment of old fridges is to recover the refrigerant from the cooling circuit at the back of the unit. The real reason and by far the more complex task, is to recover, store and destroy the blowing agent enclosed in the insulating foam. Although most fridge recycling plants are able to process waste refrigeration appliances regardless of the refrigerant in the cooling circuit or the blowing agent in the polyurethane foam, the fridge recycling industry must consider which strategy to follow in that field.

A recent study carried out by the Öko-Institut e.v. (2007) stated that the most beneficial approach is to process all CFC, HCFC, HFC and cyclopentane fridges together in a single specialised recycling plant. As part of the life-cycle assessment, the study examined the following four scenarios with respect to their environmental impact:

- Mixed-mode processing: joint processing of CFC-containing and CFC-free appliances at the same time with no prior sorting of waste appliances before treatment.
- Parallel processing: separate processing of CFC-containing and CFC-free appliances where prior sorting before treatment is required.
- Treatment in two different plants at different sites: first step in the fridge plant (removal of the refrigerant from the cooling circuit) and step two processing of fridges containing ODS in the fridge recycling plant and a separate processing of pre-treated CFC-free appliances in a car shredder.
- Use of a car shredder and fridge plant: complete treatment (steps one

and two) of CFC-free appliances in a car shredder and CFC-containing appliances in specialised fridge recycling plants.

In all of the environmental criteria used, the mixed processing mode proved to be significantly better than the other three. The conclusion of this study is remarkably clear: any prior sorting of waste fridges and freezers into CFC-containing and CFC-free appliances has a significant negative effect on the most important environmental criteria. This joint treatment may be used to argue that the requirement of specific values or rates for recovery of ODS or refrigerants and blowing agents is impossible to stipulate.

15.4 Emissions of volatile organic compounds (VOCs)

A recently published study by the Austrian research institute FHA in close collaboration with the Institute for Statistics and Probability Theory at Vienna Technical University commissioned by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management and the RAL Quality Assurance Association for the Demanufacture of Refrigeration Equipment has cast new light on the treatment of end-of-life refrigeration appliances containing hydrocarbons (FHA, 2008). The results of the field study conducted support the above-mentioned approach of joint treatment of waste refrigeration equipment. The tests performed at an Austrian recycling plant generated valuable data on the processing of waste refrigeration appliances containing hydrocarbons like cyclopentane. The study also includes a forecast of how the fraction of so-called CFC-free appliances in the waste stream will grow over the coming years.

In many recycling companies it is now common practice to adapt the fridge recycling plants originally designed to treat CFC appliances and to collect the climatically hazardous CFCs. These are now used for the joint processing of all waste types of waste refrigeration appliances.

The primary question addressed in the study was to analyse what quantities of hydrocarbons can be recovered from CFC-free appliances when processed in state-of-the-art fridge recycling plants. The study also aimed to look at differences between processing batches of CFC-containing and CFC-free fridges and joint processing modes and to determine if and how the CFC and HC recovery rates achieved in joint processing compare with those in batch processing.

In order to generate data on the amounts of hydrocarbons recovered during processing, the plant was run for several days processing only HC-containing appliances. Three different mass balance analyses due to three categories of sizes of fridges and freezers in accordance with the common international definitions (Type one appliances: domestic fridges with a storage capacity of up to 180 litres, Type two appliances: domestic fridge-freezers with a storage capacity in the range of 180 to 350 litres, and Type three appliances: domestic chest freezers and upright freezers with a storage capacity up to 500 litres) of the batch processing of HC appliances were carried out.

Following the tests of batch processing, three tests were conducted to examine the joint processing of CFC and HC appliances. Each test was performed on a sample of 1000 appliances. In the first test the ratio of CFC to HC appliances corresponds approximately to the composition of the waste refrigeration equipment currently being sent for treatment (15%), in tests two and three, the proportion of appliances with a hydrocarbon blowing agent was raised to 30% and 50% respectively. The intention of tests two and three was to simulate the composition of the waste input stream in the coming years.

The aim of these three tests was to assess whether the CFC and HC recovery rates achieved by the joint processing of CFC and HC appliances were better than, worse than or the same as those achieved in batch processing. The data indicate that joint processing of waste refrigeration had no negative effect on the recovery rate of CFCs and HC and is therefore environmentally preferable to batch processing. The advantage results mainly because no additional sorting or transport is required.

Statistically established and reliable data concerning the quantities of CFCs contained in the different types of refrigerator appliances have been available for some time (Umweltbundesamt BRD, 1998), but this information has not been available for hydrocarbon appliances so far. The tests carried out in batch mode showed that processing recovers a statistically reliable average of 130 g of hydrocarbon blowing agent from a type one appliance, 230 g of HC from a type two appliance and 340 g of HC from a type three appliance of the insulation foam. An interesting but worrying fact, however, was that in addition to cyclopentane, the hydrocarbons recovered were found to contain around 20% of other volatile organic compounds. In particular, the fraction of the CFC R141b was particularly high.

The tests carried out in joint processing mode confirmed the data acquired in the batch mode tests. When combined with the equivalent data already available for CFCs, the expected values for recovered blowing agents calculated based on the relevant ratio of HC to CFC appliances treated in all three tests carried out in joint processing mode could be achieved.

In all three tests of the joint processing of HC and CFC appliances, the actual quantities of blowing agents recovered were greater than the calculated expectation values. The results clearly refute any suggestions that the recovery of hydrocarbons would adversely affect the recovery of CFCs.

Regarding the recovery of the refrigerants in the cooling circuit, a series of tests were carried out based on the vacuum extraction of the refrigerant from one hundred undamaged appliances. In order to get reliable data, it is essential that undamaged appliances and defective appliances can be clearly distinguished. In the case of CFC appliances, an appliance is generally deemed to be defective if the pressure in the cooling circuit is measured to be 0.2 bar or less. However it was found that the pressure in the cooling circuit of the HC appliances was very often around 0.2 bar or less.

The question whether HC appliances tend to lose refrigerant from their cooling circuits much earlier than CFC appliances, or whether the pressure in the cooling circuit of an HC appliance is inherently much lower than that in a CFC appliance could not be answered. As a result, the conclusions regarding amounts of recoverable refrigerants are not so clear cut as those from tests involving one hundred CFC appliances.

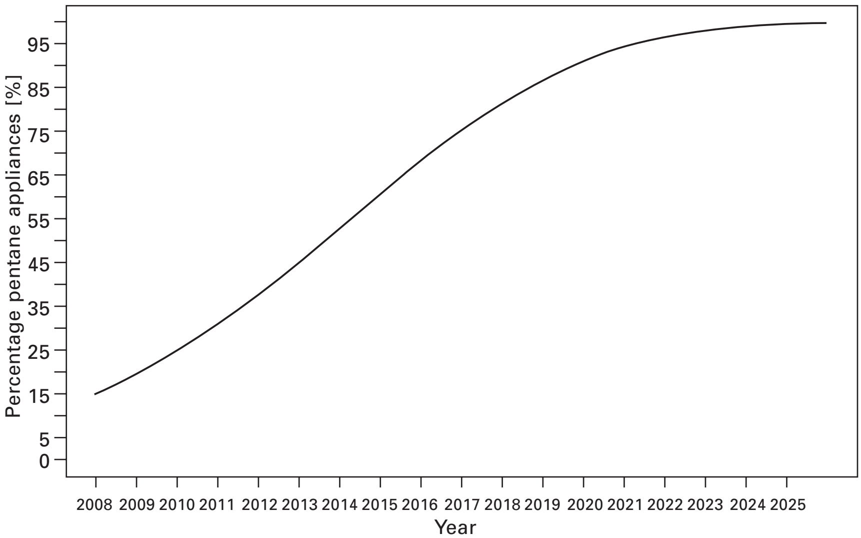
An interesting 'by-product' of the study was the information related to mis-sorting of appliances at the recycling plant. Even when the CFC and HC appliances were sorted and separated by qualified workers, around 1.6% of the incoming appliances were incorrectly sorted. This figure confirms the sorting error rate of 1% that was assumed in the life-cycle assessment study published by the Öko-Institut e.v. (2007).

15.5 Future trends

A further important part of the Öko-Institut study was the statistically reliable computation of the relative proportions of CFC and HC appliances in the waste stream sent for treatment in the future (see Fig. 15.3). The study shows that the proportion of HC appliances in the waste stream is not growing at that rate usually assumed up until now. As a result, the need for environmentally sound processing of waste refrigeration appliances containing CFCs will remain for many more years. It is obvious that the need to have recycling plants capable of recovering CFCs from waste refrigeration equipment will remain at least until the year 2020. Results show that it will be around 2014 before recyclers will face about 50% CFC appliances and 50% HC appliances.

15.5.1 Handling of removed oil/refrigerant

In order to prevent any negative effects to the environment, waste cooling and freezing appliances shall only be stored in suitable areas, taking into account the type of wastes and their hazard potential with weather-resistant covering, with impermeable and, if necessary, oil- and solvent-resistant surfaces, with spillage collection facilities and, if necessary, decanters and cleanser degreasers (BGBl, 2006). In addition, the transportation of waste cooling and freezing appliances shall be environmentally sound. Therefore waste cooling equipment shall be transported and stored in such a way that any damage is prevented that may result in the release of ODS or other



15.3 Percentage of CFC-free refrigerators in the refrigerators waste stream.

refrigerants. Waste cooling equipment shall be secured against slipping and shall not be transported or stored upside down or lying on parts of the refrigeration circuit.

Further to the requirement to use the best available treatment technology for recovery and recycling, article 6 paragraph 1 of the WEEE Directive stipulates the ‘removal of all fluids’ as a minimum standard and absolute requirement applicable to all treatments of refrigeration equipment covered by the directive. This means that specific extraction and collection of the fluids is necessary so that they can be subject to further environmentally sound treatment. The uncontrolled leakage of fluids from refrigeration equipment when treated in a car shredder would therefore be definitely not in line with the requirements of the directive.

The pre-processing stage, commonly called step one of the treatment process, involves the evacuation of the refrigerant–oil mixture from the cooling circuit and the subsequent separation of the mixture into its components by passage through a sequence of thermal and pressure treatment units. The refrigerant is filled into a compressed gas cylinder and is subsequently destroyed. The oil is separated and collected and recycled. Once the cooling circuit has been evacuated, the empty compressor is cut from the appliance.

The glass, cables, mercury switches and capacitors are also removed. All components and modules containing contaminants or pollutants are removed from the appliance for separate processing and recovery of the secondary raw materials or disposal.

One of the most specific and detailed requirements regarding the treatment of waste refrigerators and freezers is the Austrian ordinance for treatment obligations for certain types of waste published on 3 December 2004 (BGBI, 2004). According to this ordinance any waste fridge recycling process must comply with the following quality requirements. Prior to the treatment of the insulating foam, the contents of the refrigeration circuit shall be extracted and preliminary dismantling shall be performed (called *step one*).

- Refrigerant and compressor oil shall be extracted together without any losses, and shall be separated or their separation shall be arranged.
- The proper evacuation of the refrigeration circuit shall be ensured by monitoring devices that shall be adapted to the extraction system selected and to the volume of the appliance treated and shall be integrated into the extraction system.
- Suitable measurement equipment shall be used to indicate the number of appliances treated and the quantity of CFC/HCFC/HFC extracted.
- The amount of refrigerant (CFCs, HFCs, HCFCs) recovered has to be at least 115 g per appliance (determined as pure substance).
- The residual quantity of R12 (or other CFC, HFC or HCFC) in the refrigerator oil has to be less than 0.1% by weight.
- The emission of VOCs (HC) from the treatment of CFC-free cooling appliances shall not exceed 50 mg carbon per m^3.
- Adequate fire and explosion prevention shall be guaranteed.

Evidence must be provided that these figures have been achieved in the annual plant performance test and have been met by the operational performance of the plant averaged over the year.

15.6 Techniques for separation of fridge plastics

The recycling quotas of the WEEE Directive for refrigerators and freezers are achievable only if the insulation material is mechanically recycled. Furthermore the material used is mainly polystyrene, which represents a high value in terms of the market prices for this secondary raw material. The techniques for separation are usual ones like swim sink separation and hydro cyclone classifiers.

The second major fraction of plastics is the polyurethane foam (see Fig. 15.2). The recovery of CFCs from the insulating material is the most important aspect of the whole recycling process, as only about one-third of the ODS are in the cooling circuit. By far the largest fraction of these substances is contained in the insulating foam. In this second processing step, the pre-treated appliances are shredded and the various materials (metals, plastics and foam) of the fridge cabinet are separated from each other.

In order to release the blowing agents still contained in the pores of the insulation foam, the shredding and grinding especially of the foam is one of the major aspects of the whole recycling process. Because of the high vapour pressure of the ODS, it is necessary that these treatments takes place in an absolutely gas-tight treatment plant. Owing to the explosion risk of cyclopentane from the CFC-free appliances it is necessary to use nitrogen in order to prevent explosion. After the shredding and grinding, plastics and metals are separated by common techniques like air classifier, magnetic separator and sieves.

The evaporated ODS within the enclosed environment are then led to active carbon filters or fed into a cryo-condensation unit for separation. In the case of active carbon filters the ODS are later desorbed from the filters, liquefied and stored followed by their destruction in a high-temperature thermal 'cracking' reactor, such as the one operated by Solvay in Frankfurt (http://www.solvay.de/standorte/frankfurt/wissenswertes/0,,49941-4-0,00.htm) or in high-temperature incinerators. The CFC-free polyurethane powder may be recycled further on or used as oil absorbing material (http://www.usg.at/englisch/oekopur.html). Here again the Austrian ordinance for treatment obligations lays down specific requirements regarding the treatment of the insulation foam, commonly called *step two*:

- The amount of CFCs, HFCs and HCFCs (determined as pure substance) recovered from the various types of refrigeration equipment has to be at least
  - *240 g per type one appliance* (domestic fridge with a storage capacity of up to 180 litres)
  - *320 g per type two appliance* (domestic combined fridge-freezers with a storage capacity between 180 and 350 litres)
  - *400 g per type three appliance* (domestic freezers with a storage capacity up to 500 litres).
- The residual quantity of CFC, HFC or HCFC in the insulation foam has to be less than 0.2% by weight.
- The residual quantity of polyurethane foam adhering to either the metals or the plastics fractions recovered during the treatment process shall not exceed 0.5% by weight.
- VOCs (HC) contained in the insulation foam have to be recovered. The emission of VOCs from the treatment of CFC-free cooling appliances shall not exceed 50 mg carbon per m^3.

Here too, evidence must be provided that these figures have been achieved in the annual plant performance test and have been met by the operational performance of the plant averaged over the year.

15.7 Sources of further information and advice

In compiling the Austrian regulations concerning the treatment of waste refrigeration equipment, the government has chosen to adopt major elements of the guidelines on the disposal of refrigeration equipment published by the German Federal Environmental Agency UBA and of RAL's GZ 728 quality assurance test specifications.

According to their homepage (http://www.ral-online.org/index.html) the RAL Quality Assurance Association for the Demanufacture of Refrigeration Equipment Containing CFCs was created to guarantee quality in the fridge recycling process and to ensure compliance with existing environmental standards. The Quality Assurance and Test Specifications are a comprehensive compilation of requirements that cover all stages of the demanufacturing process. With complete documentation and logging stipulated for every step, the RAL standard ensures that demanufacturing is a totally transparent process.

The quality assurance specifications for the demanufacture of CFC-containing refrigerators and freezer appliances focus on the two main stages of refrigerator recycling. The first stage involves the collection and storage of the waste appliances, and the second stage is concerned with their processing. The processing stage is itself further divided into step one (extraction of CFC refrigerant from the cooling circuit), step two (extraction of CFC blowing agent from the insulating material) and finally, the handling of the output material streams from step one and step two. For further details use the link http://www.ral-online.org/html_engl/verantwortung.html.

The WEEE Forum is a European association of 39 electrical and electronic waste collection and recovery systems. According to their homepage its mission is to provide a platform for cooperation and exchange of best practices, and in so doing, optimise the cost-effectiveness of the operations of the member organisations, while striving for excellence and continuous improvement in environmental performance. Regarding the requirements for the treatment of WEEE and refrigerators there is only a draft version of the WEEELABEX available which is still under development.

15.8 Conclusions

The treatment of refrigerators and freezers is a very complex task which should be carried out in an environmentally sound manner due to the high possible environmental impact of cooling and blowing agents. Also the introduction of new cooling and blowing agents with less impact to the climate did not lead to lower technical specifications for the treatment. On the contrary, from an environmental point of view standards have to be developed in order to align the quality of collection and treatment in Europe.

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16
End-of-life options for printed electronics

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Abstract: Printed electronics is a new way to manufacture electronics utilizing an old manufacturing method combined with novel materials. It is predicted to be widely used in all different kinds of applications, but is still under development and has not yet found its place in the market. This chapter describes what needs to be considered when the printed electronics becomes waste. Such questions include the possibility for reuse, success of recycling and problems occurring if placed on the landfill, such as leaching. In particular, the use of nanomaterials raises concerns. Very little has been published on this topic up until now, so the main aim of the chapter is to discuss the potential factors to be considered in the end-of-life phase of printed electronics.

Key words: printed electronics, end-of-life, recycling, leaching.

16.1 Introduction

Printed electronics is a new way to utilize an old manufacturing method. Instead of printing text on a paper, one can print conductive, semiconductive or dielectric inks on any suitable substrate (usually plastic) to create electrical structures. Printed electronics is still under development, although the first applications are already entering the market. Because of the new manufacturing method and the use of novel materials, it is not evident what the environmental, safety and health (ESH) issues of printed electronics are throughout the life cycle. For example, does the manufacturing of materials require large amounts of energy? Are workers exposed to any unpredicted occupational health threats? Or what are the issues related to the end-of-life (EoL) phase of printed electronics? This is the focus of the current chapter. Since there is very little literature available on this subject, it is not possible to give clear answers. Thus the main aim of this chapter is more to discuss the potential factors that should be considered.

Wastes from electrical and electronic equipment are the fastest growing waste category (Bertram *et al*., 2002). In order to reclaim most of this waste, it is important to consider the ESH issues of a product's EoL phase as early as in the design phase. The maximum advantage is gained when these issues are considered while a new technology, such as printed electronics, is under development.

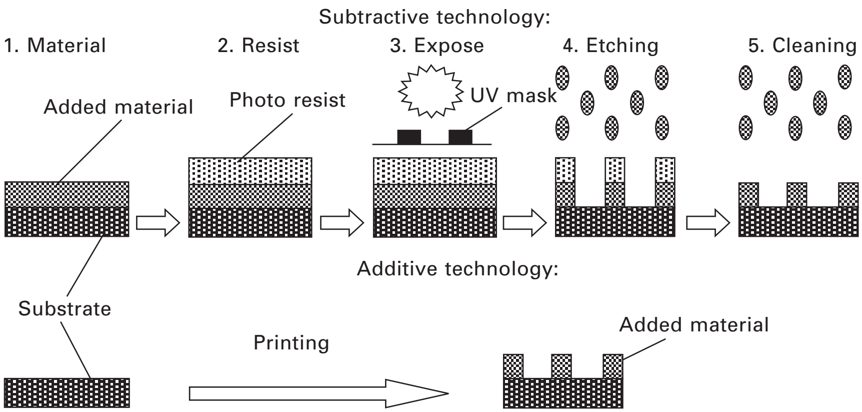
Printable electronics technology is predicted to be widely used in the future, its market being almost double that of silicon technology today (Das and Harrop, 2011). Based on the recent IDTechEx report (Das and Harrop, 2011) the market for printed electronics (including organics, inorganics and composites), will rise from $2.2 billion in 2011 to $44.25 billion in 2021. Potential applications include e-paper displays, radiofrequency identification (RFID) antennas, organic light-emitting diode (OLED) lighting, batteries, sensors and solar panels, among others. All kinds of hybrid applications are also possible, since products can include printed interconnections and passive components integrated with conventional technology. With certain limitations printed active components are also feasible. In practice this means that all the everyday electronic devices can include some printed electronics in the future – and not just electronic devices, packages, books, clothes and other traditional non-electronic products can also include electronic ‘add-ons’, increasing the functionality of the product

Given that the number of applications utilizing printable electronics may be very high in the future, what happens to the products after use requires consideration today. A large number of products also means a large amount of future waste. Can printed electronics applications be reused and recycled, and could they pose possible ESH risks if they end up in a landfill?

16.2 Printed electronics

For traditional printing and novel functional materials printing, the methods and mechanisms are the same. The manufacturing methods can be roughly divided into two categories: analog and digital printing. Analog printing includes methods already adapted to large-scale manufacturing: flexography, gravure, screen printing and reel-to-reel offset printing. Digital printing is a non-contact method allowing moderate surface roughness and accurate positioning of each droplet. The main emphasis of this chapter is on a digital printing method: inkjet printing.

Printed electronics is often mentioned as a future production technology for electronic applications. It is considered to be a potential manufacturing method for thin, light-weight, flexible and low-cost electronic devices due to the possibility of manufacturing large areas rapidly using printing technologies. Different printing techniques have their own advantages, but the common factor for all of them is that they are additive processes. This means that the electrically functional materials are added on to the substrate. Traditional electronics manufacturing, such as photolithography, utilizes subtractive process, where materials are etched away from the substrate. This requires more process steps, and also the amount of materials needed is higher, as can be seen from Fig. 16.1. Additive technology enables a change in the whole technological system of electronic devices production, including the



16.1 Process steps of subtractive and additive technology.

design and manufacturing phases, material variety and device structure and architecture.

The basics of the inkjet manufacturing process are simple. Conductive, semiconductive or dielectric inks are printed on a substrate. One kind of ink is printed at a time as a patterned layer, and over that a patterned layer of another kind of ink is printed. In the end these layers create an electrical structure, which in its simplest form can be an interconnection but can also include passive or active components.

16.2.1 Materials utilized in printed electronics

The foundation of printed electronics is the substrate on which the inks are printed. As has been said, one of the advantages of the technology is that the substrate could basically be anything from paper to skin. However, in practice these examples have quite high absorbency which is not a desired quality, and this is why mostly different kind of plastics are currently used. Popular substrates are foils made of polyimide (PI), polyethylene terephthalate (PET) or polyethylene naphthalene (PEN). Substrate can also be rigid materials such as silicon or glass, but one of the aims of the technology is to create mechanically flexible structures so these are suitable only in applications where flexibility is not a desired attribute.

The magic of printed electronics lies in the inks, and their physical properties. Finding the optimal combination of inks for creating functional electrical structures is challenging since one needs to take into consideration the printability of the inks. However, this is a topic for a complete book.

Because the technology relies heavily on the suitability and functionality of the inks, companies creating such inks are not willing to reveal the exact material content, but it is generally known that the inks include several materials. Depending on the desired function of the ink, the ‘significant’ part of the ink can be a conductive or resistive organic polymer or a conducting inorganic nanometallic ink. Beside the metal nanoparticles, inorganic conductive ink also consists of a vehicle (usually alcohol-based solvent) and of an organic dispersion agent, which prevents the agglomeration of nanoparticles. The metal in nanoparticles is usually silver, but gold or copper nanoparticles could also be used. From the EoL point of-view it is not very important what materials the vehicle and the organic dispersion agent are, since they either evaporate or are sintered and are thus not part of the final product. However, it is an important issue when considering the occupational safety in printed electronics manufacturing facilities.

For organic inks a variety of different kind of materials are available, and suitable ones depend on the requirements of the final product. Polymer inks can be either conductive or non-conductive. Some possible ingredients of the dielectric inks are for example: cycloaliphatic epoxide NOS, propylene carbonate, *n*-methyl-2-pyrrolidone, methanol, propylene glycol monomethyl ether acetate, *n*-propyl acetate, siloxane polymer, 2-methoxy-1-propanol and 1-methoxy-2-propanol (Keskinen and Valkama, 2008).

16.2.2 The advantages and disadvantages of printed electronics

There are several reasons why printed electronics is gaining in interest. First, the printing process can be applied to many different kinds of substrates, and also three-dimensional printing is possible. These facts among others are going to change the whole system of producing electronic devices, including the design and manufacturing phases, material selection, and device structure and architecture. Second, printed electronics offers better economics to electronics manufacturers. In contrast to printing, traditional electronics is only cheap on the mass production scale. In particular, inkjet printing can offer flexible and cheap production for tailored small-volume products. Third, printing offers new business models. Inkjet technology enables ‘desktop manufacturing’, which applies to small-scale micro-factories with small fixed costs.

One of the negative sides of printed electronics is that the electrical performance of applications created using printed electronics is not at the same level as that of silicon-based electronics (Pekkanen *et al.*, 2007). This shortcoming applies directly to the materials used in electronics printing. As the technology becomes more mature, performance will improve. Besides performance, the reliability of structures is also not always high, and can lead to a short lifespan of the applications. For some of the applications, long operating life is not needed, since printed electronics is predicted to be used in many disposable products such as cereal boxes, but in other applications it can be a disadvantage.

One of the biggest question marks related to printed electronics are the ESH issues of the used nanoparticles. The assessment of the ESH issues of nanoparticles is problematic for many reasons. First of all, it is impossible to generalize results gained from studies on one type of nanoparticle, since the variety of nanoparticles is far from homogeneous. Second, there is a lack of methodology, metrology and other basics, such as how to monitor nanoparticles. Third, it is still unclear which of the characteristics of the nanoparticles could cause the possible toxic effects. Possible characteristics include: size, shape, surface area, surface properties (charge, reactivity, etc.) and agglomeration. It is also possible that the solvent used and/or the presence of any coatings or environmental factors (pH, salinity, etc.) has an effect on potential toxicity (Anon., 2004; Handy *et al*., 2008).

The reason for concern about the ESH issues of nanoparticles is that they have the ability to cross cell membranes. Because of their small size (the same scale as cellular components and larger proteins), there have also been some suggestions that nanoparticles may evade the natural defenses of humans and other species and damage cells (Anon., 2004). Because of the possible ESH effects, nanoparticles are considered as a possible risk in each life-cycle phase, although the risk of exposure is rather low in each life-cycle phase. It is most significant in the manufacturing phase (if there is a lack of appropriate protective measures) and in the EoL phase if the nanoparticles are released to nature.

16.3 End-of-life options and their challenges

Since printed electronics has not yet conquered the markets, there is no knowledge about the problems that will arise in practice. Printed electronics is moving from enabling technology to application, but at the moment most of the created applications are demonstration models and not produced en masse.

The aim of this paragraph is to discuss what kinds of ESH issues should be considered with different kinds of EoL options. The focus is on the challenges posed by specifically the introduction of printable electronics technology. The issues related to certain printed electronics applications are not discussed profoundly. This is because the EoL challenges are different for each application, and there are already numerous studies on the other technologies and materials.

When studying the risks inherent in printable electronics, the whole life cycle of the printed electronics applications must be considered. This includes everything from material extraction to the EoL phase. The relative environmental importance of these different life cycle phases depends on the applications. However, the EoL phase is generally assumed to be of great significance, since according to Bertram *et al*. (2002) wastes from electrical and electronic equipment constitute the fastest growing waste category. This is because the lifetime of the electronics applications is usually rather short. If products break down, it is too expensive to repair old models and they also soon become outdated.

Short lifespan means that the consumption of products is rather high. With printed electronics the large number of possible applications also increases the amount of future waste. One of the main environmental concerns with printable electronics comes from the use of novel materials. According to the report of Finland's Environmental Administration, exposure to nanoparticles is quite unlikely in the use phase of electronics using nanotechnology, but at the EoL phase of the applications environmental risks may occur (Suomalainen and Hakkarainen, 2008).

However, nanoparticles used in printed electronics are sintered in the manufacturing phase. In sintering the nanoparticles are heated until they adhere to each other. Thus the final products should not include free/wild nanoparticles. On the other hand, it remains uncertain if all the nanoparticles are actually sintered, or how strong the cohesion is.

When printed electronics applications reach the end of their use phase, there are many options for the EoL. The product or its parts can be reused as it is, its materials can be recycled or the energy content of the materials can be utilized by incineration. Combinations of these options also occur. The worst but very likely possibility is ending up in landfill, especially if the printed electronics is part of some other product or package; for example; if the printed electronics is a simple screen game on the side of a cereal packet.

16.3.1 Reuse of products

From the environmental point of view reuse is usually the best option, but since printed electronics is planned to be used especially in low cost high volume products, many of them being disposable, reuse may not be feasible. This is because the products are not planned to be durable, and the lifespan can be short. It is also often more economical to purchase new equipment than it is to repair or upgrade older models. However, currently there are ongoing studies on the reliability of the printed structures so it might be possible to extend the lifespan, if desired. A big problem is that with cheap products the threshold to throw a still functional product to trash bin is low, so when the product first user gets bored with it, it might not find its way to other users.

16.3.2 Recycling of components and/or materials

The general challenges related to recycling include the recyclability of the products and the economics of the logistics needed to collect and recycle discarded products. With logistics the nature of WEEE is not that important, so that aspect is not discussed here, but the recyclability is an important topic.

One of the main ideas of printed structures is high integration, and the printed structures are flat and solid. This complicates the dismantling and the recovery of materials. Can the materials be separated easily? Is it possible to separate the substrate from printed structures, and is it advisable? And how do present recycling operations need to be modified and process parameters adjusted in order to properly recycle printed electronics applications? These are just some of the questions to be answered in future studies around the world.

In printed electronics, the most interesting materials for recycling are the used metals. The recovery of metals can be achieved, as presented in Chapter 10, through manual sorting or mechanical processing, such as crushing, screening or magnetic and electrostatic separation. The particle size, shape and liberation degree play crucial roles in mechanical recycling processes. Because of this almost all mechanical recycling processes have a certain effective size range (Cui and Forssberg, 2003). In order to ensure the material recovery from printable electronics applications, the most appropriate process for the applications at hand needs be determined in future studies.

The recovery of silver and other precious metals is especially important in order to avoid metals rising in price and resource depletion (Ayres, 1997; Lanzano *et al.*, 2006; Pickard, 2008). Metal recovery is also ecologically important for other reasons; this prevents the possible leaching of metals in the landfills and reduces the need to mine metals.

The use of electronics in traditionally non-electronic applications (such as cardboard packages and glass bottles) also affects the recycling of those applications. For example, Aliaga *et al*. (2011) has studied the influence of RFID tags on recyclability of plastic packaging. Normally plastic packaging becomes plastic waste, but the presence of electronic devices can affect the quality of recycled plastic if it is not removed. Based on the study, several operational problems during the recycling process were found. These include the loss of extruded plastic during the process and the obstruction of the screens, which affected negatively the process yield and created process interruptions. However, the study did not reveal a statistically significant quality difference in the recycled plastic, and some of the operational problems were believed to be easily solved in large-scale recycling plants.

16.3.3 Recovery of energy content

Whether or not the metal content could be separated, printed electronics structures also include other materials requiring handling. If the dismantling of products is difficult and not worth the effort, one possibility is to recover the energy content by incineration. The incineration of the combustible fraction of the waste has two advantages: it reduces the volume and concentrates valuable metals into the residual ash so that they can be reclaimed in a subsequent operation. However, it is uncertain how the various products of printed electronics would behave in incineration. The main concern is the possible formation of hazardous incineration gases.

The amount and nature of gases formed are mainly dependent on both the materials in the product and the incineration temperature (Stewart and Lemieux, 2003; Hall and Williams, 2007; Guan *et al*., 2008). The materials vary depending on the product, and as stated earlier, the number of different printed electronics applications can be high. Thus it may be impossible to incinerate all the applications in optimized temperatures. Especially if the printed electronics application is attached to some other product, such as a cereal packet, there is a risk that the product ends up in basic waste. After that, it can be incinerated in general incineration facilities, and not in those designed especially for waste from electrical and electronic equipment. An interesting topic for future studies is also to determine if pyrolysis could be utilized.

16.3.4 Ending up in landfill

The WEEE Directive requires electric and electronic equipment to be sold with special markings indicating that they do not belong in normal waste, but should be collected separately. Consumers recycle big EEE, but with smaller products the risk of ending up in normal landfills is bigger. The potential ‘add-on’ applications could be especially problematic as they would be printed as part of some other product, for example the afore mentioned simple screen game on the side of a cereal box or a RFID tag in shoes. The presence of electronics makes these products WEEE, but a normal consumer may not treat them as such.

The behavior of printable electronics applications in soil depends on the structure of the applications, and on the physical and chemical properties of the materials. Usually electronic devices are closed structures, and it is likely that the printed electronic applications would be inside a cover, and thus it would take some time before the materials are in contact with the elements of nature.

Instead of placing the printed electronics products in landfill, one of the future scenarios would also be to compost the products. But this requires the products to be either fully or partly biodegradable. Fully biodegradable products could be for example the earlier mentioned add-ons. If only a part of the product is biodegradable, it should be easily separated from the rest of the product. The separating should be as easy as removing batteries or accumulators, and would require clear labeling and guidance for the end-user. In the wildest scenarios products could also be edible, but that raises hygienic questions which are not relevant in composting.

16.3.5 Leaching at the landfill

If we assume that the printed electronics will actually be in contact with the elements of nature, this raises the question of leaching. Although the nanoparticles should not be free/wild after sintering, some may still be unsintered, or the cohesion may not be strong enough, causing some leaching. It is possible that the relatively large surface area of these nanoparticles causes them to be absorbed into the soil, preventing their migration. On the other hand, the small size may enable their migration much further than with bigger particles (Suomalainen and Hakkarainen, 2008). Ending up in landfill can be problematic due to leaching, for example, of silver from the discarded products (Meyer *et al*., 2009). However, it is not certain how high risk this would be, since there are contradictory results in the studies on the leachability of solder (containing silver) in printed wiring boards (Griese *et al*., 2000; Townsend *et al*., 2008).

Many different factors affect leaching, such as pH, contact time, particle size, leaching solution content and oxidation–reduction potential (Townsend *et al*., 2008). Several methods are available for leachability testing: two commonly used options for identifying the leaching properties of waste materials are one or two stage batch tests. These are commonly used in Europe as compliance tests to determine if the waste is eligible for landfill disposal. These tests are based on the European Standards SFS-EN 124572:2002 and SFS-EN 12457-3:2002.

In these tests a small sample (< 4 mm) is brought into contact with leachant under controlled conditions. The liquid to solid ratio (L/S) depends on the test. In a one stage batch test it should be 10 l/kg during the extraction. Then the capped bottle containing the sample and leachant is agitated for about 24 hours. After this the solid residue is separated by filtration, and the properties of the solution recovered from the leaching test are measured. In analysis the concentrations of constituents of interest are determined. After the test the leaching conditions (pH, conductivity, etc.) are recorded. Lithner *et al*. (2009) have made similar tests combined with toxicity tests for cut CD-Rs containing silver.

At Tampere University of Technology a one stage batch test was made for a sample of printed electronics. The tested sample consisted of two layers with varying thickness of inkjet printed and sintered silver nanoparticle ink and one layer of dielectric on PI substrate. Silver coverage was 66% of the area and the total mass of the sample was 19.3 g (Ag 0.66 g). Results indicated a 5.5 mg/kg silver concentration in the test with liquid to solid ratio (L/S) 10 l/kg. For silver 48 h EC50 (acute toxicity) for *Daphnia magna* is 0.055 mg/l. So the results indicate 100 times higher values. Although the silver detoxication can be high, leaching evidently is a topic of concern. However, it should be noted that in the EU area there is no regulated limitation for the amount of silver leaching in the landfills (Commission Directive 2003/33/EC).

16.4 Consideration of EU legislation

When developing new technology, the requirements set by the legislation might not be one of the first things in mind. However, before the applications can hit the market these also need to be taken into consideration. There are three major directives concerning environmental issues of electronics: Restriction of Hazardous Substances (RoHS), WEEE and EcoDesign Directives. RoHS and WEEE have been introduced earlier in this book, and EcoDesign focuses in practice on energy efficiency, so it is not very relevant from the EoL point of view.

The RoHS Directive, at the moment, restricts the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). All of these can be quite easily avoided in printed electronics applications, since the technology is new and there are no established methods, unlike in traditional electronics where the replacement of lead required a lot of effort. In addition to the currently restricted substances of RoHS, there is a growing demand for further restrictions of different substances. In summer 2010 MEPs suggested that nanosilver should be included in the list of restricted substances (Anon., 2010). This was not agreed on a larger scale, but although it is not banned in RoHS, it is just a matter of time before a directive concerning products including nanoparticles is created, and it is possible that nanosilver will then again be at risk of being banned. It has also been suggested that products including nanotechnology should be labeled.

One of the advantages of printed electronics over traditional electronics with regard to RoHS compliance is that the materials used are more easily traceable. In traditional electronics, products are often built from hundreds of different components each containing different materials and manufactured in different locations. For the producer of the final product it takes lots of effort to track down the material content of all of these parts. However, in highly evolved printed electronics one only needs to know what the different kind of inks contain.

The WEEE Directive focuses on the reuse, recycling and other forms of recovery of WEEE. The original WEEE Directive is quite old, and printed electronics is a new technology, so anything directly related to printed electronics is not mentioned in the directive. However, some of the instructions of annex II could be extended to include certain printed electronics applications. For example, the big printed circuit boards created with printable electronics technology could be gathered separately. Also the displays manufactured with this new technology could be included here.

In addition to the directives mentioned before, the Registration, Evaluation, Authorisation and restriction of CHemicals) (REACH) Directive also affects printed electronics. It is possible, that some of the substances will be restricted due to REACH, but it is also possible that some chemicals or substances that are not very common and not worth registering will vanish from the markets. This mainly concerns chemicals coming from outside the EU.

Printed electronics is also used to create printed batteries. The developers say that these batteries are environmentally friendly and because of the lack of toxic substances can be thrown away with regular trash. However, the Accumulator and Batteries Directive says that all batteries need to be collected in separate collecting points. It remains to be seen if an exception is created for printed batteries.

16.5 Future trends

Printed electronics is a new technology still requiring technical development before it can truly find its place in the market. However, the expectations are high: the global printed electronics market is predicted to grow to $44.25 billion in 2021. Expectations are especially high for printed photovoltaic panels, due to the constantly rising price of energy. In addition to solar cells, the major future applications of printed electronics include RFIDs, sensors, displays, e-paper, batteries, flexible OLEDs (lighting and displays) and wearable electronics.

From the EoL point of view the most significant trend is naturally the predicted rise in the amount of WEEE. One solution to this problem would be the development of biodegradable electronics. Biodegradable electronics are optimal especially in disposable electronics, but also in biomedical applications. Biodegradable materials can be already used as substrates (e.g. leather, silk, hot-pressed cotton-fiber paper), so the next step to achieving full biodegradability would require innovations in the ink development. There are lots of ongoing studies related to finding suitable biodegradable materials used in electronics. The interest in these materials comes not only from environmental point of view, but also from the economic perspective since many of the biodegradable materials are low cost. Studied materials include sugar, small molecular nucleobases, betacarotene, gelatine, indigo, food colors (indanthrenes) and cosmetic colors (perylene diimide). For example, four substances from the nucleobases family can work as dielectrics: adenine, guanine, cytosine and thymine (Irimia-Vladu *et al.*, 2010).

Since printed electronics relies heavily on nanotechnology, it is also good to mention the ongoing discussion related to new kind of waste: nanowaste. Currently very little information is available on how to treat and dispose of products including nanomaterials, and many are hoping that the waste management methods for nanoparticles are developed before great amounts of nanoproducts start to be disposed of. It is possible, that in the future nanowaste will be regulated as hazardous waste to be collected and recycled separately. For the consumer this can be a bit confusing, since electronic devices are already collected separately. Would there then be separate collection points for WEEE including nanomaterials and WEEE not including nanomaterials (Bystrzejewska-Piotrowska *et al.*, 2009; Musee, 2011)? It is predicted, that in the year 2020 over 1000 tonnes of nanomaterials for ICT purposes will be produced (Anon., 2004), and it is evident that at some point this becomes waste. Hopefully some answers related both to the possible toxicity and recycling possibilities of nanomaterials are found before we reach that point.

16.6 Sources of further information and advice

The newest developments in printed electronics are reported in *Printed Electronics World*, available at: http://www.printedelectronicsworld.com/

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17
Recycling batteries

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Abstract: Batteries are the power source for portable electrical and electronic devices, hence the use and discharge of batteries is growing all over the world along with such devices. Many directives have been elaborated, starting from the beginning of the 1990s, concerning the adequate destination of spent batteries in order to avoid metal contamination of soil and water resources. Spent batteries represent an important secondary source of metals that can be normally found at very high concentration levels, sometimes even higher than those found in natural ores. In addition, some metals are quite expensive, such as cobalt and nickel, which can be found in significant amounts in NiCd, NiMH and Li-ion batteries. Therefore, the recovery of metals from spent batteries is also convenient for economic reasons since large amounts of solid wastes can be reused as secondary raw material. In this chapter the recycling of batteries is discussed.

Key words: spent batteries, hydrometallurgical processes, pyrometallurgical processes, metals recovery.

17.1 Introduction

A battery consists of one or more electrochemical cells connected in series and/or in parallel aiming to produce electrical energy. Each cell generally has an anode, a cathode and an electrolyte. The electrical energy is produced by chemical reactions that result in a transfer of electrons from the anode to the cathode. The amount of power available in a battery is limited owing to the changes on the chemical species during such reactions. Primary batteries are assumed to be discharged when their chemicals are consumed. However, for a secondary or rechargeable battery, an external source of power can be used to change the direction of the flow of electrons, thus reversing the electrochemical process until the chemical species in the anode and in the cathode are restored to their original state, allowing its use again. Therefore, the use of rechargeable batteries instead of primary ones is preferable from the environmental point of view because their use contribute significantly to reduce the amount of spent batteries to be treated.

Batteries are the power source for portable electrical and electronic devices, hence the use and discharge of batteries is growing all over the world along with such devices. Batteries are part of a variety of electrical and electronic devices such as personal computers, mobile phones, laptops, toys, cordless phones, tools, etc.

Although batteries are a component of electrical and electronic equipment (EEE) they must be recycled separately. They might be removable or fixed inside EEE, but should be disassembled and recycled by specific processes. Consumers and recyclers might not be aware of the existence of built-in batteries. The separation of the batteries from the EEE is costly because it is done manually, nevertheless the recyclers should not neglect this important operation.

In Brazil, the annual consumption of batteries is estimated around 1.2 billion units, or nearly six units/year/person; in the USA, Japan and Europe, it ranges between 10 and 15 units/year/person. The number of mobile phone subscriptions worldwide reached 5.28 billion by the end of 2010 (MercoPress, 2011). In India, there are more than 770 million of mobile subscribers today (Headlines India, 2011). Such figures are constantly growing.

The main characteristics of the mostly used batteries are shown in Table 17.1, including their application, advantages and disadvantages, while their typical metal composition is depicted in Table 17.2. Spent batteries may represent an important secondary source of metals that can be normally found at very high concentration levels, sometimes even higher than those found in natural ores. In addition, some metals are quite expensive such as cobalt and nickel, which can be found in significant amounts in NiCd, NiMH and Li-ion batteries. Therefore, the recovery of metals from spent batteries is convenient also for economic reasons since large amounts of solid waste can be reused as secondary raw material.

17.2 Main directives worldwide for spent batteries

Many directives have been elaborated from the beginning of the 1990s concerning the adequate destination of spent batteries in order to avoid metal contamination of soil and water resources. The very first directives were focused mainly on NiCd batteries, which were mostly used in mobile phones at that time, as well as in the progressive reduction on the use of mercury, cadmium and lead in some types of batteries. Nowadays, issues such as collection systems, reduction of other heavy metals, ban of use of mercury in the production of batteries and recycling procedures are highlighted in the current directives of several countries as depicted in Table 17.3. According to these directives, the adequate destination of spent batteries may involve methods such as landfill disposition, stabilization, incineration and/or recycling processes. Safe disposal in landfills or stabilization of battery residues becomes more and more expensive due to the increasing amount of waste produced, and also to the limited storage capacity of sanitary landfills and/or special waste dumpsites. Incineration of batteries is also expensive,

Table 17.1 Main characteristics of commercial batteries. Adapted from Mantuano (2005)

Type of battery	Anode/negative electrode	Cathode/positive electrode	Electrolyte	Advantages	Disadvantages	Main applications
Zinc-carbon	Zn	MnO_2	Ammoniac, $ZnCl_2$ and water	Current density is higher than Zn-Air battery; best service at low temperatures; good resistance to leaking; high efficiency with heavy discharge.	High gas formation; sealing system must be efficient due to high sensibility to oxygen.	Domestic general use.
Alkaline	Zn	MnO_2	KOH	Higher current density; good performance to intermittent and continuous discharges; good life use and resistant to leaking; lower internal resistance; good mechanical resistance and low gas production rate.	More expensive than Zn-C battery.	Domestic general use.
Silver	Zn	AgO	KOH or NaOH	Electrical characteristics are similar to Hg-battery with higher voltage (1.55 V); very low self-discharge rate.	Low energy capacity due to its small size.	Military use; systems that require instantaneous release of energy.
Lead	Pb	PbO	H_2SO_4	Comparing to other secondary batteries, it is the most economic one; maintenance is not required.	Contain lead; heavy.	Automotive use.
Nickel-cadmium	Cd	$Ni(OH)_2$	KOH	Durability is not affected when stored even at charge; some models can perform 30 000 cycles of charge and discharge.	Contain cadmium.	Wireless devices, cameras, laptops, pagers and mobile phones.

Table 17.1 Continued

Type of battery	Anode/negative electrode	Cathode/ positive electrode	Electrolyte	Advantages	Disadvantages	Main applications
Nickel-metal-hydrate	AB_5 type: $MmNi_{3,5}Co_{0,7}Mn_{0,4}Al_{0,3}$ AB_2 type: $V_{15}Ti_{15}Zr_{20}Ni_{28}Cr_5Co_5Fe_6Mn_6$	$Ni(OH)_2$, Cobalt oxides and additives	KOH	Higher energy per volume and weight when compared to NiCd; do not contain cadmium.	Production cost is higher than Ni-Cd but lower than Li-based batteries.	Portable devices, mobile phones.
Lithium-ion	C	$LiCoO_2$	Organic solvents and/or salt solutions ($LiPF_6$)	Higher current density; higher use life; higher nominal voltage.	High cost.	Portable devices, mobile phones, hybrid vehicles.
Lithium-polymer	Li	$LiFePO_4$ or $LiMn_3O_6$	Solid polymer electrolyte (SPE), Polyethylene oxide (PEO) and $LiCF_3SO_3$	Its plastic character hence flexibility means it can be made in different shapes and thinner configurations.	Relatively low life cycle and efficiency.	Electronic devices, hybrid vehicles.

Table 17.2 Typical metal composition of commercial batteries (Veloso *et al.*, 2005; Silva and Afonso, 2008)

Element	Zinc-carbon[1]	Alkaline[1]	Silver	NiCd[2]	NiMH[2]	Lithium[2]
Ag			28.2–30.8			
Al				0.019	0.5–2.0	4.6–24
Cd				15–20		
Ce				0.43–5.5		
Co				0.600	2.5–4.3	12–20[a]
Cr				0.017	0.020–.080	
Cu						5–10
Fe	0.2–1.0	0.17	0.3–0.7	29–40	20–25	4.7–25
K		5.5–7.3				
La					1.4–6.6	
Li						1.5[b]–5.5[c]
Mn	23–30	26–33		0.083	0.81–3.0	10–15[d]
Nd					0.96–4.1	
Ni	0.007	0.010		15–20	25–46	12–15[e]
Pb		0.005				
V						15–20[c]
Zn	5	12–21	8.7–12.1	0.060	0.092–1.6	

Note: [1]Include dry black powder only; [2]Considering the whole battery.
[a]Li-ion (Co); [b]Li-ion (Co, Ni, Mn); [c]Li-polymer (V); [d]Li-ion (Mn); [e]Li-ion (Ni).

and it can even cause mercury, cadmium and dioxin emissions into the environment (Bernardes *et al.*, 2004).

In fact, the recycling of spent batteries appears as the most adequate destination for this type of waste. As pointed out by Conard (1992), the recycling of wastes is important since it may contribute to the benefit of future generations and to the preservation of raw materials. In the particular case of batteries, it is still necessary to develop an efficient collection system in order to receive the spent batteries consumed worldwide (Mantuano *et al.*, 2006). According to CONAMA 401/2008 (Conselho Nacional de Meio Ambiente, Brazilian Environmental Agency), the most adequate destination of spent batteries must minimize environmental risks and adopt technical procedures for collecting, reusing, recycling, treating and final disposal of such wastes. Such aspects are discussed as follows.

17.3 Methods for the recovery of metals from spent batteries

Recycling processes of waste materials such as batteries must be as simple and as cheap as possible. The current processes used to recycle portable batteries include pyrometallurgical and hydrometallurgical techniques (Salgado *et al.*, 2003; Bernardes *et al.*, 2004; Espinosa *et al.*, 2004).

Most collection programs receive all types of batteries, so the chemical

Table 17.3 Directives for batteries in Brazil, China, USA, Japan and European Union

Country	Directives	Main characteristics
Brazil	CONAMA 257 (1999), updated by CONAMA 401 (2008)	CONAMA Resolution 257 was the first law dedicated to the conscious use of batteries in Brazil and Latin America. It established the requirement for reuse, recycling, treatment or final disposal of batteries containing lead, cadmium, mercury and its compounds, as well as the electronic products that contain integrated non-replaceable batteries into their structure. Manufacturers and importers are responsible for processing and/or final disposal of batteries returned by users. It imposed also a gradual reduction on the limits of mercury, cadmium and lead in the composition of batteries, from January 2000 to January 2001. In 2008 it was replaced by CONAMA Resolution 401. It established an even more significant reduction in the levels of Hg, Pb and Cd in several types of batteries. It intended also to give more effectiveness to post-consumption responsibility of manufacturers and importers of batteries, according to which they become bound by the full cycle of their products, not only to be purchased by consumers. Manufacturers and importers must be registered, submit a technical report containing physical and chemical composition of batteries produced and a plan for managing used batteries. Places that sell batteries must include collection points and return collected batteries to manufacturers or importers. Advertising materials and packaging of batteries must clearly show symbols indicating the appropriate destination, warnings about the risks to human health and environment. Manufacturers, importers and distributors will be encouraged to promote environmental education campaigns for post-consumer.
China	Regulation on Restriction of Hg in Batteries (1997)	Ban, from January 2001, the manufacture of Zn-Mn and alkaline batteries containing more than 0.0025% by weight of Hg and 0.00001% by weight of Hg from 2005. Primary, rechargeable and button cell batteries were excluded from these limits.
USA	Universal Waste Rule (1995)	Reduce the amount of waste to landfills, encourage recycling and proper disposal of hazardous wastes and reduce regulatory burdens on businesses that generate these wastes in order to facilitate compliance. Provided the standardization for collection, storage and transportation of NiCd batteries, other rechargeable batteries and certain Hg-containing batteries.
	Mercury-containing and Rechargeable Battery Management Act	Standardize the labeling of NiCd and lead-acid rechargeable batteries and products containing them. Ban the sale or the offer for promotional purposes of alkaline and Zn-C batteries containing intentionally introduced mercury and button cells of mercuric oxide (except button cells with up to 25 mg of Hg), unless the manufacturer or importer define the collection site for recycling or proper

	(Battery Act, 1996)	disposal. Manufacturers and importers must propose a chronogram to eliminate the production and marketing of certain batteries containing mercury, the label must contain information on the chemical composition, the recycling symbol and a sentence indicating that the consumer must send it for recycling or proper disposal. Traders with annual sales exceeding $1 million must, from July 2006, install collection points and receive (free of charge) batteries of all types and brands as well as publicity campaigns about the benefits of recycling. For internet sales, they must inform consumers about the return of the batteries or how to dispose them properly.
Japan	Law for the Promotion of the Effective Utilization of Resources (1999, revised in 2001)	Valid for NiCd, NiMH, Li-ion and lead acid batteries. The position of recycling symbols, letters and colors to identify each battery, including in the packages of batteries, according to specific law for the recycling of packages; labeling the type of material used in the body of the batteries; development of new designs for easy removal of batteries from equipment; manufacturers are responsible to recycle the collected batteries; recycling targets were established: above 60% for NiCd, 55% for NiMH, 30% for Li-ion and 50% for lead-acid; formula for calculating the recycling rate for each type of battery (recycling rate = total weight of recycled material/total weight of collected material); electronics manufacturers must recycle or pay for it or transfer the collected batteries to the battery manufacturers that must receive them without cost.
European Union	Directive 1991/157/EC updated by Directive 2006/66/EC	Valid for all types of batteries except those used in security equipment, for military purposes and to be launched into space. Batteries with mercury content higher than 0.0005% by weight (except button cells, whose Hg content can be less than 2% by weight) and portable batteries with cadmium content above 0.002% by weight (except those for use in alarm systems and emergency medical equipment and cordless power tools) are prohibited to be commercialized after September 2009. Adopt necessary steps to promote and maximize the selective collection of batteries and minimize household waste disposal; ensure that distributors of portable batteries accept their return free of charge, and manufacturers of industrial batteries, or third parties on their behalf, accept the return of spent batteries from consumers; collect 25% of all used batteries by September 2012, increasing to 45% by September 2016; require manufacturers of products incorporating batteries that is accomplished only on condition that they are easily replaced after use by consumers and should also also inform how to proceed to allow their disposal; ensure, from September 2009, that all batteries are collected and treated using the best available techniques in terms of health and environment (batteries must be handled and stored temporarily in places totally water-proof or suitable containers. Treatment must include, at least, the removal of all fluids and acids); recycle by September 2010 at least 65% of lead-acid, 75% of the NiCd

Table 17.3 Continued

Country	Directives	Main characteristics
		and 50% of other battery types; encourage the development of new technologies for recycling and treatment for all types of batteries; encourage technological innovations that improve the performance of batteries; inform consumers through campaigns of the effects of substances used in batteries on human health and the environment; the need to send such waste to resellers, systems for collecting and recycling available, the importance of their participation in this process and the meaning of the symbols listed on labels and packaging. The labels on the batteries must bring in a visible, legible and indelible, their power, the chemical symbols Hg, Cd and Pb to the batteries containing levels higher than 0.0005% of Hg, 0.002% of Cd 0.004% of Pb, respectively, and symbols not to discard in the trash. All producers of batteries must be registered in the countries where they sell their products (Directive 2009/603/EC).

composition of battery waste might be very irregular, as shown in Tables 17.1 and 17.2. Most recycling processes were developed to recycle only a few types of batteries. Therefore, initially it is necessary to sort the batteries in order to segregate the ones that cannot be treated by that specific process. For example, in general, a process that treats Zn-C and alkaline cells does not admit contamination with NiCd batteries. However, the situation observed in the collection systems is the mixing of different types of battery. Unfortunately, there is no correlation between shape and size with the composition of batteries. This characteristic complicates the sorting processes. This step, allied with the transportation, increases the total cost of recycling processes. With the exception of NiMH batteries, in general, battery recycling processes are viable only through funding or legal obligation, i.e. the revenue does not cover the cost of operation (Bernardes *et al.*, 2004).

17.3.1 Main processing routes

Battery recycling processes are composed basically of two main steps: waste preparation and metallurgical processing. The waste preparation step begins with the screening of the waste, segregating it by chemical type. The sorting might be composed of several steps in order to improve the separation efficiency. These steps might contain manual segregation and segregation using pieces of equipment developed specially for this operation. The pieces of equipment developed to this end apply several techniques, for example: mechanical separation, magnetic separation, X-ray images, optical sensors to read bar codes located on the waste material (Bernardes *et al.*, 2004).

After sorting, the material to be recycled is prepared for the metallurgical process through physical conditioning operations. These operations are based on typical ore dressing unit operations, such as crushing, comminution, magnetic separation, electrostatic separation and dense medium separation (DMS). The crushing involves the fragmentation of the waste and its main goal is to separate most of the polymeric or metallic cover from the internal material, which contains the target metals to be recycled. The main goal of the comminution step is to diminish the particle size in order to liberate the several types of material. The other cited operations have the objective to separate materials according to specific characteristics. Magnetic separation is applied to separate magnetic materials (such as iron, nickel and their alloys) from the non-magnetic material. Electrostatic separation aims to separate conductive material from non-conductive, roughly metal from non-metal. The DMS technique segregates materials with different densities.

Therefore, the objective of the waste preparation step is to concentrate the fraction of the waste that contains the target metals using physical methods, which present relatively low costs of processing. Hence, even considering the limited efficiency of such processes, these operations might diminish the overall cost of the recycling process diminishing the amount of material that should be treated by the metallurgical processing.

The metallurgical processing can follow three different routes, pyrometallurgy, hydrometallurgy or hybrid processes that use techniques from pyro- and hydrometallurgy to obtain metals or metal compounds. There are several battery recycling facilities around the world. Table 17.4 presents some examples of battery recycling processes, showing the treated material and their limitations (Bernardes *et al.*, 2004).

17.3.2 Pyrometallurgical route

Pyrometallurgy is characterized by the use of high temperature processes. Hence, the pyrometallurgical recycling processes use high temperature to process wastes aiming at the reclamation of the target metals. During heat treatment of battery waste, several reactions may take place such as decomposition of compounds, reduction and evaporation of metals or compounds (Espinosa *et al.*, 2004).

All pyrometallurgical processes for the recycling of batteries have in common the evaporation of a metal to segregate it from the other materials that have higher boiling points. Therefore, the goal of these processes is to evaporate Hg, Zn and/or Cd.

Zinc-containing batteries can be recycled by pyrometallurgical processes since the boiling points of the containing metals (Hg, Zn and Mn) are very different. During heat treatment, after water evaporation, the elimination of Hg through evaporation takes place due to its low boiling point. Frenay and Feron (1990) observed that thermal elimination of Hg, which is linked to chlorine ions of the electrolyte, should be performed at 600 °C. Conversely, Xia and Li (2004) found that 450 °C is enough to remove Hg under vacuum. After Hg decontamination, zinc can be recovered also through distillation, but at temperatures higher than 907 °C (zinc boiling point).

The global discharge reaction of either an alkaline or Zn-C cell can be expressed as (Sayilgan *et al.*, 2009):

$$Zn + 2MnO_2 \text{ Æ } Mn_2O_3 + ZnO \qquad [17.1]$$

Therefore, one should expect to find in the waste of spent batteries not only metallic Zn, but also ZnO, MnO_2 and Mn_2O_3. Zinc oxide, when heated above 920 °C under atmospheric pressure and in the presence of a reductor (such as the carbon that is a constituent of these types of batteries), is reduced according to the following reaction (Rosenqvist, 2004):

$$ZnO + CO \text{ Æ } Zn_{(v)} + CO_2 \qquad [17.2]$$

Since the temperature at which the reaction occurs is above the Zn boiling point, Zn is produced directly in vapor form (Rosenqvist, 2004). Consequently,

Table 17.4 Examples of battery recycling processes (Espinosa *et al.*, 2004; Mantuano, 2005)

Process	Route	Treated material	Limitation	Observation
SUMITOMO	Pyrometallurgical	Household cells: alkaline, Zn-C, Zn-air and mercury	NiCd and Pb-acid batteries	Lithium batteries recycling process is patented.
RECYTEC	Pyrometallurgical	Most types of batteries, including fluorescent lamps	NiCd batteries	
SNAM-SAVAM	Pyrometallurgical	Originally NiCd batteries and Cd bearing wastes		The process treats Ni-MH batteries since 1995 and Li-ion since 2000. In 2009, starts to process alkaline and saline batteries
INMETCO	Pyrometallurgical	Dust from furnaces containing iron, zinc and lead and also several types of batteries: NiCd, NiMH, NiFe, Li-ion and Zn-Mn	Mercury	
WAELZ	Pyrometallurgical	Zinc bearing material, such as electric arc furnace dust, treatment of furnaces dust, Zn-C batteries and alkaline batteries	Mercury	
ACCUREC	Pyrometallurgical	NiCd, NiMH and Zn-containing batteries		A hydrometallurgical step is used in the process of NiMH battery recycling to reclaim rare earth metals. Li-ion recycling process is being developed.
TNO	Hydrometallurgical	NiCd batteries		
BATENUS	Hydrometallurgical	Most types of batteries	Mercury	
ZINCEX	Hydrometallurgical	Zinc bearing materials	Mercury	
RECUPYL	Hydrometallurgical	Most types of batteries	NiCd, lead and button batteries	
UMICORE	Hybrid	Li-ion and NiMH batteries	NiCd batteries	

the recycling process must be carried out in temperatures above 920 °C in order to evaporate most of the Zn.

Manganese remains solid throughout the process, but during heating the pre-reduction of the manganese oxides to MnO occurs, due to the carbon present in the charge. The material that remained solid is composed mainly of MnO and iron (from the metallic cases).

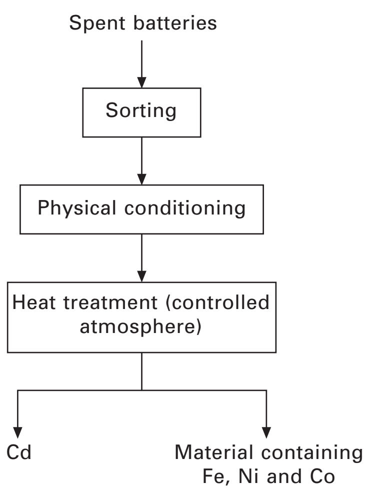
Pyrometallurgical processes for the recycling of electric arc furnace (EAF) dust (and Zn bearing materials), such as Inmetco and Waelz, accept in the charge Zn-C and alkaline batteries. In such processes, the comminuted material is mixed with a carbon-based reductor. This mixture might then be agglomerated in the form of pellets, depending on the process. Following this, the mixture or pellets are put into an open-hearth furnace or a rotative furnace, which operates at temperatures up to 1350 °C. During the process, Zn and other volatile compounds or elements are captured in the gas treatment system (Bernardes *et al*., 2004; Espinosa *et al.*, 2004).

Classical recycling processes of NiCd batteries are typically pyrometallurgical and are based on Cd distillation. Figure 17.1 shows a schematic flow sheet of a theoretical pyrometallurgical recycling process of NiCd batteries. During heating, after water evaporation, the decomposition of Cd and Ni hydroxides take place as follows (Espinosa and Tenorio, 2004):

$$Ni(OH)_{2(s)} \rightarrow NiO_{(s)} + H_2O_{(g)} \quad T = 230\,°C \qquad [17.3]$$

$$Cd(OH)_{2(s)} \rightarrow CdO_{(s)} + H_2O_{(g)} \quad T = 300\,°C \qquad [17.4]$$

The recycling process can be carried out with or without the presence of a reducing agent (usually carbon based). In order to avoid the use of a reducing



17.1 Schematic flow sheet of the operations for the pyrometallurgical recycling of NiCd batteries.

agent, the total pressure of the system must be about 10^{-4} bar to enable the decomposition of CdO at 850–900 °C producing Cd vapour (Espinosa and Tenório, 2004).

If the process is carried out with the aid of a reducing agent, the reduction of the oxides of nickel and cadmium is thermodynamically possible at relatively low temperatures (lower than 510 °C). The boiling point of metallic Cd is 767 °C, so above this temperature Cd is produced directly into vapor form.

Generally, the pyrometallurgical process to recycle NiCd batteries is performed in temperatures of about 900 °C, under vacuum, under inert atmosphere or imposing a reducing atmosphere (Espinosa and Tenório, 2006). The controlled atmosphere is necessary to avoid the oxidation of the produced metallic Cd. Metallic cadmium is produced with 99.9% purity and can be used in numerous applications including the production of new NiCd batteries. The material that remains solid during the treatment is composed basically of Ni, Fe and Co and can be used in the stainless steel production.

Pyrometallurgical recycling processes for NiCd batteries also treat NiMH batteries mixed in the charge, however only Ni is recovered and the rare earth elements present in this kind of waste are lost in the process.

17.3.3 Hydrometallurgical route

A typical flow sheet for the recovery of metals from spent batteries using hydrometallurgical methods is shown schematically in Fig. 17.2. Firstly, batteries must be classified by type because metal composition varies significantly as shown in Tables 17.1 and 17.2. Then, after dismantling for the removal of iron scraps, plastic cases and paper, the internal content of the battery is submitted to a leaching step in order to transfer metals of interest from the solid phase to the aqueous solution. Acid and alkaline solutions are normally used as well as oxidant and reducing agents.

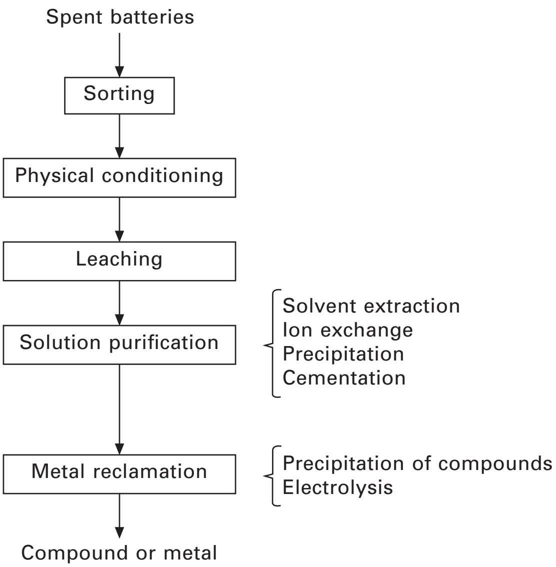
For example, in the leaching of Zn-carbon or alkaline batteries, selective leaching of zinc and manganese can be achieved by using sequential leaching steps with dilute H_2SO_4 solution in order to preferentially extract zinc, followed by leaching of the remaining residue with concentrate H_2SO_4 solution with H_2O_2 in order to extract manganese (Veloso *et al.*, 2005). The following reactions may occur in the dissolution of zinc and manganese oxides:

$$ZnO + H_2SO_4 \rightarrow ZnSO_4 + H_2O \quad [17.5]$$

$$Mn_2O_3 + H_2SO_4 \rightarrow MnO_2 + MnSO_4 + H_2O \quad [17.6]$$

$$Mn_3O_4 + 2H_2SO_4 \rightarrow MnO_2 + 2MnSO_4 + 2H_2O \quad [17.7]$$

$$MnO_2 + H_2SO_4 + H_2O_2 \rightarrow MnSO_4 + 2H_2O + O_2 \quad [17.8]$$



17.2 Schematic flow sheet depicting the main steps of hydrometallurgical recycling of batteries.

In fact, zinc oxide can be fully dissolved by sulphuric acid solutions according to Eq. (17.5). On the other hand, the dissolution of Mn_2O_3 and Mn_3O_4 oxides is partial because MnO_2 produced is insoluble [Eqs. (17.6) and (17.7)]. For instance, the leaching of alkaline battery powders with 1.0% (v/v) H_2SO_4 at 90 °C for 2 h has resulted on the dissolution of only 43% of total manganese originally present in the powder (Salgado *et al.*, 2003). A similar result (dissolution of 40% of manganese and 100% of zinc oxides) was obtained using 0.7% (v/v) H_2SO_4 at 70 °C and 3 h (Souza *et al.*, 2001). Therefore, to leach 100% of the manganese present in the powder, the use of hydrogen peroxide (H_2O_2) as reduction agent is a plausible alternative. In addition, the removal of potassium from the powder of Zn-carbon and alkaline batteries may also contribute to reduce the consumption of H_2SO_4 in the acidic leaching step.

In the case of Li-ion batteries, alkaline solutions of NaOH were used to leach aluminium in a selective way, followed by acid solutions of H_2SO_4 in order to leach cobalt and lithium (Ferreira *et al.*, 2009). Many other aqueous systems including HCl, HNO_3 and H_2SO_3 in the presence or not of H_2O_2 have been evaluated to leach Li-ion batteries as shown in Table 17.5.

After leaching, the aqueous solution is submitted to a purification step that may comprise several separation methods such as cementation, precipitation, solvent extraction, adsorption, ion exchange, and others. Finally, the metal species are recovered from the purified solutions as pure metals or as metal oxides, hydroxides and/or salts.

Table 17.5 Summary of operational conditions for the metal recovery from Li-ion batteries (adapted from Ferreira *et al.*, 2009, reprinted with permission from Elsevier)

Reference	Leaching step				Liquor treatment step		
	Leaching agents	T (°C)	S/L ratio (g/mL)	Main leaching results	Methods	Reagents	Main liquor treatment results
Ferreira *et al.* (2009)	NaOH, followed by H_2SO_4 + H_2O_2	30 to 70	1/10	Alkaline leaching: Al (60%), Co (negligible) and Li (10%). Acid leaching of Al, Li and Co around 80–100%. H_2O_2 improved $LiCoO_2$ leaching, mainly Co	Crystallization by evaporation	–	Purified $CoSO_4 \cdot H_2O$ was obtained
Shin *et al.* (2005)	H_2SO_4 + H_2O_2	75	1/20	Co (95%) and Li (100%) at the presence of H_2O_2 (15% v/v). Granulometry effect was found significant for Co only	–	–	–
Swain *et al.* (2007)	H_2SO_4 + H_2O_2	75	1/10	Co (93%) and Li (94%) with 2 M H_2SO_4 and H_2O_2 (5%)	–	–	–
Mantuano *et al.* (2006)	H_2SO_4	80	1/30	Low recovery of Co (30%). Acid concentration and temperature were found significant	Solvent extraction	Cyanex 272	Co/Li separation at pH = 5. Co/Al and Co/Cu separations were found difficult
Dorella and Mansur (2007)	H_2SO_4 + H_2O_2	65	1/30	Co (75%) and Li (100%) at the presence of H_2O_2 (1% v/v)	Precipitation and solvent extraction	NH_4OH and Cyanex 272	Al (80%), Co (8%) and Li (13%) were precipitated at pH = 5. A stripping solution Co (63 g/L) and Li (0.4 g/L) was obtained
Lee and Rhee (2002, 2003)	HNO_3 + H_2O_2	75	1/100	Co (95%) and Li (95%) with H_2O_2 (1,7% v/v)	Precipitation	Citric acid	Pure $LiCoO_2$ was obtained

Table 17.5 Continued

Reference	Leaching step				Liquor treatment step		
	Leaching agents	T (°C)	S/L ratio (g/mL)	Main leaching results	Methods	Reagents	Main liquor treatment results
Contestabile *et al.* (2001)	HCl	80	–	n-Metilpyrrolidone solubilized PVDF aiming to separate powdered materials from Al and Cu foils	–	–	–
Zhang *et al.* (1998)	HCl, NH_2OH, HCl and H_2SO_3	80	1/100	Co (>90%) and Li (>90%) with concentrated $NH_2OH \cdot HCl$ and HCl. H_2SO_3 showed low metal recoveries	Solvent extraction	D2EHPA and PC-88A	PC-88A was found more selective: Co (>99.9%) and Li (12.6%) extracted with 0.9 M PC-88A
Nan *et al.* (2005)	NaOH and H_2SO_4	25 and 70	1/10 and 1/5	NaOH leached Al (98%) selectively. Co (>90%), Li (>90%) and Cu (<10%) were leached with H_2SO_4	Precipitation and solvent extraction	Ammonium oxalate, Acorga M5640, Cyanex 272	Co (90%) precipitated with 0.5% impurities. Cu (97%) and Co (97%) extracted with Acorga and Cyanex 272, respectively
Lupi *et al.* (2005)	–	–	–	–	Solvent extraction and electrolysis	Cyanex 272	Full extraction of Co (100%). Electrolysis solution containing Co (<1 ppm) and Ni (<100 ppm) was obtained

In hydrometallurgical processes, zinc can be recovered from the aqueous solution by electrolysis but the presence of contaminants may affect its efficiency as well as the quality of the zinc produced; for example, in the presence of cadmium, both metals will deposit thus reducing the purity of metallic zinc. Therefore, the purification step of the leach solution is crucial for the operation success so very selective methods are used for the purification of zinc such as solvent extraction (Mansur *et al.*, 2002; Salgado *et al.*, 2003), cementation (Feijó, 2007), ion exchange and precipitation (Veloso *et al.*, 2005).

In the solvent extraction method, an organic phase containing an adequate extractant depending on the metal to be extracted is put into contact with the aqueous leach liquor. The metal is transferred to the organic phase which is scrubbed if necessary to remove co-extracted species and then submitted to the stripping step when the extracted metal is transferred to another aqueous phase. The metal of interest is separated and even concentrated depending on the aqueous/organic ratio as well as other operating conditions. This method is largely used to separate several metals such as zinc, cobalt, nickel, manganese, copper, rare earths and many others. A review of solvent extraction applied to metal systems is given by Ritcey and Ashbrook (1984), Habashi (1993) and Rydberg *et al.* (2004). Ion exchange works in a quite similar way to solvent extraction but the leach aqueous solution is put into contact with a solid resin containing the extractant which reacts with the metal of interest. After this stage, the loaded resin is submitted to an elution step aiming to recover the extracted metal to another aqueous solution. Ion exchange is discussed elsewhere (Zagorodni, 2006). The use of precipitation has various purposes as in the case of water treatment for instance but in the case of battery recycling it is mainly used in the selective separation of metals; it is carried out by controlling the pH of the aqueous phase with the addition of precipitating agents like NaOH, CaO, Na_2CO_3 and many other reagents. In the treatment of spent zinc-carbon or alkaline batteries, iron can be removed from the solution by precipitation in pH higher than 4.0 and with the use of an oxidizing agent. Finally, the cementation method uses a dislocating reaction to promote the metal separation that is carried out by adding a less noble metal species in the solution aiming to reduce the more noble metal species. For example, the addition of zinc powder promotes the precipitation of nickel according to the following equation:

$$Ni^{2+} + Zn_{(s)} \rightarrow Ni_{(s)} + Zn^{2+} \quad [17.9]$$

In the hydrometallurgical treatment of NiCd batteries, the internal material obtained from dismantling is previously milled and subsequently leached in acidic medium resulting in an aqueous leach solution containing nickel, cadmium and iron. After iron removal by precipitation, nickel and cadmium are separated by solvent extraction and then recovered by electrolysis.

Similarly, for the case of NiMH batteries, previous treatment is required to separate the internal parts of the battery which is leached with H_2SO_4, resulting in a leach solution containing rare earths, nickel and cobalt. The former can be separated by precipitation while the last metals are separated by solvent extraction. Some studies revealed that hydrometallurgical routes to NiMH may include one step to recover cadmium because several NiCd batteries were found to be labeled as NiMH (Bertuol *et al*., 2006; Rodrigues and Mansur, 2010).

Hydrometallurgical routes are commonly more complex and require a higher number of steps in comparison to pyrometallurgical routes; however, they are efficient, more flexible, more energy saving and present high metal selectivity, so hydrometallurgical routes are becoming more frequent to treat spent batteries which contain several different metals in their composition. In addition, the leaching agents and reagents can be regenerated and reused several times in closed circuit operation. From the environmental point of view, the generation of gases is relatively lower so Conard (1992) has pointed out the hydrometallurgical route to be used in the treatment of various wastes thus contributing to the sustainable development. In fact, the recycling of spent batteries has advantages not only from the environmental point of view because the natural resources are finite (Gupta and Mukherjee, 1990), advantages are also economic because metals content present in spent batteries are quite higher as well as their purity than those commonly found in their ores.

17.4 Future trends

The future trends on recycling of batteries are directly related to the market of electro/electronic portable devices. In the last two decades, the substitution of NiCd batteries, in most portable devices, by NiMH and lithium-based batteries has occurred. The main reasons for this change were environmental policies. Hence, technical concerns were less important in this substitution. Probably in the next decades these systems should be optimized to improve their capacities.

The waste of post-consumer spent batteries is a mix of several types of batteries. So, if the existing recycling processes were selected to recycle this kind of waste, the spent batteries should be segregated by type prior to recycling. One possible trend is the development of a new process that treats more types of spent batteries, avoiding this initial separation; another is the improvement of the segregation methods.

A new potentially important application of batteries is electric and hybrid vehicles. The market for such vehicles is increasing, mostly due to environmental concerns. The waste generated by this type of use is different from the waste post-consumer spent batteries. The vehicles are equipped with one specific type of rechargeable batteries, making it easier to segregate the batteries upon disposal.

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18

ErP – the European Directive on ecodesign

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Abstract: This chapter gives an overview of the European Ecodesign Regulation for Energy-related Products (ErP). This is helpful in order to highlight different regulatory approaches compared to waste electrical and electronic equipment (WEEE) and to show the potentials for collaboration or for conflicts between the two regulations.

Key words: ecodesign regulation, Framework Directive, energy-using products (EuP), energy-related products (ErP).

18.1 Introduction

The Framework Directive for the setting of ecodesign requirements for energy-related products (in short either 'Ecodesign Directive', 'ErP directive' or sometimes still referenced as 'EuP (energy-using products) Directive') has been in force since 2005 and targets environmental requirements for a large section of the EEE market (Commission Directive 2009/125/EC, replacing Commission Directive 2005/32/EC). There are two main reasons for including this directive in a book on waste electrical and electronic equipment (WEEE) practices. First, the directive is slightly newer than the original WEEE and Restriction on Hazardous substances (RoHS) Directives, and is based more closely on 'new approach' principles and on 'IPP', the integrated product policy (European Commission, 2001, 2012a). Secondly, as the ErP Directive holistically covers all environmental aspects of various product groups, there is a potential for overlaps, for contradictions or for cooperation between the different directives.

Rather than covering the exact status of the ErP Directive implementation, which is a moving target due to the Framework Directive construct, this chapter will focus on the legislative mechanisms involved, and on the potential for conflict or constructive cooperation between ErP and WEEE. Nevertheless, the basics of the ErP Directive, and its predecessor the EuP, need to be covered for those readers not familiar with the directive and its implementation procedures.

18.2 Trends leading to ecodesign regulation

The ErP targets a large variety of products with the intention of reducing life-cycle impacts by either setting requirements, which have to be incorporated at the design stage of the products, or by accepting or promoting industry-led initiatives, which must be set up to achieve comparable magnitudes of environmental improvements. The ErP is of interest both to explore legislative trends, but also the trends of new products and technologies and the consumption patterns.

From the legislative trends, the ErP incorporates various elements of 'new approach', and as a Framework Directive leads to a nearly continuous implementation and review process. The acceptance of voluntary agreements instead of a specific legislation is one of the influences of the new approach. These aspects will be explained in more detail in a later section of this chapter.

From the environmental perspective, the ErP follows the fundamental approach of addressing the whole life cycle of products, which is clearly desirable when compared with other topic-specific pieces of legislation. In principle this allows a more balanced approach to environmental improvements without the danger of regulating one aspect of a product to the detriment of other environmental aspects or increased impacts in other life-cycle phases, as discussed in Chapter 6. The directive is built on the assumption that the highest potential for improving the environmental performance of a product lies in the design stage.

Procedures for focusing on the most relevant environmental impacts per product group are established in order to keep the requirements lean and effective. Hence, while holistic in outlook, the directive is also very pragmatic and market oriented in implementation.

Another market oriented aspect is that the requirements are tailored to achieve the best environmental improvement without increasing costs (purchasing and use phase costs together) for the customers. As a trend this means that there is a built-in procedure to make the environmental requirements economically sound as well.

On the product scope the ErP Directive has express provisions to target horizontal effects across many product groups, such as the standby topic. In the mix of product group specific requirements and horizontal requirements there is a chance to cover fast-changing product configurations, which in other directives can only be included in scope through a lengthy directive recast. Thus the ErP is at least in this respect more flexible and specifically suited to the fast-changing electronics sector.

As a counterbalance to the flexibility of adapting the scope, planning security is very important for the affected companies. In line with the new approach the elements of published work plans and of stakeholder inclusion have turned out to be very important. Advance warning is therefore given about which specific product groups will come under investigation within the following one to two years. And the start of an investigation does not mean that new legislative requirements have to result – it is really an open process, which is moderated among the stakeholders.

18.3 Introducing the ErP Directive

The ErP Directive is the 2009 recast of the original EuP Directive dating from 2005 (Commission Directive 2009/125/EC, replacing Commission Directive 2005/32/EC). As a Framework Directive it needs both transposition into national laws in the EU member states and so-called implementing measures, which define the actual requirements and time lines for products and manufacturers. Through the nationally transposed framework, the implementing measures enter into force in all member states directly.

An analysis of the scope may be a good way to understand core elements of the directive. The short name of the directive 'EuP' derives from 'energy-using products'. Hence, from the original directive, the scope is much larger than the 'EEE' from 'WEEE'. It covers not only electrical energy, but also gas and oil operated products, has no inherent limit on voltage levels and can – in principle – target not only full products, but also components. Contrary to the WEEE and RoHS scope there is no Annex with a list of product categories to define the scope, and only means of transport for persons and goods are summarily excluded from the scope of the Framework Directive.

The scope has been further enlarged with the recast as the 'ErP' Directive, now covering all 'energy-related products'. Energy-related in particular targets products, which during the use phase do not need any type of energy carrier, and yet have a large influence on the energy use of other products. Prime examples are insulating materials, windows or water-saving shower heads. However, since these products are further removed from the WEEE scope, the discussion in this chapter will remain focused on electrical products, which were already in scope with the original EuP Directive.

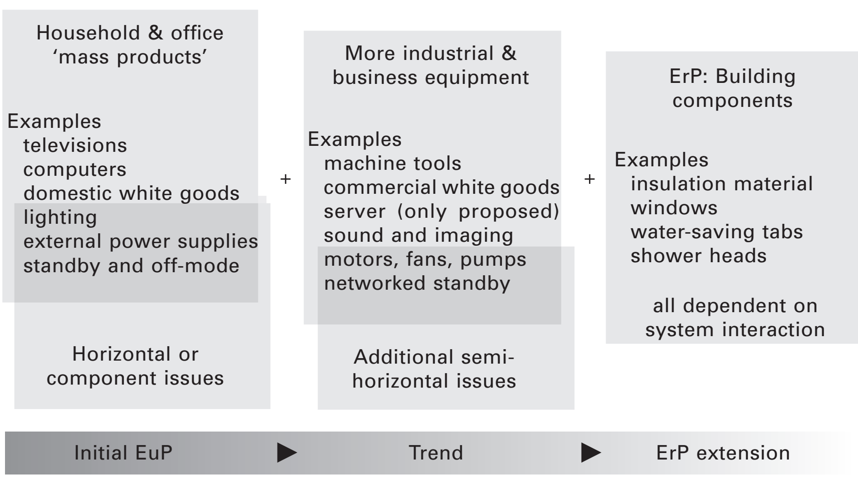
The open scope is only practical, because the ErP is set up as a Framework Directive, which in itself does not pose any obligations on products, on manufacturers or on other market players. Only after an open development and decision process can ecodesign requirements influence the market, giving a few years of advance warning and of intensive stakeholder inclusion in most cases. This will be explained more in detail in the next section of this chapter.

One important filter mechanism to select product groups with high environmental relevance is that more than 200 000 units of the product category must be placed on the market per year. This criterion shows that mass products, such as those employed in home and office environments, are the first candidates for consideration under the directive. By now, many of these product groups have been analysed and various implementing measures have been passed or are in preparation. Table 18.1 in Section 18.6 summarises the progress of implementation. The focus in terms of investigated products has shifted more to larger, industrial products and will now expand to the 'energy-related' products as explained above and illustrated in Fig. 18.1.

Another important aspect on the directive's scope is that 'horizontal' measures, such as setting limits on standby power consumption, are directly addressed in the directive. Therefore, not only products which are technically and environmentally similar enough to put them into one product group for a 'vertical' regulation, but also functionalities and components, which are used across many very different product types, can be targeted in an implementing measure. 'Motors' are an example of a product group, which can also be seen as a component regulation or a horizontal improvement approach.

Long before the development of the EuP Directive, the ideas for IPP were developed (European Commission, 2001). EuP and ErP can be seen as one cornerstone of IPP implementation for electronics, complementing approaches such as environmental labelling, green public procurement and – where implemented nationally – financial incentives for environmentally preferable products. WEEE and RoHS are sometimes also subsumed under IPP principles, but mainly due to one aspect only as they were set up to strengthen the producer responsibility.

Starting from the holistic ideas of IPP, the EuP follows two main principles. First, the reduction of environmental impacts of products is best incorporated into the design phase. And second, to make environmental requirements effective the whole life cycle and all quantifiable environmental impacts should be analysed before focusing on those aspects, which can be improved in a cost-effective and competitive manner.



18.1 Scope extension from household to industry to ErP products, based on Nissen *et al.* (2010). Copyright Fraunhofer IZM.

So, at the core the ErP Directive sets up the goals and procedures by which the EU Commission can start stakeholder interactions (through studies and consultations), which may or may not lead to implementing measures of ‘vertical’ or ‘horizontal’ character.

18.4 Examining the Framework Directive concept

A Framework Directive is more complicated but also more flexible than setting up individual directives for each and every product group coming under environmental scrutiny. To some extent the processes follow the ‘new approach’ principles, developed in 1985 (European Commission, 2012b, European Standards Organisations, 2006). These propose a clearer distinction between legislation (‘essential requirements’) and standardisation for the actual conformity procedures. As an aside, even the harmonised standards remain voluntary, meaning that a company can give proof of conformity without directly using the standards.

Strong stakeholder inclusion – in the development of the requirements and in the development of the standards – is not a necessity under the new approach, but is often attributed as a logical consequence of these principles. Even though the ErP and the pursuant implementing measures are not listed as regulations belonging to the new approach, mandates to the European standardisation bodies have resulted from several of the implementing measures. The ErP conformity is integrated into the CE marking scheme like some of the stricter new approach directives, which means that the producer declares conformity with all EU regulations pertaining to the product by affixing the CE mark. It is a self-declaration, which may afterwards be challenged by authorities.

Apart from the first phase of implementation starting in 2005 there is a fixed sequence of procedures to determine whether an implementing measure is justified, and if so, how to develop it until implementation.

The work plan announces the type of ErPs to be examined in the following years. In the work plan study the magnitude of the market, the relevance of the environmental impacts caused and the potential for improvement are already checked, but on a highly aggregated basis. Stakeholder involvement starts during the work plan development, meaning that not only industry representatives but also consumer organisations, environmental non-governmental organisations (NGOs) or EU member state representatives can at certain points comment and contribute.

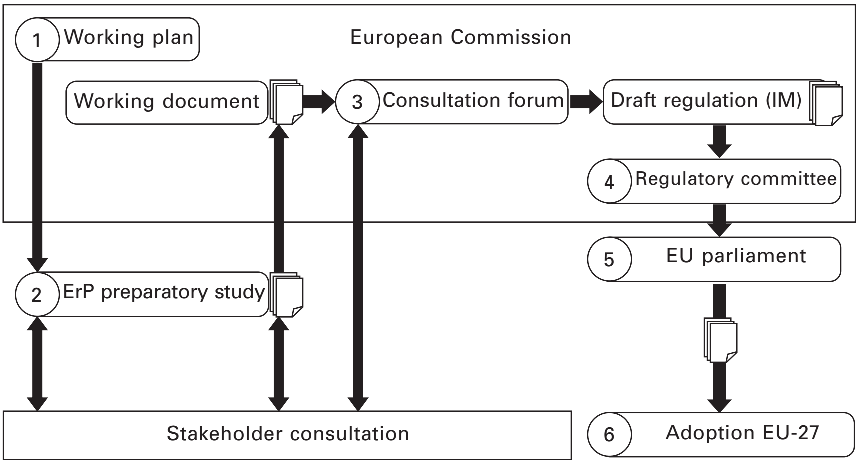
Based on the work plan the European Commission may start so-called preparatory studies, usually by public tender to independent experts and consortia of experts. The preparatory studies examine the environmental improvement potential in more detail and explore different policy instruments for each product group or horizontal aspect. There is a common procedure and calculation tool for the different preparatory studies, ensuring that the results of studies on different product groups performed by different experts are compatible. At the end of the studies a recommendation for the commission is formulated, which may combine a mix of policy instruments, i.e. ecodesign requirements via an implementing measure, setting requirements via voluntary agreements led by industry, or input to ecolabeling and financial incentive schemes, which are both actually outside the ErP scope.

Interim results of the preparatory studies and the final results up to the policy recommendations are published for stakeholder interaction. The study recommendations are also made publicly available, but not always before the end of the formal stakeholder discussion. The preparatory studies are the most active part for broad stakeholder involvement, with study durations of typically 18 months, and registered stakeholders per study going into the hundreds. From the process the industry gains a good warning for when and how requirements could impact their products and markets. Niche products and smaller producers still face the danger of being surprised by eventual measures, especially if scope clarification happens after the start of a study, but on the whole information networks and the work of industry associations distribute the relevant notifications.

The non-industrial stakeholders have the chance to challenge the industrial status quo and present arguments for stricter requirements, or for more user-oriented implementation of requirements. Since NGOs and non-industrial associations often lack the financial backing to follow the many parallel and quite technical discussions in the preparatory studies, the European Commission has provided some funding for these purposes since 2008.

From the study results the Commission first decides on whether to pursue a legal act in the form of an implementing measure, or whether a voluntary agreement by industry might be a viable and effective alternative, or whether no action is suitable at that point.

If a legal provision is part of the most effective instrument mix then the commission drafts a so-called working paper for an implementing measure, which is then published and discussed in the so-called consultation forum. The consultation forum comprises the member state representatives at the core but also includes industrial and non-industrial associations. If the consultation forum raises only minor or medium objections the commission goes ahead with transposing the technical requirements into a legal text. An impact assessment showing the benefits and potential costs or unresolved objections is mandatory at this point, and will likewise be made public, though not for a formal round of stakeholder feedback. A regulatory committee consisting of member state representatives will once more check the validity of the proposal, before the final legal text is prepared for publication in the official journal. A graphical overview of the procedures until adoption of an implementing measure is given in Fig. 18.2.



18.2 Overview of the main steps and documents leading to an implementing measure. Copyright Fraunhofer IZM.

In most cases the implementing measures contain at least two tiers of requirements with staged introductory dates. The first tier should enter into force no earlier than 6 months after official publication of an implementing measure, with 12 to 24 months now being the standard. This is the time frame that even companies not following the earlier stakeholder process have for redesigning all affected products after the final requirements and their exact phrasing are known.

In that respect even 12 months can be very short as a redesign period, considering that even a small company might have to redesign several products with the full chain from component selection up to product re-qualification and documentation. Clearly, without advance warning from the preceding stakeholder process this is not possible for many product types.

All together the process for creating ecodesign implementing measures takes three to five years typically. Forty-one product groups or horizontal aspects have undergone the process or are currently being investigated. Fifteen implementing measures are in force at the time of writing, and only two product groups are close to being accepted for implementation as voluntary agreements. See Table 18.1 in Section 18.6 for more details on the status of implementation. An update of the methodology for the preparatory studies and a new work plan are currently under development. In essence, the ErP is now a near-continuous process for all stakeholders and for the European Commission.

18.5 Comparing ErP and WEEE approaches

The original WEEE and RoHS Directives are sectorial and product centric approaches, but do not incorporate a full life-cycle perspective. Instead, two distinct environmental aspects of growing importance have been tackled in isolated form: the reduction of hazardous substances and the improvement of end-of-life (EoL) treatment. Both aspects needed to be regulated, because the precautionary principle and the producer responsibility principle could not be met by letting the market forces rule.

Following from IPP, which was already around during the development of WEEE and RoHS, ecological products should be put in a position to have a better market position, if environmental costs such as depollution, disassembly and recycling would have to be borne by the manufacturers. In addition to reducing the waste treatment costs in formal recycling in the long run (it takes a long time for RoHS-compliant products to reach recycling), the RoHS aims to reduce chemical risks in total – be it from misuse and accidents in the use phase or from informal recycling around the globe.

Although impact assessments were carried out for both directives, there was no open and transparent stakeholder process, where technical, financial and environmental effects of the implementation and of the timelines for introduction could be discussed. In hindsight, many people and especially industry still claim that the inception and implementation of the directives were not only missing transparency, but were totally unrealistic and unbalanced between economic costs and environmental gain.

The story has more facets of course, since industry in a way collectively declined to discuss technicalities of specifically the ban of lead at some point in order to stop exactly such a substance-focussed legislation. But once the precautionary principle is in place as a motivation then economic arguments can take second place – as long as the common market within the EU is not affected, products could even be forced to become more expensive to phase out a substance, which is only potentially harmful. So, environmental and health legislation may in cases be enacted disregarding economic costs, although most legislative procedures are by now required to investigate such effects in a more thorough impact assessment.

The WEEE Directive is less disputed from that angle, as it deals mostly with costs and less with risks. However, for the WEEE implementation the disparity between intentions and implementation might be even larger than for the RoHS Directive. The cost allocation for WEEE treatment – and whether the original individual producer responsibility would be feasible and preferable – will be covered in other sections of this book. In this chapter let us concentrate on design-related aspects.

The WEEE Directive has one explicit design-related goal that producers should improve the re-use, disassembly and the recyclability of their products. However, only two incentives are at all relevant in the implementation: the costs for recycling and more indirectly the information that producers are supposed to provide for recyclers.

In almost all member state implementations the producer pays per kilogram of product put on the market. Improvements or any specific design aspects of the product do not reduce the system fees in any way, unless the weight of the product is reduced. Therefore, WEEE disposal fees have had a negligible effect on improving 'design for recycling' (DfR).

Likewise the secondary effect that better product design would necessitate less effort for the generation of additional documentation for recyclers did not and will not materialise. While some companies really do publish disassembly documentation, most recyclers prefer to use intuition and experience of their work force instead of accessing such documentation from the companies. Unless for very complex, high value products, the workflows of recyclers still do not incorporate checking the original manufacturers' websites. All manner of projects that have tried to bring the electronic information on disassembly directly to the work bench have not progressed beyond the pilot stage.

Without incentives to improve their products regarding disassembly, recycling and disposal, manufacturers are mostly putting their design efforts elsewhere, or have even reverted to optimising for low cost and ease of assembly only. There are three exceptions to this trend: niche markets, producers with own recycling facilities and platform designs. Apparently, good DfR appears in niche markets, where specialised design features, long-lived design and repair friendliness are rewarded.

A clear incentive for good design is also apparent for the few companies, which have internal recycling facilities, such as Fujitsu Computers in Germany. Combining re-use with efficient recycling of their own products is mostly based on business to business products, which can be reclaimed from the market in large batches of one product configuration.

As a third option some large brands do have good platform designs maintained and slowly modified over the years, despite missing market incentives. But since good disassembly designs also offer advantages in assembly and repair these proven designs also are viable for products sold in millions.

The WEEE legislators have now recognised that incentives in the current WEEE and likely in the coming recast do not achieve better product design choices directly. Since 2008 draft documents for the WEEE recast mention the Ecodesign Directive. The original commission proposal from 2008 makes reference to the EuP/ErP Directive, but still puts the burden on the member states to 'encourage measures to promote the design and production of electrical and electronic equipment notably in view of facilitating re-use, dismantling and recovery of WEEE, its components and materials.' An additional clause deals with measures to be taken by the member states so that producers do not prevent re-use through specific design choices.

Although the WEEE recast will hopefully be finalised by the publication of this book, it may be of interest to take a look back at some of the interim viewpoints on the WEEE to ErP linkage. The European Parliament proposed in 2010 to add a time limit until end of 2014 for implementing WEEE-related requirements in ErP implementing measures. This proposal was also part of the first reading version of the WEEE recast in February 2011.

This would be a new quality of cooperation between the directives, but also a potential source of conflict: whereas national WEEE implementation would still have to define measures for product design to facilitate re-use and recycling and to prevent countermeasures to re-use, the ErP implementation would likewise be tasked to develop and incorporate ecodesign requirements. The fixed deadline of less than two years after a presumed recast publication would be a special challenge to the ErP procedures. The earliest reviews of implementing measures will most likely start in 2013, but would not be expected to finish by the end of 2014. However, as is usual in such draft stages the date could still change according to the overall progress of the recast.

The common position of the European Council in July 2011 moved the explicit cross-link with the ErP from Article 4 'product design' to the recitals section. The new recital would be: 'Ecodesign requirements facilitating the re-use, dismantling and recovery of WEEE should, where relevant, be laid down in the framework of measures implementing Directive 2009/125/EC. In order to optimise re-use and recovery through product design, the whole life-cycle of the product should be taken into account.' This is complemented by the following recital, which was already part of the original commission proposal: 'The establishment, by this Directive, of producer responsibility is one of the means of encouraging design and production of EEE which take into full account and facilitate its repair, possible upgrading, re-use, disassembly and recycling.'

After that, the draft amendments for the second reading from the environmental committee of the parliament suggested that the recitals could nearly stay the same, but that the parliament would wish to keep the ErP cross-link in Article 4, including the explicit date for revised implementing measures.

In summary, from the different proposals it seems likely that two different design-related obligations might be incorporated in the WEEE recast. One is the WEEE internal obligation that addresses member states to develop measures, which in turn should encourage or promote designs more optimised for WEEE purposes. Depending on the final wording, member states may have the freedom to develop non-uniform measures across Europe or to restrict these activities to measures which are non-mandatory for companies.

A second impetus for design improvements would be to recommend or in harder wording to require that ErP-implementing measures define WEEE-related ecodesign requirements. Once such ecodesign requirements were in place, they would apply directly and uniformly across all of Europe. But the required processes on the ErP side are unlikely to produce results within the next two years, or even within a fixed time horizon of, for example, the next five years.

18.6 Status of ErP implementation and coverage of end-of-life (EoL) aspects

Fifteen implementing measures are in force under the ErP Directive. Table 18.1 shows the status of adopted and pending implementing measures at the beginning of 2012. All of these concentrate on energy efficiency, which for most of the products means electrical energy. The main reasons why energy is central in the current ecodesign requirements, are the dominance of energy in the use phase in most environmental assessments, and that the compliance can be tested on the final product.

Table 18.1 Overview of implementation status under the ErP Directive (adapted from European Commission, 2012c)

Product groups (with lot number and responsible DG)	State of play of regulation	Year of adoption or foreseen adoption
1. Heating, water heating equipment, HVAC (heating ventilating air conditioning) systems		
Boilers and combi-boilers – (ENER Lot 1)	Pending	2012
Water heaters and storage tanks – (ENER Lot 2)	Pending	2012
Airco + comfort fans – (ENER Lot 10)	Pending	2012
Domestic ventilation/kitchen hoods – (ENER Lot 10)	Pending	2013
Large air conditioners > 12 kW – (ENER Lot 10)	Pending	2013
Water-cooled air conditioners – (ENER Lot 10)	Pending	2013
Large ventilation systems – (ENER Lot 6)	Pending	2013
Local room heating systems – (ENER Lot 20)	Pending	2013
Central heating products using hot air to distribute heat (other than CHP) – (ENER Lot 21)	Pending	2013
2. Electric motor systems		
Circulators – (ENER Lot 11)	**Adopted**	**2009**
Electric motors – (ENER Lot 11)	**Adopted**	**2009**
Electric pumps – (ENER Lot 11)	Pending	2012
Fans – (ENER Lot 11)	**Adopted**	**2011**
3. Lighting in both the domestic and tertiary sectors		
Domestic lighting I (light bulbs) – (ENER Lot 19)	**Adopted**	**2009**

Table 18.1 Continued

Product groups (with lot number and responsible DG)	State of play of regulation	Year of adoption or foreseen adoption
Domestic lighting II (reflector lamps and luminaires) – (ENER Lot 19)	Pending	2012
Tertiary sector lighting I (lamps and ballasts) – (ENER Lots 8,9)	**Adopted**	**2010**
4. Domestic/professional appliances and food preparation		
Commercial refrigeration – (ENER Lot 12)	Pending	
Domestic refrigeration – (ENER Lot 13)	**Adopted**	**2009**
Domestic dishwashers – (ENER Lot 14)	**Adopted**	**2010**
Domestic washing machines – (ENER Lot 14)	**Adopted**	**2010**
Solid fuel small combustion installation – (ENER Lot 15)	Pending	2013
Household tumble driers – (ENER Lot 16)	Pending	2012
Vacuum cleaners – (ENER Lot 17)	Pending	2012
Domestic and commercial ovens incl. when incorp. in cookers – (ENER Lot 22)	Pending	2013
Domestic and commercial hobs and grills, incl. when incorp. in cookers – (ENER Lot 23)	Pending	2013
Professional washing machines, dryers and dishwashers – (ENER Lot 24)	Pending	2013
Non-tertiary coffee machines – (ENER Lot 25)	Pending	2012
Commercial refrigerating equipment – (ENTR Lot 1)	Pending	2013
5. Office equipment in both the domestic and tertiary sectors		
Personal computers and displays – (ENER Lot 3)	Pending	2012
Imaging equipment – (ENER Lot 4)	Pending	***Voluntary agreement expected 2012***
External power supplies – (ENER Lot 7)	**Adopted**	**2009**
6. Standby losses for a group of products		
Standby and off-mode losses – (ENER Lot 6)	**Adopted**	**2008**
Networked standby appliances – (ENER Lot 26)	Pending	2012
7. Consumer electronics		
Televisions – (ENER Lot 5)	**Adopted**	**2009**
Complex set-top boxes – (ENER Lot 18)	Pending	***Voluntary agreement expected 2012***
Simple set-top boxes – (ENER Lot 18)	**Adopted**	**2009**
Video players and recorders, video projectors – (ENTR Lot 3)	Pending	
Game consoles – (ENTR Lot 3)	Pending	Voluntary agreement proposed for 2012

Table 18.1 Continued

	Product groups (with lot number and responsible DG)	State of play of regulation	Year of adoption or foreseen adoption
8.	**Industrial applications**		
	Laboratory and industrial equipment (furnaces and ovens) – (ENTR Lot 4)	Pending	2014
	Machine tools – (ENTR Lot 5)	Study ongoing	Voluntary agreement proposed
9.	**Transformers**		
	Distribution transformers, power transformers, small transformers – (ENTR Lot 2)	Pending	2013
	Pumps for private and public waste water and for fluids with high solids content – (ENER Lot 28)	Study to be launched	
	Pumps for private and public swimming pools, ponds, fountains and aquariums, as well as clean water pumps – (ENER Lot 29)	Study to be launched	
	Motors outside the scope of the Regulation 640/2009 on electric motors – (ENER Lot 30)	Study to be launched	
	Compressors (ENER Lot 31)	Study to be launched	
	Uninterruptible power supply (UPS) – (ENER Lot 27)	Study to be launched	
18.	**Water-using equipment**		
	Water-cleaning appliances	Under consideration	
	Irrigation equipment	Under consideration	

Many preparatory studies have investigated and discussed EoL in terms of magnitude within the life cycle, improvement potentials and possible cost effects. Examples are shown in Table 18.2. Only very few of the studies have prioritised EoL ecodesign requirements in their analysis, or offered specific proposals for how DfR-related requirements could be formulated. None of the active implementing measures have included specific EoL ecodesign requirements.

Obviously there are fundamental problems with integrating DfR-related requirements into the final legal version of implementing measures. Since these directly impact the planned interaction between WEEE recast and ErP some more analysis is provided.

At the core, the procedures during the development of implementing measures disadvantage non-energy-related requirements. This has also been the focus of a study led by consultant Global View – Sustainability Services (GV-SS) for the UK Defra published in May 2011 (Maxwell *et al.*, 2011).

Table 18.2 Examples of non-energy or DfR related aspects in selected preparatory studies (adapted from Maxwell *et al.*, 2011)

ErP Product Group and Prep Study (Lot No.)	Non-Energy Measures Recommended or Addressed	
	Environment	Economic
Imaging equipment (Lot 4, IZM, 2008)	Consumables efficiency (duplexing)	Economic benefit of duplexing will depend on purchase price and use, due to the relative cost of printers and paper costs.
	Raw material/production: 80% of total energy consumption related to paper consumption, even higher share of water consumption	
	Effective utilisation of plastics	
	Design for refurbishment of toner cartridges	Reuse of waste toner may have significant economic benefits.
		Potential cost savings from refurbished cartridges depends on quality.
	EoL: WEEE	
Battery chargers and external power supplies (Lot 7, Bio IS, 2007)	Shift from linear transformers to switch mode power supplies result in both, higher energy-efficiency/reduced no-load losses & fewer impacts in production due to lower material use.	
	The life cycle of chargers for power tools is dominated by production impacts.	
	Lifetime extension, multiple use & reuse through standardisation of connectors.	
	EoL: WEEE	
Domestic lighting (Lot 19 part 1& 2, VITO, 2009)	Materials & EoL: Electronic component in integrated ballasts have relatively high environmental impacts compared to materials such as glass and metal.	Several EU countries have a 'disposal/recycling' contribution in the sales price – connected to the WEEE Directive.
	EoL: WEEE, in particular for mercury-containing types	

Motors (Lot 11, ISR, 2008)	Raw materials, in use: resource use of copper – trade off between energy efficiency versus material consumption. Generic requirements to enhance material separation for recycling.	
Fans for ventilation in non residential buildings (Lot 11, ISI, 2008)	Generic requirements to enhance material separation for recycling and noise level declaration but without quantifying the possible effect	
	EoL: WEEE, and GWP from refrigerants of concern	
Complex settop boxes (Lot 18, Bio 2008)	Production: VOCs, PAHs, heavy metals emissions to air, water and eutrophication	Use of alternative wire coatings - heavy metal free / recycling potential. But increased cost.
	EoL: WEEE	Design for recyclability – cost neutral or even reduction.
DVD/video players and recorders, video projectors, video game consoles (Lot ENTR 3, AEA, 2010)	Weight reduction, PVC free and BFR free products, improved recyclability, increased durability, minimum recycling content for plastics as aspects for generic requirements.	Very low cost items (e.g. mass produced DVD players) are designed for short life and frequent replacement.
	EoL: WEEE	Design for reduced polymer types: reduce cost barrier to recycling.

Note 'EoL: WEEE' means product is covered by WEEE, but exports and resource dissipation are of concern.

As a secondary effect EoL assessments for WEEE products in the prescribed method for the ErP preparatory studies are based on assumptions leading to comparatively low impacts.

One major driver introduced above is the question of enforcement. In the current status ecodesign requirements have to be centred on features, which can be examined and quantitatively assessed on the final product as shipped. Any other aspects, even when identified as relevant earlier, which cover upstream players in the supply chain or downstream processes, such as EoL, will likely end up as 'generic' requirements only. Generic requirements will for the time being be very hard to enforce, because no pass/fail test or compliance procedure can be defined for a requirement like 'producers have to ensure through proper design the highest suitable level of re-use'.

The assessment procedure in the preparatory studies and the related 'eco-report' tool additionally include a bias to keep EoL assessments low. Since the EuP came into force after WEEE was already in place, there is a prescriptive assumption to use 'post WEEE implementation' values. For the WEEE-relevant product groups this means that proper high-tech recycling within the European Union is assumed as a standard. This simplification in return means that environmental impacts from disposal are underestimated, environmental gains from recycling are overestimated, and the increasingly critical 'dissipative resource loss' is not part of the modelling. Table 18.2 shows examples for studies, which have examined DfR-related aspects or have proposed requirements, which are not related to energy or CO_2 emissions.

None of the implemented measures was able to define specific ecodesign requirements, however. Even though the commission and the stakeholder community are aware that ErP has so far not delivered its real potential regarding a full life-cycle perspective, the next steps and the related time frame are still unclear. For the time being it is likely that new or revised implementing measures will still only pose energy-related specific requirements.

18.7 Conclusion

The ErP Directive has strong points in formalised stakeholder integration. Such stakeholder interaction is still weak in the more traditional regulation approaches including the WEEE Directive. The expected expansion of scope predetermined from the RoHS recast could, for example, profit from more stakeholder inclusion. Even very long introduction phases will mean that new companies are faced with a complex regulation, which to them is for all practical purposes new.

Regarding the influence on design a new cooperation between WEEE and the ErP is envisioned, where WEEE concentrates on maximising the resource recovery and ErP would be responsible for improving the products through design. However, there will be two main obstacles to transferring this responsibility between the directives: the time gap until such design requirements could be integrated in existing or new implementing measures and the need to justify such requirements within the ErP rules.

Problematic in this area will be that recycling and disposal in current ErP analysis are of comparatively lower importance for most environmental impact categories. So even though saving of valuable resources is considered of growing importance, the calculation basis for ErP assessments will usually point out that use phase and production phase offer larger potentials for environmental improvement. And since requirements in implementing measures have to be cost effective over the life cycle (orientation on point of least life cycle costs; usually from the customer perspective) it could happen that after a lengthy process additional 'design for recycling' requirements would not be incorporated into the ErP measures after all.

The basic idea to organise the directive scopes into 'better processes and costs of recycling' (WEEE) and 'better design' (ErP) has large merit, but might not be compatible with the procedures for the setting of ecodesign requirements in their current form.

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19
Sustainable electronic product design

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Abstract: Design for sustainability and the ecodesign of electronic products are driven by legislation and other policy instruments, rising resource prices for limited resources, as well as consumer demand and market opportunities. Designers and engineers need to design electronic products so that they are beneficial for environment, society and the economy. This can be achieved by starting with a real demand and then searching for sustainable solutions that are eco-efficient and effective, based on sustainable materials, minimizing energy consumption in the production and use phase, designing products that can be re-used and recycled at the end of their life, or are non-toxic and biodegradable so that they can be given back to nature as food for ecosystems. In addition they have to be embedded in sustainable production and consumption systems. The more general background and rationale as well as several tools and methodologies, case studies and more radical concepts for such more sustainable electronic products are described in this chapter.

Key words: design for sustainability (DfS), ecodesign, green design, EuP, WEEE, RoHS, green public purchasing, ecolabels, sustainable materials, life cycle design, biomimicry, best practice, supply chain management, standardisation, market demand, consumer awareness, systems thinking, tools and rules for DfS, scarcity of resources.

19.1 Introduction

This chapter explores what sustainable design is and how it includes strategies such as ecodesign, design for disassembly and recycling and what this means for electronic products. It discusses drivers, methods and tools for sustainable electronic product design, especially focusing on re-use, recycling, choice of sustainable materials and processes, scarcity of resources, best practice examples and future trends. As an introduction the next two sections will first discuss why design for sustainability (DfS) is needed and how the movement has evolved in the past 50 years.

19.1.1 Why Sustainable Design?

The world sees two major crises at the moment: the financial/economic and the climate; it seems that they are connected. The difference is that we can still be hopeful that, by implementing better regulations and control mechanism for financial institutions, we can overcome and avoid future financial crises. However, once we have destabilised the climate of our planet, no regulations will save us from the dire consequences scientists are predicting. Even without knowing the total scientific truth about how much climate change is caused by people and how the planet will react to increasing levels of CO_2 and other greenhouse gases in the atmosphere, the probability of human activities being a major part of this problem should be reason enough to follow the precautionary principle and establish effective measures to avoid the worst. Climate change is not just an environmental issue but has severe social consequences as well, from displacing people from the regions where they used to live for generations to increasing food prices. In addition climate change will pose economic threats to a lot of countries in a magnitude that is comparable to world wars (Stern 2007).

Even without 'talking climate change', there is a third severe crisis we are already facing: the depletion of limited natural resources. For mineral oil the problem is well known but the same applies to a lot of other natural resources, e.g. rare earths and precious metals as discussed in Section 19.4.2. An increasing number of wars and conflicts are occurring around availability of land, water, food and mineral resources, which is an obvious proof that the highly resource-intensive production and consumption systems of industrialised and emerging countries are reaching natural limits and cannot be a model for our planet to nurture 9 billion people in the year 2050. Despite some efforts in increasing efficiency the industrialised nations still consume around 70% of all resources worldwide, while they host only 20% of the world's population. Three consumption domains are mainly responsible for this: food/agriculture, mobility/tourism, and housing/energy consumption in buildings. These three domains cause about 80% of environmental impacts of European countries (European Environment Agency 2007).

Since the Brundtland Commission formulated the paradigm 'sustainable development' in 1987 (World Commission on Environment and Development 1987) as a development that meets the needs of present (generations living on our planet) without compromising the ability of future generations to meet their needs, and over 170 nations agreed in 1992 to strive for sustainable development (see Table 19.1), a lot of activities have been started and efforts undertaken to move towards more sustainable societies. Nevertheless, it seems that progress towards triple bottom line thinking, which means to marry the three dimensions of people, planet and profit and to search for solutions that are beneficial for society, natural environment and economy, has not been reached. We are still far away from having a protocol on climate change with real CO_2 reduction goals that all nations agree on. We are not moving towards reaching any of the Millennium Development Goals on fighting poverty (see http://www.un.org/milleniumgoals/). The few rich are getting

Table 19.1 Principles of sustainable development (United Nations 1992)

Sustainable development is not a static situation but a state of dynamic equilibrium between human and natural systems. The document in which this principle is laid down is the 'Agenda 21', the blueprint for sustainable development where tasks for the fields of production, consumption and policy are formulated and possible steps are suggested. While a broad and complex issue, there are six principles describing how a sustainable community should interact with other communities and with nature:

- **Environmental protection:** Protection of the resources and life support systems needed for continuance of human well-being and all life.
- **Development**: Improving 'quality of life' of which economic development is part but not the sole objective.
- **Futurity:** Considering the interests of future generations in what we leave behind.
- **Equity:** Sustainability will not work if the world's resources are unfairly distributed or if the poor pay a disproportionate part of the costs of the transition to sustainability (as everyone has a part to play). The special situation and needs of developing countries, particularly the least developed and those most environmentally vulnerable, shall be given special priority.
- **Diversity:** Diverse environmental, social and economic systems are generally more robust and less vulnerable to irreversible or catastrophic damage. It also allows individuals to choose more sustainable options.
- **Participation:** Sustainability cannot be imposed but requires the support and involvement of all sections of the community and all communities. This requires ensuring opportunities for participation in decision-making.

Furthermore, sustainable development is a process with the following features:

- conservation of resources;
- respect for all stakeholders' viewpoints;
- cooperation and partnership;
- following the precautionary principle;
- encouraging subsidiarity: decision-making at the lowest practicable level;
- promoting personal freedom: meeting needs without harming the environment or people;
- addressing aesthetics: protecting and creating places and objects of beauty.

richer, the poor are getting poorer in developing as well as industrialised countries, and multinational corporations cannot be governed by national governments any longer.

19.1.2 The design for sustainability movement

Since Rachel Carson was a major actor in starting the environmental movement in the US with her publication *Silent Spring* in 1962, in which she described the human- and eco-toxicity of DDT and other pesticides, a small but growing group of designers started focusing on sustainability issues in theory and practice, such as Victor Papanek, who published *Design for the Real World* in 1971 and *The Green Imperative* in 1995. There have been important networks set up such as O_2 global network of eco- and sustainability designers founded in 1988 by Danish designer Niels Peter Flint (www.o2.org), and more recently most larger design networks and institutions have started some kind of activities in DfS.

While a lot is still relatively superficial talk and some initiatives especially by large companies can be detected as green washing (false or exaggerated green claims in advertisement without real action), the movement in DfS is definitely growing. Meanwhile the North American IDSA (Industrial Designers Society of America), which expelled Viktor Papanek in the 1970s for his harsh criticism of the industrial design profession, has published its own guideline for ecodesign (*Okala Ecodesign Guide*, IDSA 2010; see www.idsa.org/okala-ecodesign-guide), etc.

Thus it is surprising that the design professions are still lagging behind the current market developments and demands, and that there are too few educational programmes available for the growing number of young and enthusiastic students who like to get involved in DfS.

So far designers (in the broadest sense of the word including engineers and creative marketers) are still much too often part of the currently predominant economic system, seeing quantitative growth as the only goal, encouraging growing consumerism, wasteful throwaway concepts, inducing massive resource flows from nature to waste dump within a shockingly short period of time, and selling ‘stuff’ that no one needs in advertising and communication that promotes the modern throwaway lifestyles as the only adorable model of well being to everybody around the world. So far not much has changed since Papanek’s criticism – or things got even worse. Furthermore designers and engineers are often not the decision makers in companies but work at the end of the chain of command. To make a real change, sustainability designers have to sit at decision-making tables. They have to be equipped with sustainability knowledge based on research and evidence, and analysis as well as guidance tools to enable evidence-based design decisions. They have to know about the history, problems and drivers of DfS practice and theory, and they have to adopt a more participatory design practice by listening to the stakeholders first, understanding their problems and motivations and then trying to develop more sustainable solutions (cf. Charter and Tischner 2001).

It has to be understood that DfS is more than green/ecodesign (all too often people substitute one term for the other) and DfS is not equal to design for longevity and durability (see Tischner *et al*. 2000). Instead DfS looks into the larger consumption and production systems, starts with real demands and problems, and tries to find solutions that are good for socio-economic systems as well as natural environments. ‘Don’t try to be less bad, try to be good’, as Michael Braungart and William McDonough, the founders of MBDC, promoting cradle to cradle design, suggest (see www.mbdc.com).

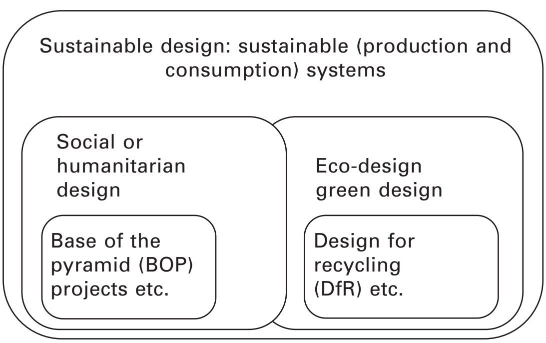
DfS normally looks into global, local and personal dimensions of problems and solutions and is created in teams consisting of several different experts and stakeholders searching for radical solutions and system improvements. Thus, ecodesign focusing on environmental and economic aspects, or design for recycling, as well as humanitarian and social design, such as base of the pyramid (BOP) projects, focusing especially on underprivileged groups, can all be grouped under the umbrella of DfS as Fig. 19.1 shows.

19.2 Drivers for sustainability and ecodesign

Indeed there are increasingly strong drivers for DfS supporting the DfS movement as described above, such as:

- the crises mentioned above and thus more consumer awareness for these issues and demand for sustainable solutions;
- more legislation requiring more producer responsibility from companies and green/sustainability purchasing programmes;
- companies taking the lead receiving considerable competitive advantage;
- the development of social responsibility and the urge of business owners and consumers alike to invest their money and effort into something sensible and useful for people and the planet, thus the LOHAS (www.lohas.com) and Sociopreneur (an entrepreneur with a social-environmental cause) movements (see also www.sociopreneur.com; Tischner *et al*. 2010).

More detail regarding drivers for sustainable and ecodesign of electronic products is given in the next sections.



19.1 Design for sustainability and its relation to other design strategies.

19.2.1 Legislation

The most relevant legislative instruments in EU concerning design of electric and electronic equipment aim at energy saving, end of life management and resource efficiency as the major issues. One of the first legislative acts that came into force in the year 2003 and has been updated recently is the European Directive 2002/96/EC on Waste from Electrical and Electronic Equipment (WEEE-Directive) together with the Directive 2002/95/EC Restrictions of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS). The EC established these directives due to the increasing amount of problematic waste created by the increasing production and use of electronic and electrical equipment, which contains large amounts of hazardous substances (Hora 2006). This type of waste poses a serious problem for soil and groundwater, for example, if not treated and disposed of properly. WEEE and RoHS Directives are part of a legislatory strategy to increase producer responsibility regarding financing recycling and disposal, minimizing the impacts of electrical and electronic products on the environment and supporting more recycling of valuable materials.

In addition to WEEE and RoHS Directives, the Directive 2005/32/EC (European Commission 2005b) on establishing a framework for setting ecodesign requirements for energy using products (EuP) is also important, covering the whole product life cycle of energy using products and developing specific ecodesign criteria for specific product groups through stakeholder consultation processes. After addressing end-of-life issues in the WEEE and RoHS Directives, the environmental relevance of the use phase because of energy consumption became obvious also in connection to the increasing threats of climate change. Thus the EuP Directive aims at energy efficiency of electric and electronic products in the first place. However, additional design requirements for certain products (e.g. dishwasher, washing machines) that consume water and detergents during the use phase, are considered in the EuP documents and reports, as well as products that have a certain influence on energy consumption, such as insulation, windows, water fixtures, etc.

Another relevant legislatory framework is the new waste hierarchy introduced in the European Waste Directive, which promotes reduction and preparation of waste for re-use and recycling of materials and components. This will influence the design requirements further, e.g. in terms of easy access to valuable materials and economic re-use and recycling possibilities. The set of these four directives can be seen as an attempt to implement the objectives of the integrated product policy (IPP) of the EU.

19.2.2 Green and sustainable public purchasing

Powerful policy instruments to support sustainable design activities include ‘green public procurement’ (GPP) or ‘sustainable procurement’. The public sector typically represents 10–20% of the GDP and the annual investment by public procurement alone in the EU amounts to €2 trillion or 17% of the GDP (see http://ec.europa.eu/environment/gpp/what_en.htm). For instance, in the US federal purchases (2–3% of GDP) helped achieve high penetration rates for Energy Star labelled products (90% or more) (Singh *et al*. 2010). Examples for implementation of GPP programmes can be found worldwide (e.g. Europe, Asian countries like Japan and South Korea). GPP has an increasing relevance in Europe. However, the pace of implementation varies widely among the different European countries. Actual developments in European policy and the EU strategy 2020 (Monti 2010) strengthen further ambitions in the field of green public procurement and its implementation in practice. Most EU member states adopted national action plans for sustainable procurement, including targets and implementation measures.

19.2.3 Eco- and social labels

Eco- and social labels are instruments for companies to communicate sustainability aspects of their products and services towards clients and consumers, for policy to educate and motivate companies to produce more sustainable products and consumers to prefer more sustainable offers, and generally to establish and increase sustainability performance of offers in the marketplace. Although the increasing amount of labels is often criticized, labels remain a useful instrument for quick information transfer along the supply chain and towards consumers. Preconditions for a functioning label are that the label is known and widely accepted, that it is developed, controlled and certified by independent and trustworthy organisations and that it is designed and communicated in a way that the main criteria for labelling are easy to understand by non-expert audiences.

Meanwhile there are standards available, e.g. for ecolabels (ISO EcoLabel Type I). The criteria of these types of ecolabel include the most relevant ecodesign features (material based, energy consumption, recycling attributes) and are used, for example, by the European Commission to develop product- and service-specific environmental criteria for Green Public Procurement. Furthermore they describe the best available technology (BAT) for setting specific targets in ecodesign directives. Accepted and common Ecolabels that include electronic products are, for example, the Nordic Swan, the German ‘Blue Angel’ (Blaue Engel) and the US ‘Energy Star Label’, the EU ecolabel or the several energy efficiency labels established in different countries and by the EU for specific product categories such as large household appliances (for a comprehensive overview on ecolabels for electric/electronic products see http://www.ecolabelindex.com/ecolabels/?st=category=electronics, accessed 25 June 2011).

19.2.4 Eco and sustainable supply chain management

Legislation, companies downstream the supply chain as well as consumer organisations, media and stakeholders increasingly demand more information about environmental and sustainability impacts from end producers, suppliers and retailers. Thus the traceability of materials and components throughout the whole supply chain up to the original source becomes very important. Providing information about compliance with the EuP requirements is obligatory for everybody introducing energy using products in European markets and for their suppliers. In the US the legislation 'Section 1502, Dodd-Frank Wall Street Reform and Consumer Protection Act' (US Government 2010) requires companies to use independent experts to certify whether their minerals are conflict-free. Problematic minerals are widely used in electric and electronic equipment (e.g. tantalum, gold, tungsten and derivatives). Thus the management of information along the supply chains, standardisation and digitalisation of relevant information, and a way to do that while respecting the confidentiality and competitive advantage of such information are needed.

19.2.5 Standardisation

A lot of national and international standards are relevant for more sustainable design of electronic products. ISO (International Organization for Standardization) published in 2002 the technical report ISO/TR 14062, Environmental management – Integrating environmental aspects into product design and development. This report on methods, tools and best practices for the integration of environmental aspects into product design and development is currently transferred into ISO standard 14006 on Implementation of EcoDesign in Environmental Management Systems as part of the ISO 14000 series (ISO 14006: 2011, Environmental management systems – Guidelines for incorporating ecodesign). Neither, the technical report nor the new standard is intended for use as a specification for certification and registration purposes. Nevertheless, certification institutions and companies already use these documents for labelling activities, e.g. environmental declarations for cars (e.g. KIA and Daimler, undated).

19.2.6 Market demand and consumer awareness

Consumers' demand for sustainable products increases constantly. New eco- and social conscious target groups have been identified by consumer research agencies (e.g. Sinus Institut Heidelberg, www.sinus-institut.de/en) describing their values and consumption behaviour. These groups are named LOHAS (Lifestyle of Health and Sustainability, see www.lohas.com), socioecological (Sinus 2011), naturalists and drivers (Natural Marketing Institute 2011) and described to be each between 7% and 24% of the market. Thus more and more companies start communicating eco- and social features and benefits of their offers in marketing campaigns, e.g. energy saving and water-saving features of household appliances, fuel efficiency of cars, health aspects of cosmetics and food, social and health aspects of clothing etc. It is essential for a successful consumer campaign to first do the right thing and then talk about it. 'Green washing' nowadays gets quickly and publicly criticised by watchdog and consumer organisations as well as competitors, and thus backfires on the companies trying to impress with superficial and sometimes even false claims.

19.3 How to do design for sustainability (DfS)

There are a few basic principles of DfS that can be applied to all product categories including electronics, such as:

- start with a real demand, a real problem and try to find socially, environmentally and economically beneficial solutions;
- think in functions and services first, not in products, e.g. do not start with designing a washing machine but search for ways to enable people to make a good impression with neat and clean clothing, or develop ways to clean clothing in a sustainable manner;
- apply life-cycle and systems thinking as described below;
- include users, stakeholders and different experts in the design process as much as possible;
- try to research and look into all different dimensions and criteria, but set the right priorities, in line with your time frame and scope of the project.

19.3.1 Life-cycle thinking and systems thinking

Life-cycle thinking is an absolutely necessary and highly important element of DfS. It includes considering all phases of a product's life from raw material extraction and manufacturing of materials and components via assembly of the final product to use phase and end of life, where strategies of re-use and recycling take place as well as bio-degradation, incineration and final disposal. The aim of DfS is to find ways to improve sustainability of the overall system at all stages of the product's life, e.g. eliminate toxic substances, increase efficiency and effectiveness, encourage re-use and recycling as much as possible in the overall system or between systems. In the ideal world there would be no virgin materials extracted from nature and no waste would occur in the system as all materials would be re-used and recycled over and over again, in the best sense of industrial ecology systems (see www.is4ie.org) or cradle to cradle concepts (closing natural and/or technical cycles, see www.mbdc.com).

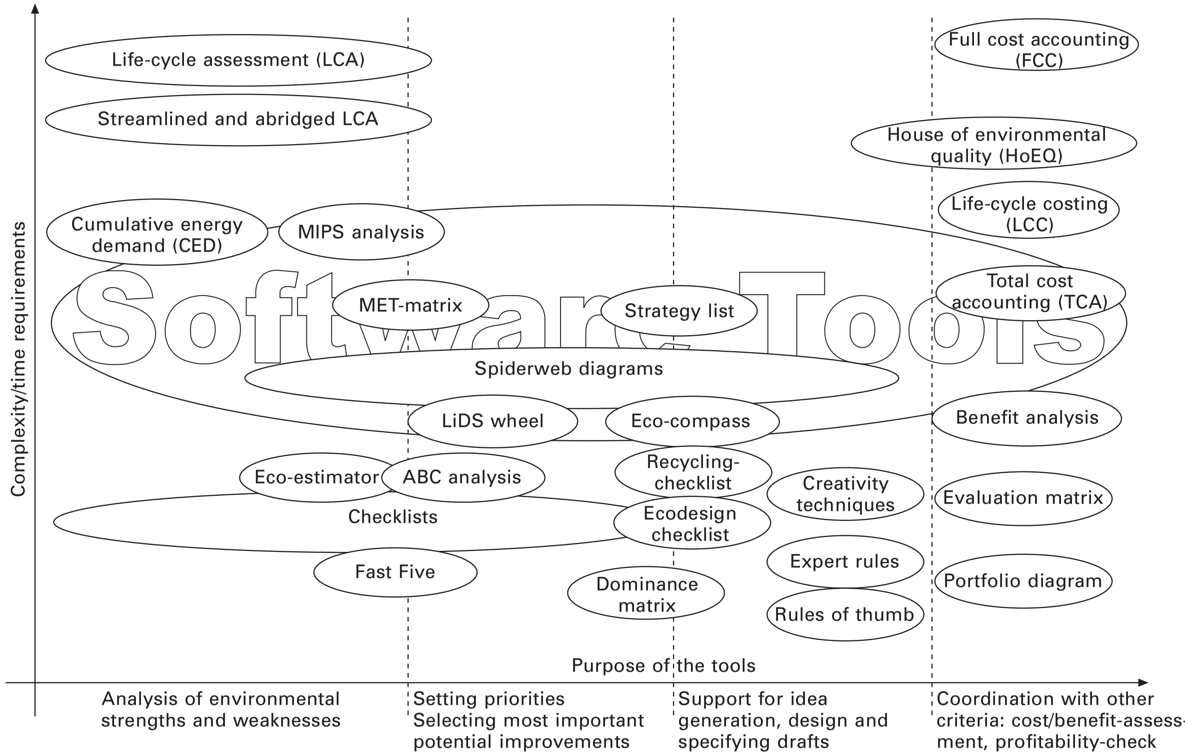
In addition DfS analyses the context of use and the systems in which products and services work adding to life-cycle thinking the perspective of sustainable product-service-system design (as described in Tukker and Tischner 2006). If we take a mobile phone as an example, life-cycle thinking would mean to analyse all phases of the life of the phone (e.g. using life-cycle assessment or the ecodesign checklist, see below) and improve it at each stage, e.g. use biodegradable materials for the housing, make the electronic parts upgradable and reusable, construct the phone in a way that disassembly is very simple and fast, so that parts can be separated, reused and recycled. Toxic elements would be eliminated and the product would be designed in a way that consumers love it and like to keep it for a long time etc.

When designing sustainable product service systems the focus would be on the whole system in which this phone would be used, e.g. the provider would not sell the phone any more but only rent it out together with the communication service contract. All phones would be returned to the service provider, refurbished and upgraded, so they would be especially designed for multiple use and upgrading. All materials and components would be re-used in the system. The whole system including the use and end-of-life phases would be designed and controlled by the service and phone provider. Thus more radical innovation towards sustainability can take place.

The system perspective is so essential, because if we cover only individual stages in the product's life it is easy to focus on the wrong priorities. For a cotton T-shirt on the first glimpse the extreme use of pesticides and water in raw material production phase seems to be the most important sustainability aspect together with the labour conditions in the production. In fact, when analysing the whole life cycle of the T-shirt, figures show that the laundering in the use phase is one of the major environmental impacts. Thus a DfS expert would search improvements in at least three stages of the T-shirt: production with social and environmental impacts, use phase with environmental impacts and the end-of-life phase, as recycling cotton fibres into new T-shirts would eliminate all the negative impacts of cotton production from the life cycle.

19.3.2 Tools and rules for DfS

To make life easier for sustainability designers there is already a wealth of tools and methods available that help integrating environmental, social and economic aspects in design processes (see Fig. 19.2 for an overview of different tools and Fig. 19.3 for a typical ecodesign checklist). The most complex is life cycle assessment (LCA), and the most simple are the rules of thumb that experts have formulated to give guidance in the design process.



19.2 Overview of different methods and tools for ecodesign; the higher they are in the box the more complex. MIPS, material input per service unit; MET-matrix, material–energy–toxicity matrix; LiDS, lifetime design strategies; ABC analysis, environmental analysis scheme with ranking from A = bad to C = good; Fast Five, checklist by Philips for the five most relevant environmental impacts. Source: Tischner *et al.* (2000).

ECODESIGN CHECKLIST: For environmental design and evaluation of products. Please mark the appropriagte values: + = good solution, +/- = indifferent solution, – = bad solution, o = not relevant

Extraction of raw materials, choice of raw materials	+	+/–	–	o
• minimising material input				
• minimising energy imput				
• minimising land use (raw materials extraction, production)				
• avoiding input or emission of hazardous substances				
• avoiding emissions (e.g. by transport)				
• minimising waste production, recycle materials				
• preferring regional raw materials				
• using renewable raw materials produced by sustainable methods				
• using socially acceptable substances that will pose no health hazards				
• using recycled materials				

Production	+	+/–	–	o
• minimising material input				
• minimising energy input				
• minimising land use				
• avoiding input or emission of hazardous substances				
• avoiding emissions (e.g. by refinement procedures)				
• minimising pre-consumer waste production, recycle materials				
• preferring regional suppliers along the whole supply chain				
• minimising packaging				
• using renewable ancillary materials produced by sustainable methods				
• using socially acceptable processes that will pose no health hazards				

Use/service	+	+/–	–	o
• creating excellent customer benefits				
• appropriate design for target group				
• minimising complaints and returns				
• keeping service available				
The following alternative strategies might be discussed				
• design for longevity (strategy 1)				
• timeless design				
• 'long life' guarantee				
• robust, reliable wear-resistant design				
• design for easy repair and maintenance				
• possibilities of combination				
• variability, multifunctionality				
• possibility of re-use and shared use				
• design for update to the best available technology				

19.3 A typical ecodesign life cycle checklist, Source: Tischner *et al.* (2000).

	+	+/–	–	o
or				
• design for short-lived products (strategy 2)				
• fashionable design				
• design for product take back				
• design for recycling				
• design for environment-friendly disposal, e.g. compostable				
• understandable design for the user				
• design for self controllable and optimisable functions				
• dirt-resistant, easy to clean design				
• minimising material and energy input during use				
• avoiding input or emission of hazardous substances				

Re-use/recycling (closing technical material and energy cycles)	+	+/–	–	o
• recycling strategy in place?				
• guarantee for take back in place?				
• re-use of the complete product (e.g. second-hand, recycling cascade)				
• recycling of components (e.g. upgrading, re-use of components)				
• recycling of materials				
• dismantling of products				
• separability of different materials				
• low diversity of materials				
• low material and energy input of re-use/recycling				

Final disposal	+	+/–	–	o
• biodegradable, fermentable products (closing biological cycles)				
• combustion characteristics				
• environmental aspects at deposition				

Result: Total value: number of marks:	Name the 8 most important criteria for improvement		Comments
good solution	1.	2.	
bad solution	3.	4.	
indifferent	5.	6.	
not relevant:	7.	8.	

19.3 Continued

Through the body of knowledge that has been developed in the past decades several rules of thumb relevant for DfS are available, such as:

- for longer-lasting products that consume considerable amounts of energy, fuel, water, and other consumables during their lifetime very often the major environmental impacts occur during the use phase, which is true

for a lot of electric and electronic products – thus reducing use phase consumption is key;
- for longer-lasting products that move, e.g. vehicles, and consume energy to do so, the weight and other impacts on energy consumption in the use/active phase normally are most important;
- for consumables, i.e. products with a very short lifespan that disappear or are dispersed in use, it is most essential that they are non-toxic and biodegradable.

19.3.3 Considering the use phase of electronic products

As pointed out above, the energy minimisation during the use phase of electronic products is the main target of the EuP Directive. EuP criteria for different product groups cover for instance energy consumption during usage of appliances and stand by energy consumption. Although thresholds for energy consumption are obligatory for all products addressed by the directive, no specified design strategies or additional measures to encourage sustainable user behaviour are mentioned. Furthermore the use phase consists of several steps (see Table 19.2), and the user behaviour in each step is difficult to predict and influence by design. More effort needs to be invested during the design process into influencing user behaviour, e.g. features and information can be included in product, packaging consumer information to encourage sustainable user behaviour.

Design strategies to optimise the use phase include:

- provision of information, necessary infrastructure, and opportunities for sustainable usage and after use collection;
- service design for maintenance;

Table 19.2 Processes to specify the use phase further (Oberender and Birkhofer 2005)

Process	Activity/ Environmental impacts
Purchase	Travel to shop, Internet usage, shipping
Start-up procedure	Packaging waste, reading instructions (maybe only once)
Use	Preparation for use (energy consumption, consumables, waste) Initial use (energy consumption, consumables, waste) End of usage (working materials, energy, e.g. for reloading, waste)
Maintenance	Travel to shop/service, shipping, wear parts, consumables
Reparation	Travel to shop/service, shipping, spare parts, consumables
Disposal	Recycling, disposal (energy, waste, emissions)

- inclusion of design features to decrease energy consumption (e.g. display information about efficiency rate for vacuum cleaners – alarm message when filter change is necessary);
- encouragement and motivation for consumers to re-think their behaviour, e.g. drying laundry on the line, washing only with full loads and cold temperatures etc. Enable doing this in a fun and enjoyable way, create consumer awards and communities (see The Fun Theory: http://thefuntheory.com/).

19.3.4 Design for re-use and recycling of electric/electronic products

Through the new EU waste hierarchy the obligatory priorities for electronic products are: prevention of waste, followed by re-use, followed by recycling, other recovery, and final disposal, if economically and environmentally sound. Table 19.3 shows the connection of the EU waste hierarchy with the term re-use as suggested in the German VDI guideline 2343 'Recycling of electrical and electronic products' (VDI, 2002; see www.vdi.de/uploads/tx_vdirili/pdf/1520137.pdf).

Also the WEEE legislation includes a clear obligation to facilitate re-use and recycling of products in its Article 4: Product Design. Moreover, member states are obliged to take measures that prohibit producers from preventing re-use by using specific design features or certain manufacturing processes, unless such features or processes are required by law or present overriding advantages. During the product design, possibilities for the re-use of a product have to be assessed and compared to recycling and disassembly strategies to figure out which of these strategies are more beneficial.

Table 19.3 Waste hierarchy, scope and proposed terms in VDI Guideline 2343 for Re-Use I and Re-Use II (Brüning *et al.* 2010)

EU waste hierarchy (Waste Framework Directive, 2008)	Waste property	Explanation regarding re-use	Proposed nomenclature of term re-use	Addressed in German Federal Law (ElektroG, 2005)
Prevention	No waste (substance/material/product)	Using directly again; same purpose as before	Re-Use I	No
Preparing for re-use		Preparing for further use	Re-Use II	Yes
Recycling Other recovery Disposal	Waste			

Table 19.4 Criteria for implementing Re-Use strategies and concepts (after Brüning *et al.*, 2010)

Technical criteria	e.g. kinds and variety of parts and materials used, suitability for disassembly, cleaning, testing
Quantitative criteria	e.g. amount of returning products, timely and regional availability
Value criteria	e.g. value added from material/production/assembly
Time criteria	e.g. planned product lifetime versus effective lifetime
Innovation criteria	e.g. replacement of products a long time before they reach their economic end of life
Disposal criteria	e.g. efforts and cost of alternative processes to recycle the products and possible hazardous components
Criteria regarding compatibility of re-used devices with standards of new electrical and electronic equipment (EEE)	e.g. competition or cooperation with original equipment manufacturers (OEMs)
Other criteria	e.g. market behaviour, liabilities, patents, intellectual property rights

Re-use concepts can encompass either single components or the whole product, depending on its age and condition. Re-use can take place for the same purpose in the same system or for serving another purpose.

The following aspects have to be considered during the design of re-use concepts or possibilities (Table 19.4). Design strategies that support re-use and recycling include the following:

- Modular design, standardisation of components (model series management). Modular construction enables designers to create structures, which can be easily repaired, upgraded or refurbished if necessary. Further environmental benefits can be gained though increased efficiency during production and use of materials.
- Longevity design: choice of materials, stability, controlled material ageing, attractive patina, prolongation of life cycle by exchanging parts subject to wear.
- Design for recycling: recyclable material choice, low materials diversity, low toxicity, materials labelling and ease of disassembly:
  - recovery of precious materials in electronic products (e.g. material production causes around 60% of the environmental impact in the production process);
  - disassembly of parts that contain harmful substances (e.g. fridges with chlorofluorocarbons (CFCs), lead containing glass of TV screens, printed circuit board (PCB)-containing components, batteries);

  - disassembly of parts that hamper recycling technologies (e.g. cables in shredder).
- Design for upgrading: enabling technical up scaling (e.g. computer hardware).
- Design for disassembly and assembly: easy detachable connections, non-destructive dismantling, making disassembly and recycling processes economically successful, avoid fasteners/joints that require high forces, need for specific tools or time-consuming disassembly, jamming and wedging of parts, easy accessible parts, rapid removal and exchange. The ideal assembly process is reversible.
- Design concepts to make wear of parts detectable and visible: easy access for repair and exchange, allow testing of product and components, predefined wear facings to prevent attached components to be affected, signals and signs to point out wearing.
- Providing instructions and information for recyclers and disposal instructions for end users.
- Design of product-service-systems: maintenance, take-back and repair, upgrade renting, leasing, sharing, pooling services.

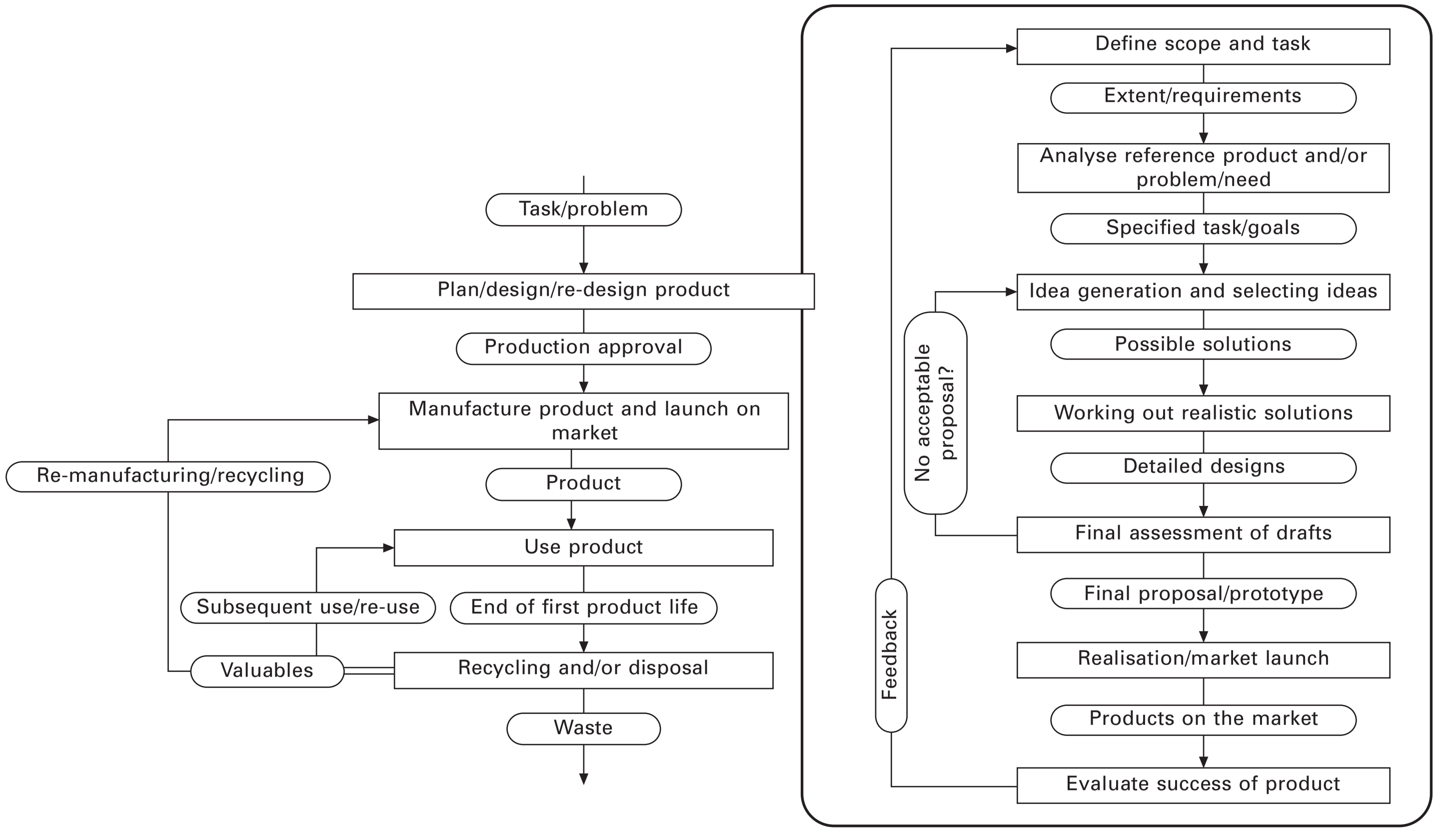
All these strategies have in common that they depend very much on their surrounding systems. Established take-back systems, waste management systems and logistics (e.g. quality of transport without causing damage) influence the recovery rates as well as re-use concepts. This is also one of the findings of Rifer *et al*. (2009) that confirms that design for end of life (DfEoL) includes two main aspects: first the actual design elements, and secondly communication of those elements to the end-of-life industry. Some examples for re-use are given is Table 19.5. Re-use, recycling and remanufacturing are processes leading back into several life-cycle steps as Fig. 19.4 shows.

Normally re-use is the priority from an environmental point of view, because resources (materials and energy) are preserved that have been invested in the product during manufacturing. This is followed by the re-use of parts and components in remanufacturing processes. The above strategies require non-destructive disassembly. However, currently the most common practice is material recycling, where materials are preserved and geometric

Table 19.5 Examples for re-use

• Re-use of alternators Source: http://premiumtec.eu/images/lichtmaschine_1.png
• Refurbishing of electric motors Source: www.frank-dvorak.at/motoren_e.html
• Refurbishing and repair services for mobile phones

Source: www.recellular.com



19.4 A product's life cycle including re-use, remanufacturing, and recycling. Source: Tischner *et al.* (2000).

details are lost. This strategy allows destructive disassembly and is also common practice for recovery of valuable materials (e.g. platinum and gold in electronics).

In a product's life cycle re-use and recycling strategies can be implemented as follows:

- Increase recycling during the production:
  - Use of recycling materials (take back, alternative recycling materials)
  - Recycling in production processes (zero waste strategies)
- Increase recycling options for customer/use phase:
  - Information about recycling and end-of-life management
  - Re-use options and recycling options for consumer (prolongation by easy exchangeable and reparable components)
  - Recyclable components/materials for consumables/consumable parts during the use phase
- Increase recycling after end-of (first) life:
  - Take-back/exchange programmes
  - Second-hand markets
  - Non-destructive disassembly and reassembly
  - Recyclability of product
  - Minimisation of materials used in the product

When developing and evaluating re-use and recycling strategies, economic considerations are crucial, e.g. the cost of recycling versus the cost of virgin materials. Fortunately the rising world market prices for raw materials benefit re-use and recycling activities. Furthermore we have to be aware of rebound effects, e.g. re-use of inefficient products can be environmentally negative when much more efficient and environmentally beneficial new products and technologies are available.

What type of design for re-use and recycling is sensible also depends on the actual or planned system of recycling. If 'mass-recycling' is a common practice for most appliances after end of life, e.g. shredding of whole TVs becomes economically attractive compared with manual or active disassembly because of improved automated sorting technologies, then design for disassembly might be less important.

19.4 Sustainable materials and manufacturing processes

19.4.1 Choice of sustainable materials and processes

Besides of influencing life cycle and use phase of products, the choice of materials and manufacturing processes is also an important element of DfS.

There are eight basic criteria for more sustainable material and process choice:

- *Consumption of resources*: How resource intensive (including water) is the production and supply of the material/the production process? Is it a renewable or non-renewable material or scarce resource? Try to reduce resource consumption as much as possible, prefer efficiently grown/harvested renewable materials and production processes with high materials efficiency.
- *Consumption of energy*: How energy intensive is the production and supply of the material/the production process? Try to reduce energy consumption as much as possible, prefer efficient materials and processes. Prefer renewable energy sources.
- *Hazardous substances/emissions*: Are there any hazardous substances involved in production, supply, or use, recycling/waste disposal of the material? Are there any hazardous substances needed in the production process or occur as emissions in production? Try to eliminate and reduce hazardous substance use and emissions as much as possible, e.g. WEEE and RoHS Directives restrict the use of the following hazardous substances in electronic products: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated diphenyl ethers.
- *Origin and transportation*: Where does the material come from and how much transportation is involved in production and supply? Try to reduce transportation distances as much as possible and prefer environment-friendly and efficient transportation means. Check if regional production (close to the point of sale) is an option and makes sense from environmental as well as socio-economic viewpoints.
- *Aspects of lifespan*: How easy or difficult are the maintenance and repair of the material? Can the material be reused and recycled and therefore used again and again? How easy or difficult is the (legally prescribed) environment friendly disposal of the material? Try to use materials that have the right lifetime for the product and purpose it is used for, and enable easy re-use, recycling and easy disposal, if nothing else is feasible.
- *Waste generation*: How much waste is caused by production processes and supply of the material, as well as use of the material in production, during use of the product and at the end of life phase? Go for minimal and zero waste options.
- *Biodiversity and protection of natural areas*: Do material supply or production processes reduce biodiversity and threaten protected natural areas? Try to use materials and processes that do not threaten any protected natural areas, endangered species or areas that fulfil important biological functions, e.g. rainforest. Care for sustainable management of forestry and sustainable agriculture.

- *Social aspects*: Do production processes, supply, use and recycling/disposal of the material have any negative social aspects, e.g. neglect of human rights, health risks, destruction of living space, restriction of freedom, exploitation etc.? Try to use materials with positive social and socio-economic effects.

When trying to find the most sustainable materials and production processes, first all the important specifications, e.g. price, stability, lifetime, available production methods, corrosion resistance, aesthetics etc. should be identified. Then Internet, databases, material suppliers, literature and magazines can be consulted to find the best solutions that meet the requirements and are most sustainable at the same time. Helpful online material databases include:

- www.materia.nl
- http://extranet.kingston.ac.uk/rematerialise
- www.materio.com
- http://formade.com/material.html
- www.matweb.com
- www.neuematerialien.de
- www.materialsense.nl
- www.materialconnexion.com

It is obvious when working with an established company in an established supply chain that the introduction of radical new materials and production processes is a challenge as it is connected to higher risks and transition costs than just continuing the current way of producing and designing. However, methods like simultaneous engineering where radical research and innovation are done in parallel to regular product development and then fed into the product development process over time, or starting a new product line, a new company, or entering a new market niche with an existing company might be ways of overcoming the inertia of change of traditional large companies. DfS can be most radical in companies with a well-established innovation culture and learning organisations.

To judge the sustainability of materials and production processes and design solutions on a regular basis in companies, software tools for life-cycle assessment such as Simapro (see www.pre.nl) or GABi (www.pe-international.com), software modules integrated in existing CAD systems such as Autodesk integrating eco-materials assessment (Autodesk Inventor CAD software, see http://usa.autodesk.com), or SAP product life-cycle management tools (see http://www.sap.com/solutions/business-suite/plm/index.epx) might be useful. Meanwhile more and more software solutions for integration of sustainability aspects in product development and design are available.

19.4.2 Consideration of scarcity of resources in design of electronic products

In the production stage of electronic products most often the production of materials used is responsible for more severe environmental impacts than forming and assembling of the product. Thus closing recycling loops effectively will become more and more important environmentally, and with rising prices for resources also economically. Recently urban mining became an interesting approach, because valuable resources are stored in the infrastructure (e.g. buildings, transportation equipment) and products as well as landfills around us and can be recovered effectively. The increasing demand for resources worldwide is also a strong argument against incineration of waste. Once burned we cannot recover any of the valuables hidden in so-called 'waste'. The use of precious metals and rare earths for electronic parts is especially interlinked with un-sustainable resource extraction and conflict areas and wars (see e.g. how gold mining fuels the war in Congo, www.nodirtygold.org) as well as disastrous environmental consequences.

Rare earth elements (REE) or rare earth metals (REM) are a set of 17 chemical elements in the periodic table. Although the name suggests otherwise, rare earths are much more present than other metals (e.g. gold or lead), but they are dispersed in small sized deposits thus complex to extract. Over 90% of the world's supply of rare earths is produced in China. REMs are mainly used in the following areas and applications:

- hybrid technologies;
- electric motors;
- UV protection in glass, catalysts;
- fuel cell technology (hydrogen storage);
- superconductors;
- light-emitting diodes (LEDs);
- monitors; and
- magnet technology (storage media).

All these applications have in common, that they are also considered key technologies for sustainable solutions. Examples for these elements are listed in Table 19.6.

Similar to REMs precious and rare metals used in electronic components (e.g. circuit boards, transistors, multilayer capacitors) pose important economic threats to the industry and environmental threats to society. Metals from this group include indium, selenium, tellurium, tantalum, bismuth und antimony. Further elements from the platinum group are palladium, rhodium, ruthenium, iridium and osmium, which belong to the precious metals according to their electrochemical properties (Behrendt *et al*. 2007). These are mainly used

Table 19.6 Rare earth metals and their fields of application

REM	Field of application
Cerium	Most frequent REM, availability comparable with copper, used in flints, catalysts, optical industry
Thulium	Rarest REM, availability comparable with iodine, used in microwaves and Geiger counters, energy-saving lamps, X-ray technologies
Neodymium	Most important REM, used in laser technology, magnet production for high tech products (e.g. mp3 player)
Yttrium	Used as fluorescent substance in monitors, TVs, fluorescent tubes (energy-saving lamps)
Europium	Used as red pigment in flat screens
Gadolinium	Used in plasma screens and CDs
Terbium	Green and yellow light in monitors and TVs, permanent magnets
Lanthanum	Optical glasses, electrodes in fuel cells, nickel metal hydride cells in cars and laptops

in electronic, chemical and medical technologies, e.g. relay contacts, spark plugs for cars and catalysts.

Manufacturing processes of electronic products are responsible for major consumption of precious metals, e.g. 12% of gold, 30% of silver and 15% of palladium production annually goes into the electronic industry (Chancerel 2010). These are used in integrated circuits (ICs), contacts, bonding wires, e.g. in mobile phones and computers. Material advantages of precious materials such as gold, silver and palladium, e.g. high corrosion resistance and high conductivity, have to be considered when searching for alternatives as well as their environmental impacts.

Experts predict that especially platinum, indium, tantalum as well as uranium are being used at an alarming rate. Even reserves of such commonplace elements as zinc, copper, nickel and the phosphorus used in fertiliser will be depleted in the not-too-distant future (Cohen 2007).

Despite of the fact that we are facing scarcity of precious metals and REM, recycling of these elements is costly and technologies and systems to recover them are still lacking. Further new technologies (digital cameras, mp3 players) and the ban of lead caused increasing demand for alternative precious materials such as tin, copper, bismuth and indium. These newer materials have to be included in the design of recycling processes, e.g. in metallurgical plants, which are currently efficient only for gold, silver, platinum and some other metals (Hagelüken and Corti 2010).

Positive developments are, for instance, that owing to the high use in energy-saving light bulbs, processes to recycle fluorescent materials have been patented, and for some materials recycling quotes are promising, e.g. the amount of tin-doped indium oxide regained in the 'sputter process' produced during the production of flat screens (Elsner *et al*. 2010). Thus it is very important from a sustainability design perspective to construct electronic products in a way that enables removing metal-containing components easily before the products or components might enter other recycling and disposal streams.

To regain the highly valuable rare earth metals, take-back services, labelling of relevant parts and components and sufficient information for recyclers have to be provided. In general the basic design rules for dismantling and recycling aiming at closing material loops are applicable.

19.5 Examples of sustainable electronic product design

The following sections describe some best practice cases starting with established companies and ending with more radical student projects.

19.5.1 Nokia, eco mobile phones

According to Greenpeace, Nokia is one of the leading companies for sustainable electronics (Guide to greener electronics, Greenpeace, see http://www.greenpeace.org/international/en/campaigns/toxics/electronics/Guide-to-Greener-Electronics/). Nokia developed take-back systems in 85 countries and offers eco-applications, e.g. CO_2 compensation, a software feature called OVI in their mobile phones to encourage people to walk instead of using cars or similar (navigator for pedestrians). In addition eco-profiles of their products are available via Nokia's website (see http://www.nokia.com/environment/devices-and-services/devices-and-accessories/eco-profile). Since 2007 some renewable materials have been used in Nokia products (e.g. bio-plastics) as well as recycled metals (see www.nokia.com/environment/devices-and-services/creating-our-products).

19.5.2 Hewlett-Packard (HP): sustainable printing

Hewlett-Packard implemented their Design for Environment programme in the early 1990s. Using the life-cycle approach, environmental experts, designers and developers are working together to decrease the product's environmental impact (e.g. material, end of life, energy, manufacturing, distribution). Strategies for disassembly and recycling are considered in the development process. Sustainable services include a carbon footprint calculator for computers and printers, the EcoSMART software, which supports customers to print sustainably, e.g. using less paper and energy (see http://www.hp.com/hpinfo/environment/index.html and http://www.hp.com/hpinfo/globalcitizenship/environment/sustainable_design.html).

19.5.3 Kärcher GmbH, sustainable design of cleaning equipment

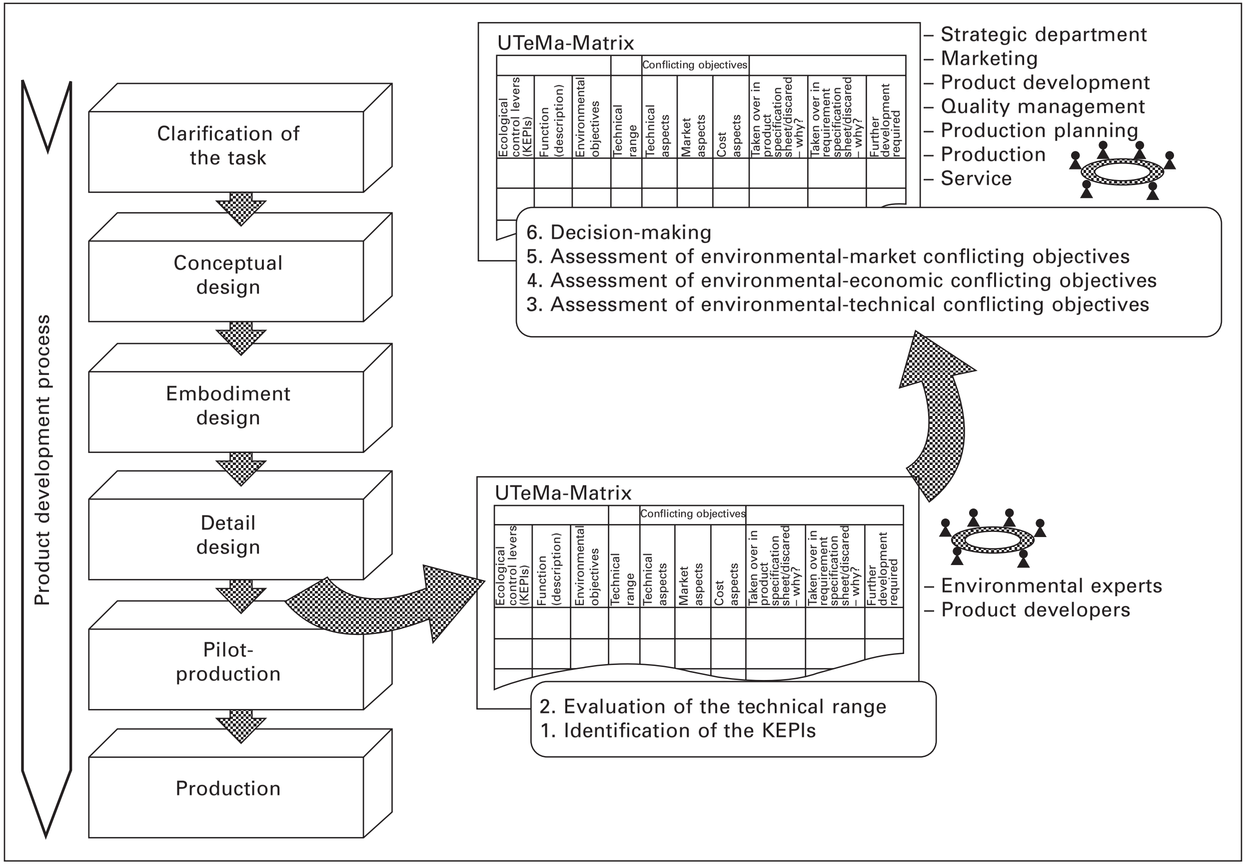
Kärcher GmbH & Co. KG, a leading German manufacturer of cleaning equipment for business and consumer markets, has implemented ecodesign in its product development process. The implementation is based on a tool called UTeMa-Matrix, which was designed according to Kärcher's requirements of product specific strategic decisions within the design process (Hermenau *et al.* 2006):

- adapted to the necessities of the concept design phase;
- collecting and structuring information;
- inclusion of market, cost and technological perspective alongside environmental concerns.

In addition a number of practical tools, e.g. an environmental material database or tools for environmental assessment of electronic parts or electric motors, have been implemented. The UTeMa-Matrix supports environmental decisions during the early and most significant stages of product development and design. In Kärcher's product development workflow it is used twice: first at the end of the development process, before production. At this time all relevant product information is available to carry out an environmental assessment, which is necessary for the identification of key environmental performance indicators (KEPIs). Later on the UTeMa-Matrix is used as a knowledge repository by storing the developer's knowledge about the current product to make it available for further use in future development processes. Thus the knowledge provided by the matrix is the basis for an environmental, economic and technical appreciation of current product features at the beginning of the development of the next product generation. Figure 19.5 shows the integration of UTeMa-Matrix in the product development process.

19.5.4 Trevor Baylis's wind-up media player

One of the pioneers of human powered electronic products is the British inventor Trevor Baylis who developed the clockwork radio in 1991. Since then several companies designed torches, radios, mobile phone chargers and other smaller electronic devices to be charged by human power. Under the brand name Ventus several of Baylis's wind-up products are available, such as the Ventus SPIN Media Player (Fig. 19.6).



19.5 The integration of UTeMa-Matrix in the product development process. Source: Hermenau *et al.* 2006.

(a) (b)

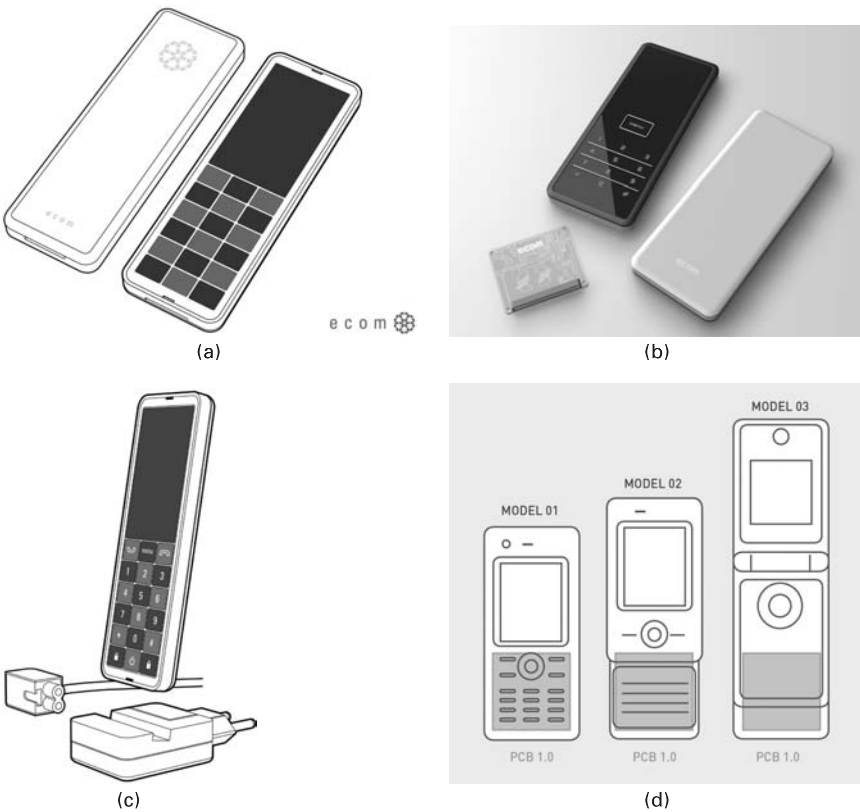
19.6 (a) Ventus SPIN Media Player; (b) wind-up mechanism. Source: http://www.ventusfreeenergy.com/vip7374.html.

19.5.5 Sustainable design of a smart phone: the Ecom phone

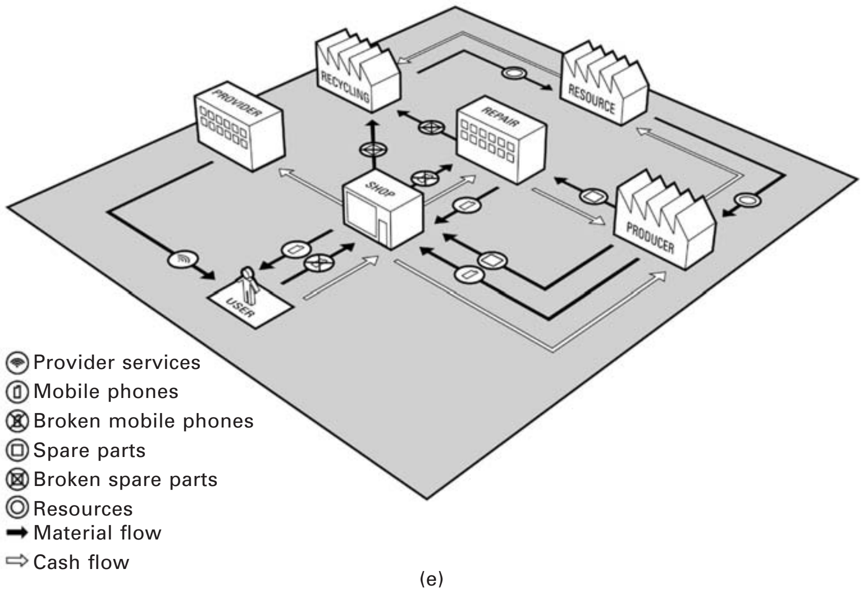
Joel Baumgartner graduated in 2007 from University of Design and Art Zurich and designed an eco mobile phone in his graduation thesis. He analysed and criticised the fact that today mobile phones are replaced year by year even though the majority of the devices are fully operating. What seems to be an advantage for the manufacturer is a large disadvantage for the environment. His aim for the project was to create an alternative concept, which extends the use phase of the devices without compromising competitiveness.

He researched which percentage of the production energy usually is allocated to the different components of a mobile phone and discovered that 90.5% of the energy is used for the production of the PCBs while the housing accounts for only 3.5 %. Accordingly a significant improvement of the life cycle wide environmental impacts can be achieved by extending the use time of the PCBs as the most energy-intensive components. The other components can be replaced more frequently causing much lower environmental impacts. A further goal was to reduce the energy consumption during use.

To guarantee long use of the most energy-intensive components, the Ecom concept combines the phone with a product service system. The user subscribes to the communication service and borrows the eco phone device until they want to terminate the service. Exchange of phone and technological upgrades are possible in between. After termination, PCBs and electronic components of the returned phone are remanufactured by the provider to generate an updated phone for a new customer. To allow a soft evolution of the devices, the Ecom phones are characterised by a modular construction with standardised components. The key element is the PCB, which provides modular connections for the other electronic components, which can be connected via slots. Owing to the small size of the modular PCB shape the functionality of the phone can be designed almost without any limitations. The Ecom phone also includes other features such as a screen based on energy-efficient e-ink technology, a charger and docking station that do not create any stand-by energy consumption, organic LED lighting unit (OLED) etc. An energy balance of the scenarios 'business as usual' with yearly exchange and disposal of mobile phones, versus re-use and remanufacturing of the Ecom phones showed that the Ecom system consumes only about half the energy of the business-as-usual system (Fig. 19.7).



19.7 (a) Design sketch, (b) final model, (c) phone with charger and docking station, (d) variations based on the same PCB, (e) the Ecom Service system.



19.7 Continued.

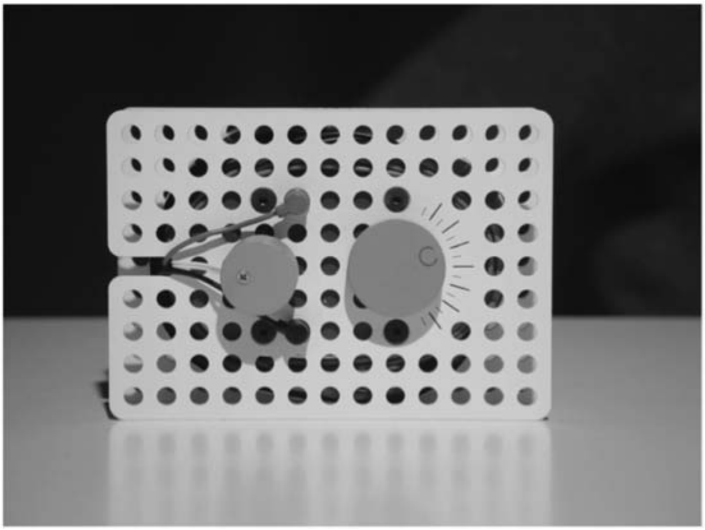
19.5.6 The refugee radio

Design Academy Eindhoven graduate Mareike Gast designed a radio for emergency situations that harvests energy from the radio waves surrounding us (Fig. 19.8). The goal of this project was to distribute information in refugee camps. The solution is a radio that is based on the existing technology of the 'crystal radio' that runs on radio waves alone, not using any external energy. Two variations are available: the prefabricated radio and a do-it-yourself kit that can be assembled and designed by the users (Fig. 19.9).

19.6 Future trends

19.6.1 Renewable energy sources

There is no doubt about the increased energy consumption through ubiquitous electric and electronic products. Besides of increasing energy efficiency of the appliances and their use, different renewable sources for energy have to be explored. From thin film or organic solar cells, to mimicking photosynthesis of plants. Human power can be energy source in wind up concepts (see http://www.alternative-energy-news.info/technology/human-powered/ accessed 24 July 2011) as well as adding a drop of bio-fuel or water in mini fuel cells. Also the problem of batteries with toxic substances and limited availability of lithium has to be solved and researchers explore

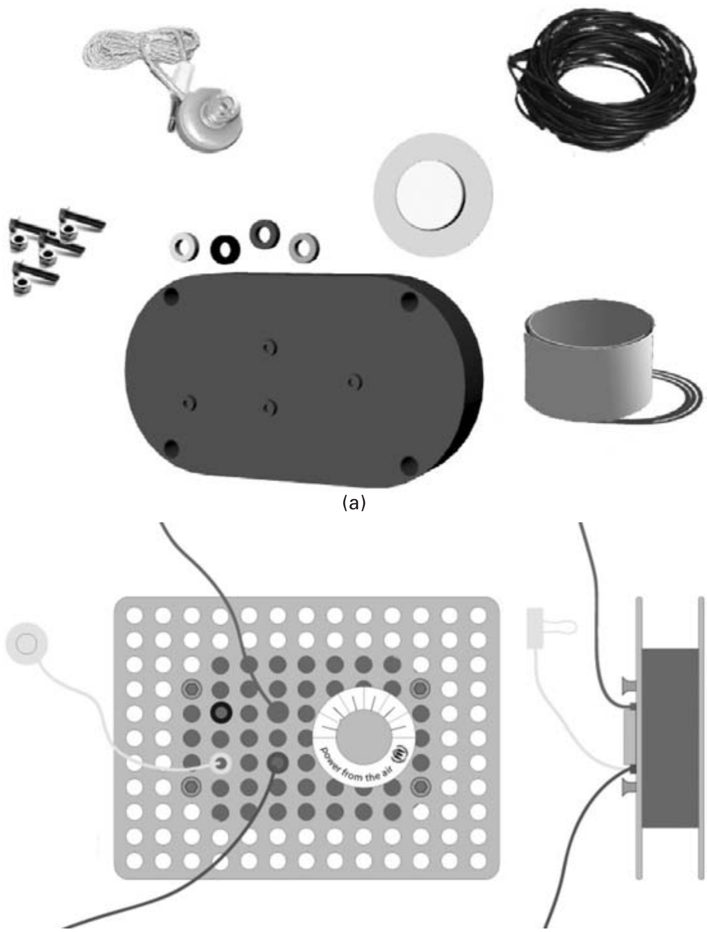


19.8 Prototype of the refugee radio by Mareike Gast, photo Ursula Tischner.

alternatives, such as batteries based on lemons, potatoes or oranges (see e.g. http://www.alternative-energy-news.info/new-battery-technology-self-powered-devices/, http://www.wisegeek.com/what-is-a-lemon-battery.htm both accessed 24 July 2011).

19.6.2 Digitalisation

Digitalisation is the core of the electronic industry and has already been happening for decades; however, the desirable dematerialisation that was predicted to come with it has not always been achieved. For instance instead of reaching the ideal of a paperless office we consume more paper than ever. As Alex Wissner-Gross (see *Times Online*, January 11, 2009, How you can help reduce the footprint of the Web, http://www.timesonline.co.uk/tol/news/environment/article5488934.ece) describes in his research, performing two Google searches from a desktop computer for several minutes can generate about the same amount of carbon dioxide as boiling a kettle, or about 7 g of CO_2 per search. Google claims that a one-hit Google search produces about 0.2 g of CO_2, and various other experts put forward carbon emission estimates for such a search of 1–10 g depending on the time involved and the equipment used. Thus from a sustainability perspective digitalisation should be realised in a way that the net consumption of materials in a system can be reduced. Furthermore the energy consumption should not increase considerably and energy should be generated from renewable and carbon neutral resources.



(a)

(b)

19.9 (a) Radio DIY kit and (b) assembled version. Source Mareike Gast (2005).

19.6.3 Miniaturisation and integration of functions

We are already on a good way of eliminating products and integrating several functions into one device, smart phones or home entertainment centres are such integrative multifunctional objects. However, at the same time more new gadgets are created every day that can be questioned in terms of their usefulness and certainly their sustainability. Integrating functions can be sustainable, if overall the production and consumption of physical objects per person can be reduced. Wouldn't it be wonderful to have only one personal portable electronic device that could combine all the functions of computers, phones, agendas, cameras, MP3 players, scanners, printers, magazines so that we could get rid of all the electronic and physical gadgets we carry around, forget and lose eventually, sit on or collect in our drawers? Actually several companies follow this path, but they can still do better (e.g. Apple iPad, http://www.apple.com/ipad/ or Motorola XOOM http://www.motorola.com/staticfiles/Consumers/xoom-android-tablet/us-en/overview.html).

19.6.4 Human chip implants and bio-chips

The technology is already developed to mix electronic chips with biological matter. Snail cells grow on and communicate with microchips. Scientists have restored the ability of previously blind patients to recognise letters, fruit and other items using light-sensitive microchips implanted in the inner surface of the eye. RFID (radiofrequency identification) chips can be implanted under human skin to identify a person, open doors and perform other functions. While the latter is discussed critically because of studies that show a risk of cancer connected to RFID implants, for medical purposes and to create highly potent bio-chips the interaction of biological cells and electronic components is a very interesting area of research (Zeck and Fromherz 2001; http://web.mit.edu/newsoffice/2010/cytomorphic-0225.html accessed 24 July 2011).

19.6.5 Biomimicry

Biomimicry is a field of science where we try to understand natural systems and organisms and learn from them to solve problems in our technical world. Nature can tell us a lot about better design of electronic products. Interesting principles are, for instance, just-in-time production of substances, like snakes do with their venoms, self-assembly of materials in water like shells, or timed degradation of mussels threads that can be used as models for timed automatic disassembly of products etc. (see e.g. Benyus 1997).

19.6.6 Smart materials and automatic disassembly

Smart materials or memory materials (e.g. shape memory alloys like nickel-titanium (NiTi)) allow creating connections and joints that are able to regain their original form. They can consist of metals as well as polymers and need certain physical attributes to be activated (e.g. temperature, magnetism, energy) (see Chiodo 2005; www.activedisassembly.com accessed 24 July 2011). These features can be used for self-disassembly products, e.g. products disassemble when increasing the temperature during treatment of electronic waste.

19.6.7 Smart systems and adaptronics

The field of adaptronics or smart systems aims at creating a new class of intelligent structures or systems that adapt automatically to different operating conditions by means of self-regulating mechanisms. This works by linking sensors and actuators on the basis of smart materials such as piezo-ceramic fibres and films using adaptive regulators. These smart systems simultaneously have supporting as well as actuating and sensing tasks, making them a multifunctional technology. The market for smart systems is growing in aerospace, plant engineering, car and transport industry (European Commission 2005a; Breitbach 2006). From a sustainability perspective these technologies are useful, for instance, in creating active lightweight structures, using less resources and thus increasing material and energy efficiency as well as functionality, e.g. additional security features or self-monitoring systems. It has to be noted that recycling/re-use of complex composites might pose some problems and thus end-of-life strategies should be developed together with such advanced high tech materials and structures.

19.6.8 Moving from products to services and closed loop concepts

Electric and electronic products should simply not be sold but only handed out to users, to be used alone or in groups for a convenient period of time and then handed back to the producers, who can upgrade, re-use and recycle them in an efficiently and effectively designed closed loop system. This requires effective distribution and re-distribution systems as well as design and production facilities that are able to smoothly integrate materials and components in the next product generations. Material cycles can either happen in the technical realm with long-lasting recyclable high tech materials or in the natural realm with non-toxic biodegradable materials. These kinds of loan systems already seem to be common in some countries in the Far East but are not widely used by Western countries as yet. With increasing prices of raw materials due to increased scarcity these kinds of concepts will make a lot of business sense (see also Tukker *et al*. 2008).

19.6.9 Electronic products as enablers for socio-economic improvements

Electronic products and infrastructure can have positive impacts on systems and regions where the traditional infrastructural systems do not exist, e.g. in so-called developing countries. In some rural areas in Africa or India mobile phones have enabled a whole new micro-economy based on people who own mobile phones becoming providers of all sorts of services for others, who do not own one.

Another example is the organisation Worldreader.org, which wants to deploy the Amazon Kindle to give developing countries access to books, since e-books are less than one-third of the price of a printed book. The organisation works to help subsidise the devices through fundraising to offer affordable prices for local governments. The first e-reader test in the developing world began in March 2010 in the village of Ayenyah, Ghana. The organization aims at improving reading rates and demand for books and at the same time supporting sustainable business ecosystems to create content for, distribute and support e-readers in developing communities (see http://www.worldreader.org/).

Introducing affordable electronic devices in developing and emerging regions can be sustainable as it enables educational and socio-economic progress while at the same time allowing those regions to leapfrog to more dematerialised and efficient digital technologies. However, one also has to be aware that concepts developed by Western designers and companies to be applied in developing countries often fail because they are developed and introduced without proper knowledge about and involvement of local people and communities. Furthermore, they often are considered neo-imperialism by the locals. The one laptop per child project (see http://one.laptop.org/) for instance has encountered these kinds of criticism.

19.7 Sources of further information and advice

Because of legislatory and economic drivers as well as increasing consumer awareness and research funding, the electronics industry as well as associations and non-profit organisations have set up websites and published guidelines on eco and sustainable design of electronic products. Table 19.7 shows a selection of interesting links. Electronic product designers and engineers should use the existing knowledge and tools to integrate sustainability aspects into their daily routines.

Table 19.7 Overview of helpful links for eco and sustainable design of electronic products

General

- Care Electronics (CARE = Comprehensive Approach for the Resource- and Energy-efficiency): international and environmental R&D network within the EUREKA framework, www.care-electronics.net/
- Sustainable Electronics Initiative of University of Illinois USA, http://www.sustainelectronics.illinois.edu/
- Sustainable Electronics Design Report of Pike Research http://www.pikeresearch.com/research/sustainable-electronics-design
- Asia EcoDesign electronics product (aede), http://www.cfsd.org.uk/aede/
- European EcoDesign website and tools especially for SMEs, http://www.ecosmes.net/cm/index-EP
- Envirowise guides for cleaner electronics design, http://envirowise.wrap.org.uk/uk/Sectors/Electronics/Sector-Services/Key-publications.html
- EcoDesign Awareness Raising Campaign for electrical and electronics SMEs, http://www.ecodesignarc.info/servlet/is/349/
- European Recycling Platform, http://www.erp-recycling.org/

Table 19.7 Continued

Ecolabels

- Global Ecolabelling Network, http://www.globalecolabelling.net/
- European Union Ecolabel, http://ec.europa.eu/environment/ecolabel/, www.ecolabel.eu
- German Blauer Engel/Blue Angel, http://www.blauer-engel.de/en/index.php
- Nordic ecolabel (Nordic Swan), http://www.nordic-ecolabel.org/
- Energy Star Programme (U.S. Environmental Protection Agency), http://www.energystar.gov/

Green Public Purchasing

- IGPN International Green Purchasing Network, http://www.igpn.org/index.html
- European Commission Environment GPP (Green Public Procurement), http://ec.europa.eu/environment/gpp/index_en.htm
- DEFRA (Department for Environment, Food and Rural Affairs), http://www.defra.gov.uk/environment/economy/purchasing/

Legislation

- Environmental legislation in Europe: http://europa.eu/legislation_summaries/environment/index_en.htm
- Environmental legislation for electronic products in EU, http://ec.europa.eu/enterprise/sectors/electrical/documents/additional-legislation/index_en.htm
- EcoDesign Directive EuP, http://www.eup-network.de/updates/ and the EuP pages of The Centre for Sustainable Design, http://www.cfsd.org.uk/seeba/EuP/eup.htm

Biomimicry

- Janine Benyus biomimicry institute and guild, http://www.biomimicry.net/
- 'Ask nature', biomimicry examples, www.asknature.org

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20
Reducing hazardous substances in electronics

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Abstract: Many governments have recognised the necessity of banning hazardous substances in electrical and electronic equipment (EEE) to prevent harm to people and the environment. This has resulted in legislation such as the EU RoHS Directive on the restriction of use of certain hazardous substances. However, the substitution of hazardous substances in EEE may provoke manifold unwanted side-effects, such as increased energy consumption in production and increased losses of scarce metals. In some cases, there are no potential substitutes that can provide the same mechanical and chemical properties as the hazardous substances found in EEE. Therefore this chapter argues for a more differentiated and holistic approach, hence, taking into account the actual environmental and health risks related to the use of hazardous substances compared with the substitutes, as well as more eco-efficiency-oriented measures to achieve a result that contributes to sustainable development.

Key words: hazardous substances, electronics, export of e-waste, developing countries, lead, use of lead in electrical and electronic equipment, RoHS Directive, collection and treatment of e-waste.

20.1 Hazardous substances and their functions in electrical and electronic equipment (EEE)

Even though often interpreted as information and communication technology equipment, the term ‘electrical and electronic equipment’ (EEE) covers a wide range of products, from cooling and freezing equipment and washing machines to information and communication technology as well as consumer electronics. Annex I of the European WEEE Directive (2003), for example, lists 10 categories of EEE. All these products have in common that they contain hazardous substances. Older cooling and freezing equipment contains chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) depleting the stratospheric ozone layer. They were substituted in new equipment by butane and other less ecotoxic substances starting with the Montreal Protocol in 1987 (Linde 1994, Fedorowicz 2005).

The printed wiring boards (PWBs) in EEE may bear components containing toxic metals such as beryllium, lead and cadmium. Metal parts such as

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housings and screws may be protected against corrosion with a layer of carcinogenic hexavalent chromium, and some components as, for example, specific switches and the backlights of liquid crystal displays (LCDs) contain mercury. Hazardous organic substances like polychlorinated biphenyls (PCBs) may be found in capacitors. Plastics in EEE use brominated flame retardants to cope with fire safety requirements. Some substances of this group have a high dioxin and furan potential if they burn, e.g. polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE).

The reasons why producers apply these substances are manifold. Most of them have useful physical and chemical properties which make them technically valuable. Lead, for example, has a low melting point in tin–lead solders, allowing low temperature soldering: it is ductile thus preventing the early breakage of solder joints and components under thermomechanical stress, it can be used for vacuum sealing of some specific components, and it prevents whiskers that might cause short circuits, to give some examples. Whiskers are thin needles growing out of surface coatings, for example on the pins of electronic components.

Processing of materials such as lead-containing solders in manufacturing of EEE is comparably simple, and industry has gathered a lot of experience over the decades. A shift to less hazardous substances often makes manufacturing more complex, or at least the production processes have to be changed and adapted as soon as the necessary research and experience provides sufficient know-how. At the same time, most of the hazardous materials are cheaper than their potential substitutes. Thus, even if the hazardous substances can be substituted for more environmentally friendly substances, they are not applied unless legally required.

In the last years, legal restrictions have been the strongest driver for the reduction of hazardous substances in EEE. The most prominent and important legal substance restriction is the European Restriction on Hazardous Substances (RoHS) Directive (RoHS 2003). Some of the substances, however, cannot be substituted in specific applications, as scientifically and technically viable substitutes are not available. Thus, despite of the ban of lead in the RoHS Directive, the banned substances cadmium, hexavalent chromium, lead, and mercury are still present in new EEE, even though their concentrations have been greatly reduced over the last years.

20.2 Legislative bans of hazardous substances in EEE: the RoHS Directive

The European Directive 2002/95/EC (RoHS Directive) entered into force in 2003. It stipulated that from 1 July 2006 on, the following substances were no longer to be used in electrical and electronic equipment:

- lead
- cadmium
- hexavalent chromium
- mercury
- polybrominated biphenyls (PBB)
- polybrominated biphenyl ethers (PBDE)

The substance bans in the RoHS Directive (2011) affect almost all parts of EEE. Metal casings may contain lead as an alloying element, plastics may have cadmium as softener, electronic components carry thin layers of tin–lead (finishes) to improve their solderability, and printed wiring boards (PWBs) may have tin–lead finishes as well and can be soldered with lead-containing solders to attach the components to the substrate. As the producers of the final product are responsible for the RoHS-compliance of their products, they have to conduct comprehensive supply chain investigations and analyses of all product parts to ensure the phase-out of the banned substances and to enable the monitoring of the supply chain.

Despite the obligations to collect and treat e-waste separately from private households according to the WEEE Directive (2003):

> […] significant parts of waste EEE will continue to be found in the current disposal routes inside or outside the Union. Even if waste EEE were collected separately and submitted to recycling processes, its content of mercury, cadmium, lead, chromium VI, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) would be likely to pose risks to health or the environment, especially when treated in less than optimal conditions. […] Taking into account technical and economic feasibility, including for small and medium sized enterprises (SMEs), the most effective way of ensuring a significant reduction of risks to health and the environment […] is the substitution of those substances in EEE by safe or safer materials […] to enhance the possibilities and economic profitability of recycling of waste EEE and decrease the negative impact on the health of workers in recycling plants. (RoHS 2011)

The recast Directive 2011/65/EU (RoHS 2011) thus continues the policy of the RoHS 2003. It is a precautionary measure demanding the avoidance of hazardous substances in the production stage of products in order to protect health, safety and the environment and to improve the end-of-life (EoL) situation of EEE.

Producers of EEE have to find alternatives to avoid the use of the six substances restricted in the RoHS Directive. A restricted substance can be either substituted or eliminated. Substitution means that the restricted substance is replaced by one or several more others, which are not restricted, in order to achieve RoHS compliance. Tin, silver and copper, for example, may replace lead in solders (see Fig. 20.2 below). Elimination means shifting to a technology that does not require the restricted substance. The use of conductive adhesives instead of solders would be an example for elimination. Conductive adhesives do not contain lead, but silver or other conductive substances. The shift from soldering technology to adhesive technology makes the use of solder and thus the use of lead obsolete.

The hazardous substances are used because they have specific properties which are strongly related to the physical and chemical properties of the substances. Substitution may hence be impossible in some cases, and alternative technologies avoiding the restricted substances may not be available either. For these cases, the RoHS Directive allows the continued use of restricted substances. Such exemptions can be granted:

- if the substitution or elimination of the restricted substance is scientifically and technically impossible;
- if substitutes are not reliable;
- if the substitution or elimination causes higher overall adverse impacts on the environment, health and safety than the continued use of these substances.

RoHS (2011) additionally allows taking into account socio-economic impacts and the availability of substitutes as justification for exemptions. Currently, RoHS (2011) lists 38 main exemptions with some sub-specifications for general use in EEE (Annex III), and 20 exemptions that may only be used in medical equipment and in monitoring and control instruments (Annex IV). RoHS-compliant equipment hence may still contain lead, cadmium, mercury and hexavalent chromium. No exemptions allowing the continued use of PBB or PBDE have so far been granted.

20.3 Environmental, technological and economic impacts of the RoHS substance restrictions

20.3.1 Substitution of lead in solders and finishes

The substitution of restricted substances poses a technological challenge for producers in some applications. The most onerous task has been the substitution of lead in solders and finishes. Until 2006, soldering with tin–lead solders was the standard bonding technology in the electrical and electronics industry. Solders and finishes have various applications in EEE:

- Solders are used to fix electrical and electronic components to the PWB. The standard solder used was tin–lead solder with 37% of lead.
- Solders are used in packages of electronic components. The solders used were tin–lead solders with a high share of lead (SnPb85 and higher).
- Finishes are used as surface layers on the lands of PWBs and on the pins of electrical and electronic components to achieve better solderability.

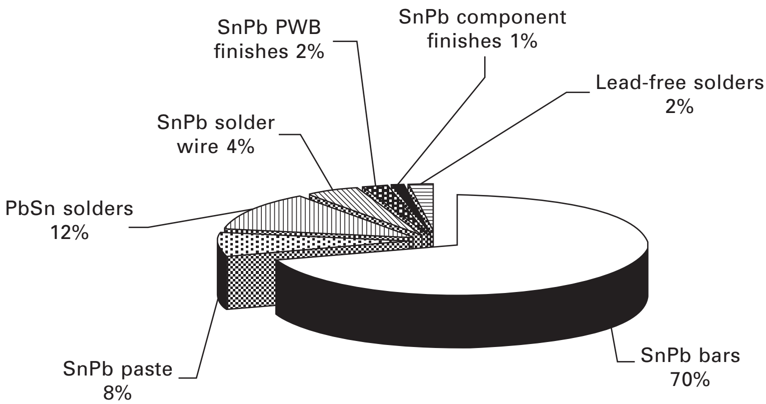
Tin–lead solder for finishes was SnPb20. Other solders with varying shares of lead were applied as well.

The use of alternative bonding technologies such as glueing with conductive adhesives for technical and economic reasons was not a viable general alternative to eliminate the use of lead in bonding. Its substitution in solders hence was the most appropriate alternative. Even though the RoHS Directive applies only to EEE put on the European market, RoHS-restricted substances were phased out globally in most EEE. Most EEE is manufactured for the world market so that substance restrictions in an important market trigger their world-wide phase-out. Globally, the manufacturers of EEE used around 90 000 t of lead-containing solders prior to the ban of lead for various purposes, as illustrated in Fig. 20.1.

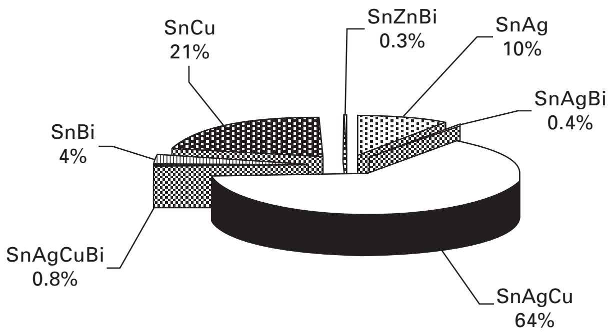
Industry uses a variety of different lead-free finishes and solders, because a drop-in lead-free solder solution is not available. Figure 20.2 shows a possible substitution scenario for different lead-free solders and finishes in the global manufacturing of EEE based on interviews with producers (Deubzer 2007). The tin–lead solders and finishes used depend on the exact application and the manufacturers' preferences. The above substitution scenario reduces the use of lead in electronics, but increases the use of their substitutes and thus triggers a variety of environmental and resource effects.

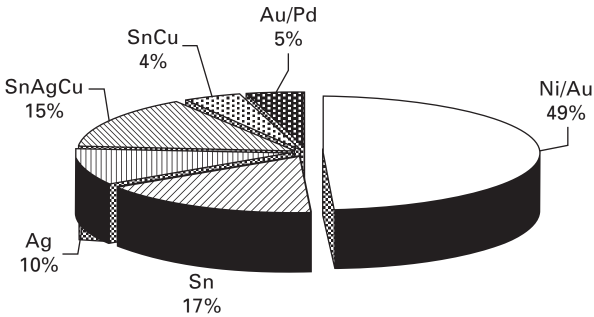
20.3.2 Impacts of lead-substitution on resource consumption

Figure 20.3 shows the additional consumption of metals for lead-free solders and finishes as percentages of the annual worldwide mining productions. It was assumed that worldwide around 10% of EEE is collected and treated

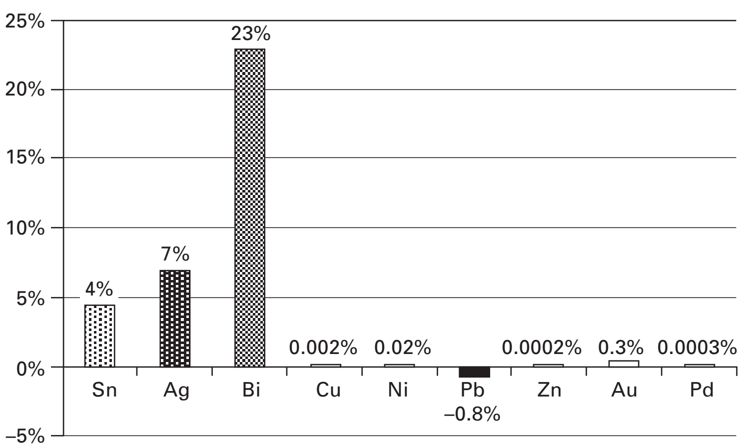


20.1 Composition of the tin–lead solder market for the electrical and electronics industry (figures rounded) (Deubzer 2007).





20.2 Lead-free solders (top) and finishes (bottom) replacing lead solders and finishes (figures rounded) (Deubzer 2007).



20.3 Additional use of metals in EEE for lead-free soldering in percentages of annual mining (Deubzer 2007, values rounded).

in order to recycle the metals. Lead-free soldering in this scenario would moderately increase the use of tin and silver in EEE, but should, however, not seriously endanger the supplies. The other metals show a slight demand increase only.

The ban of lead saves around 23 000 t of lead in solders and finishes (Deubzer 2007), assuming a global collection and treatment rate of around 10%. This amount roughly corresponds to approximately 1% of the annual lead mining and even less compared to the annual use of lead. However, prior to the ban of lead e-waste with around 17% were the second biggest source of lead in household wastes (Landesamt 2003).

The four percent use of tin–bismuth (SnBi) solders replacing lead-containing solders (see Fig. 20.2) surprisingly would result in a high increase of more than 20% (Deubzer 2007) of annual bismuth mining. Such an increase could stress bismuth supplies considerably. It is, in particular, critical looking at the origin of lead: around 85% of primary bismuth originate from lead mining (Deubzer 2007). This situation brings in an aspect, which has so far been neglected in ban and substitution policies of heavy and other hazardous metals. Metals are interlinked in the ores. Even though mines are called ‘lead mines’ or ‘copper mines’, lead and copper are just the main economic driver of mining, whereas other metals are co-mined with lead and copper. Figure 20.4 illustrates the interlinkage of metals in ores.

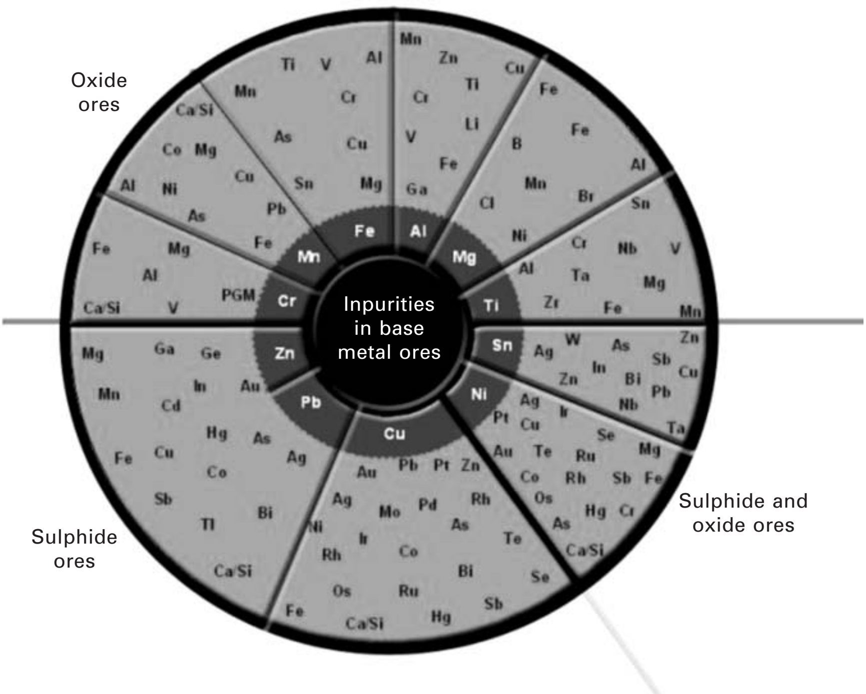
Lead ores are an important source of several other metals. Besides 85% of bismuth, around 30% of silver originates from lead-mining as well. The ban on a metal can thus influence the mining and supplies of other metals as well, or can even result in more mining of the banned metal in order to have sufficient amounts of substitutes for the banned metal. To appraise this situation, the horizontal efficiency concept was introduced (Deubzer 2007). It is a model that makes sure that bans of metals avoid the situation described above. The horizontal efficiency η_H is defined as follows:

$$\boldsymbol{n}_H - \frac{\text{ecological resource value of metals used from mined ores}}{\text{ecological resource value of mined metals}}$$

$$- \frac{\sum_i m_i \cdot \boldsymbol{J}_i \cdot \boldsymbol{I}_i}{\sum_i m_i \cdot \boldsymbol{J}_i} \qquad [20.1]$$

where m_i mass of metal i in mined ores
i type of metal
ϑ_i ecological value of metal in ore
λ_i overall use rate of metal i contained in mined ores in %

The ‘ecological resource value’ can be interpreted as scarcity, which may, for example, be measured with the surplus energy concept used in life-cycle analysis (LCA) (Goedkoop and Spriensma 2001).



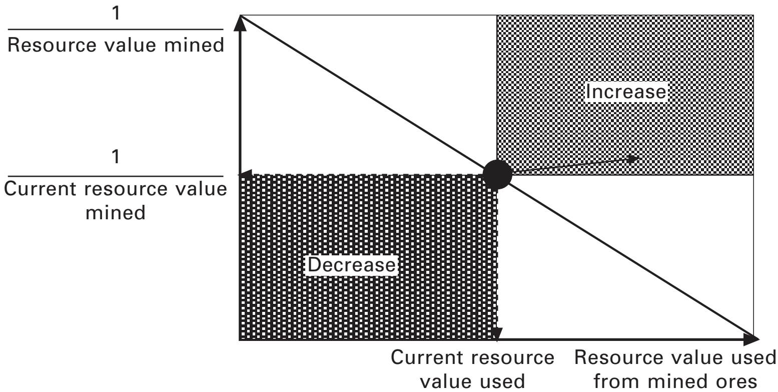
20.4 Interlinkage of metals in ores (Verhoef, Reuter in Deubzer 2007).

The horizontal efficiency complements the well-known material efficiency that less material should be used in a product or service to achieve the same functionality or service result. As this kind of efficiency applies to the upstream material use after mining and refining, it was demarcated as 'vertical efficiency' from the horizontal efficiency, which applies before materials can be used upstream. Figure 20.5 shows that the use of bismuth instead of lead increases the horizontal efficiency of lead mining.

The substitution of lead by bismuth may decrease demand for lead. The resource value mined thus can decrease as well, as less lead ore is mined. Even though bismuth is mined with lead, lead-mining produces a surplus of bismuth, which so far has not been put on the market. If this surplus bismuth is used instead of being disposed of, the resource value used from the mined lead ores increases. The result is an increase in horizontal efficiency, as the arrow indicates in Fig. 20.5 (Deubzer 2007).

20.3.3 Impacts of lead and its substitutes in EoL of EEE

The RoHS Directive assumes that the restricted substances create problems in the EoL of EEE, and that lead substitutes are more environmentally



20.5 Change of horizontal efficiency through lead-substitution by bismuth (arrow) (Deubzer 2007).

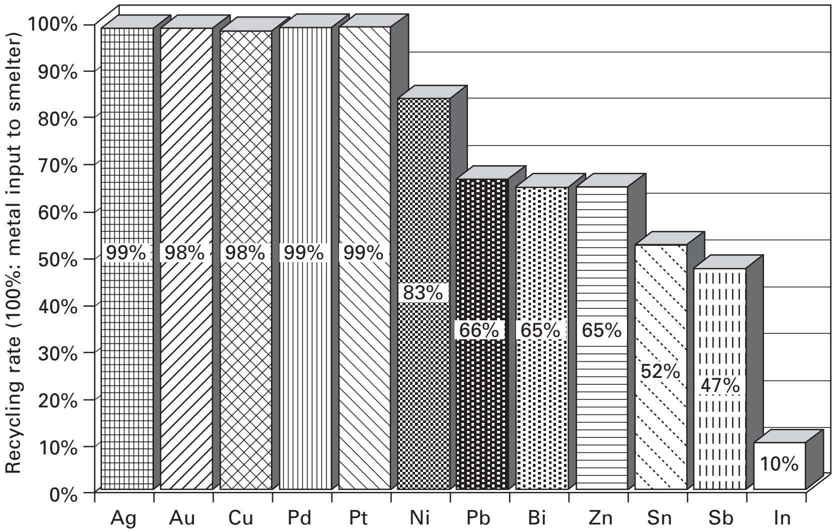
friendly. An in-depth assessment for lead and its substitutes in solders and finishes in the EoL phase of EEE shows that this is only partially right. In Europe, collected e-waste must be treated separately according to the WEEE Directive (2003). After removal of certain hazardous substances, most equipment undergoes a shredding and mechanical separation process resulting in four fractions:

- iron fraction;
- aluminium fraction;
- copper fraction;
- plastics fraction.

The three metal fractions are treated further to prepare the recycling of the metals in smelters, or go directly into the smelters. The plastics fraction is normally used in other plants such as cement kilns to replace fossil fuels.

The most important fraction is the copper fraction, which is the target fraction for tin and lead, as well as for its substitutes in lead-free solders and finishes, silver, gold, palladium, bismuth and nickel. Copper smelters can recycle a wide range of different metals to a high percentage and in good quality. Figure 20.6 shows the average recycling performance of European copper smelters including the treatment in downstream smelters of fractions generated in the processing in the copper smelters, like for example in tin smelters.

According to Fig. 20.6, copper and the precious metals (PM) gold, silver and palladium, which replace lead in solders and finishes, can be recycled very well from such copper fractions with recycling rates of around 99%. For all other metals, the recycling rates are lower. Approximately 70% of lead and bismuth can be recycled, and around 50% of tin. For nickel, one of



20.6 Recycling rate of metals from e-waste copper fractions (Deubzer 2007).

the lead substitutes in finishes, the copper smelters achieve recycling rates of around 80%.

Copper and PMs can be recycled to metals with the same purity and quality as primary metals. Nickel is recycled as nickel sulphate, which may be used, for example, in electroplating. Most of the other metals leave the copper smelter as alloys, as, for example, tin–lead alloys, or as salts, from which the metals can be recycled in further treatment steps at other plants.

Lead does not create problems in copper smelters, which can handle it in their processes. Either it can be recycled, or it is immobilised in slags. Partially, it ends up in filters, together with tin, which then are either recycled or disposed of in special landfills. The lead substitutes in solders and finishes, PMs, copper and tin can be recycled as well. While the recycling rates for copper and PMs are very high, tin rates are lower than for lead. If the copper fraction metals are directed into other fractions, they are not likely to be recycled. They end up in slags, filters, or as contaminations in the recycled iron and aluminium.

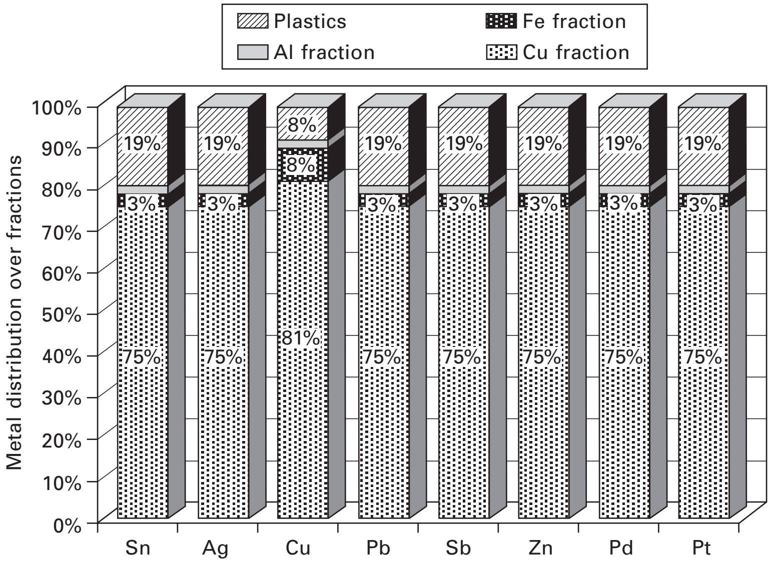
Some of the substitute metals of lead may, however, disturb the recycling processes. Copper smelters may in principle have problems with processing bismuth or nickel, depending on the processes they apply (Deubzer 2007). The smelters tolerate certain threshold levels of such metals and charge extra fees if these levels are exceeded in the fractions to be treated in the smelter. The smelters dilute such inputs with other materials to reduce the concentrations of such metals to the tolerable threshold levels.

The recycling of lead as well as its substitutes thus depends on whether and how far they can be directed into the copper fraction during the comminution and mechanical separation process. Figure 20.7 shows the separation performance in an optimum experimental process setting.

Figure 20.6 shows that copper smelters can successfully recycle metals other than aluminium and iron from copper fractions generated in the pre-processing of e-waste. It is therefore crucial that the pre-processing of e-waste directs as much as possible of these metals into the copper fraction. Figure 20.7 shows that an experimental shredding and mechanical separation process can direct around 75% of the different metals into the copper fraction, while the rest ends up in one of the other fractions, mainly in the plastics fraction. The metals are not likely to be recycled from these other fractions, but are rather an unwanted contamination in these fractions.

The above performance of the experimental pre-processing shows what might be achievable in an optimal process with an ideal input into the process and ideal ratios of manual dismantling and mechanical treatment. For economic reasons, such a processing is not viable in the real conditions of the daily e-waste treatment. Schöps *et al*. (2010) in Table 20.1 show figures for gold, silver and palladium for the treatment of PCs in two other processes. PM-rich components such as the motherboards, plug-in cards and connectors were removed mechanically or manually prior to the comminution process and treated directly in the copper smelter.

Chancerel *et al*. (2009) showed that even with a state-of-the-art shredding



20.7 Mechanical separation of metals in e-waste into different fractions: 100% is the content in e-waste fed into the shredding and mechanical separation process (Deubzer 2007).

Table 20.1 Recycling rates for gold, silver and palladium with removal and direct treatment of PM-rich components in copper smelters (Schöps *et al.* 2010)

	Gold	Silver	Palladium
Recycling rate in % of total content in treated e-waste	70–80	49–75	41–66

and mechanical separation process, the performance may be low if pure mechanical treatment is applied. The plant processed e-waste from information and communication technology and consumer electronic devices with just the legally indispensable manual disassembly. Only 26% of gold and palladium contained in the processed e-waste was found in the copper fraction, and as little as 12% of silver. The rest was distributed over the other fractions and dusts, from which they are not likely to be recycled. The process succeeded in directing 60% of the copper to the copper fraction. The assessed process yields acceptable results for copper, but obviously is not adequate to treat PM-rich components.

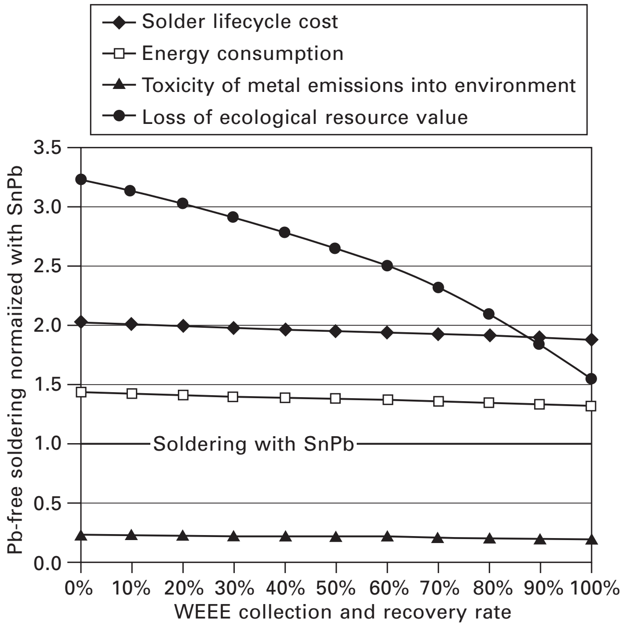
The results show that the pre-processing of e-waste can achieve a satisfying or even good separation yield if state-of-the-art technology is combined with the disassembly and removal of PM-rich components prior to further treatment of the e-waste. The presence of lead does not disturb the EoL treatment. The loss of precious metals in the pre-processing phase, among other aspects, affects the environmental and economic performance of the lead substitution.

20.3.4 Environmental impacts of lead substitution in solders and finishes

The restriction of lead use and its substitution in solders and finishes triggers a variety of environmental and economic effects, as illustrated in Figure 20.8. The results are based on the experimental data in Fig. 20.7, as for the other pre-processing procedures, no data were available for the other metals besides the precious metals. The results in Fig. 20.8 hence must be considered as best case results.

The impacts are normalised with the impacts of soldering with tin–lead solders and finishes. Solders and finishes in EEE, which are not collected and recycled, are accounted as emitted into the environment, as well as the solder and finish metals, which are not recycled in the recycling processes.

The toxicity of metal emissions from lead-free soldered EEE, measured in toxic potential indicator (TPI) units (see Nissen 2001), is clearly lower, and collection and recycling of e-waste will even reduce it further. The energy consumption, however, increases by around 50%. The higher melting points and the resulting increased energy consumption in the soldering processes



20.8 Environmental and economic effects of lead substitution in solders and finishes (Deubzer 2007).

contributes to a minor degree only to this effect. The increased use of PMs, which consume a lot more energy in mining and refining compared to lead, is the main driver behind this effect. This explains why the increased collection and recycling of EEE reduces energy consumption, as in particular PMs highly benefit from recycling.

The ecological resource value can be measured with the surplus energy concept (Goedkoop and Spriensma 2001). The use of PM is the main driver behind the increased loss of ecological resource value from lead-free soldered EEE, even though tin and other metals like bismuth also contribute to this effect. Collection and recycling of e-waste are crucial to reduce the resource losses, but they cannot be compensated compared to tin-lead soldering.

Finally, the life-cycle cost of lead-free soldering is considerably higher. The substitute metals tin, bismuth and in particular the PMs are more expensive than lead. Recycling of e-waste can recover some of this value, but recycling causes cost as well, and the overall recycling rates are far below 100%. The increased energy cost for the soldering processes has a minor impact only on the overall cost. In total, the operative life-cycle cost of lead-free soldering comprising material and energy cost amounts to around €1 billion per year globally for the producers of EEE (Deubzer 2007).

The question whether the ban of lead in solders and finishes is actually environment friendly cannot be answered on the base of natural science. It is a societal decision whether the avoided emissions of hazardous lead are more important than the increased energy consumption, the higher losses of scarce metals and the higher cost.

Figure 20.8 shows that increased collection and separate treatment of e-waste improves the adverse environmental and cost effects of lead-free soldering. They can, however, not be compensated, not even with 100% collection and treatment of e-waste, which is not achievable. Nevertheless, separate collection and state-of-the-art treatment of e-waste are crucial to reduce adverse environmental impacts of lead-free soldering. It is crucial also to reduce emissions of lead from e-waste, as, despite of the RoHS Directive, EEE put on the European market after June 2006 still contains lead.

20.3.5 Lead, cadmium, hexavalent chromium and mercury in new EEE

The RoHS Directive requires substitution or elimination of lead, cadmium, hexavalent chromium and mercury as well as the flame retardants PBDE and PBB in EEE. While the flame retardants could be phased out in EEE put on the market after June 2006, new EEE still may contain the four metals, as technically viable substitutes are not yet available for all their applications. Hexavalent chromium and cadmium are only allowed in few exemptions in Annex III, and in medical equipment as well as in monitoring and control instruments according to Annex IV of RoHS (2011). Their use in new EEE thus is limited to a maximum of several hundred kilograms worldwide for each of the metals in the Annex III exemptions (Öko-Institut/Fraunhofer 2009, 2007, 2006). No data are available for the amounts used in Annex IV exemptions. Lead and mercury for technical reasons are still applied in high amounts, as in several of their functions technically viable substitutes are not available. Mercury is mainly used in lamps according to the exemptions 1 to 4, in particular compact fluorescent lamps ('energy-saving lamps'), and in the backlights of LCDs. More detailed data about the amounts of mercury applied are not available. Mercury is thus restricted to specific parts in certain types of EEE, which can be collected and treated accordingly.

For lead, the situation is different. It is still applied in almost all types of EEE. Lead is a key substance in electronics. Lead is still indispensable in some applications in EEE so that several exemptions in Annex III and Annex IV of the RoHS Directive (2011) allow the continued use of lead. Table 20.2 gives an overview on the different amounts of lead in exemptions of Annex III of RoHS (2011). No data are available for the amounts of lead used in exemptions of Annex IV.

The use of lead in solders of servers etc. allowed in exemption 7b accounts for the largest amount of lead in EEE put on the market after 2006, lead in high melting point (HMP) solders for the second largest one. It must be

Table 20.2 Amounts of lead used in exemptions of Annex III of the RoHS Directive (2011) (Ökoinstitut/Fraunhofer 2006, 2007, 2009)

Exemption no.	Wording	Amount of lead in EEE put on the European market in kg (rounded)*	Amount of lead in EEE put on the global market in kg (rounded)*
7b	Lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signalling, transmission, and network management for telecommunications	5 000 000	15 000 000
7a	Lead in high melting temperature type solders (i.e. lead-based alloys containing 85% by weight or more lead)	3 300 000	10 000 000
34	Lead in cermet-based trimmer potentiometer elements	500 000	1 500 000
25	Lead oxide in surface conduction electron emitter displays (SED) used in structural elements, notably in the seal frit and frit ring	360 000	1 100 000
13	Lead in white glasses used for optical applications, and lead and cadmium in filter glasses and glasses used for reflectance standards	50 000	150 000
26	Lead oxide in the glass envelope of black light blue lamps	50 000	150 000
11	Lead used in other than C-press compliant pin connector systems	35 000	105 000
18	Lead as activator in the fluorescent powder (1% lead by weight or less) of discharge lamps when used as speciality lamps for diazoprinting reprography, lithography, insect traps, photochemical and curing processes containing phosphors such as SMS ($(Sr,Ba)_2MgSi_2O_7:Pb$), and lead as activator in the fluorescent powder (1% lead by weight or less) of discharge lamps when used as sun-tanning lamps containing phosphors such as BSP ($BaSi_2O_5:Pb$)	600	1800
7c	Electrical and electronic components containing lead in a glass or ceramic other than dielectric ceramic in capacitors, e.g. piezoelectronic devices, or in a glass or ceramic matrix compound; lead in dielectric ceramic in capacitors for a rated voltage of 125 V AC or 250 V DC or higher; and lead in dielectric ceramic in capacitors for a rated voltage of less than 125 V AC or 250 V DC	300	900

Table 20.2 Continued

Exemption no.	Wording	Amount of lead in EEE put on the European market in kg (rounded)*	Amount of lead in EEE put on the global market in kg (rounded)*
21	Lead and cadmium in printing inks for the application of enamels on glasses, such as borosilicate and soda lime glasses	33	100
24	Lead in solders for the soldering to machined through hole discoidal and planar array ceramic multilayer capacitors	17	50
17	Lead halide as radiant agent in high intensity discharge (HID) lamps used for professional reprography applications	10	30
33	Lead in solders for the soldering of thin copper wires of 100 μm diameter and less in power transformers	0.33	1.00
32	Lead oxide in seal frit used for making window assemblies for argon and krypton laser tubes	0.0005	0.0015
	Totals in kg (rounded)	**9 000 000**	**28 000 000**

* Where only figure for European or worldwide use of lead were available in the sources, it was assumed that Europe accounts for one-third of the total consumption of EEE.

assumed that exemption 5a (lead in glass of cathode ray tubes) deploys a large amount of lead as well. Data are not available, but the global market for CRT-TVs and monitors is shrinking and the use of lead in this exemption hence will decrease continuously over time. Other large sources of lead may be its applications in steel, aluminium and copper according to exemption 6. Data on the total amounts of lead used under this exemption were not available.

In total, around 9000 t of lead are put on the European market in EEE. The worldwide use of lead in EEE in the various exemptions amounts to at least 28 000 t in new EEE. This is in a similar range to the around 28 000 t of lead worldwide (Deubzer 2007), which are no longer used in EEE due to the RoHS Directive.

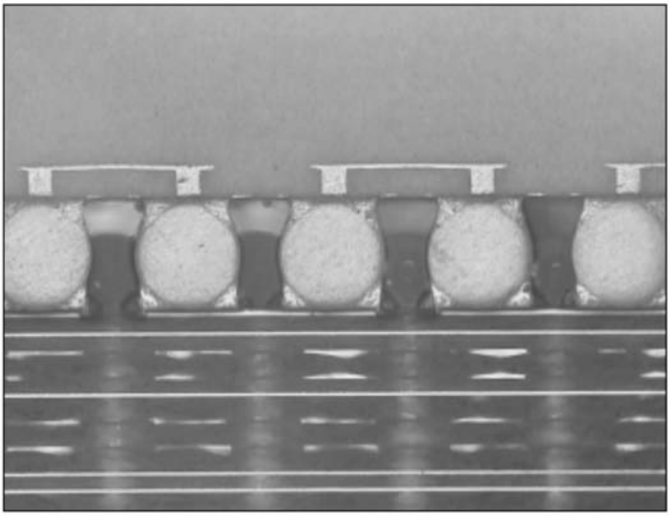
Almost all exemptions in the RoHS Directive are worded in a way that restricts the use of the banned substances to a specific technical application in certain types of devices, e.g. the use of lead in the glass envelope of black light blue lamps according to exemption 26. This allows a clear identification of lead sources in certain devices of e-waste, and even its exact position within the devices. Sources of lead, cadmium, hexavalent chromium and mercury for such exemptions can easily be identified with a single look into Annex III or Annex IV of the RoHS Directive (2011).

Other exemptions cover the use of banned substances in certain components and materials such as in exemption 7c allowing the use of lead in capacitors and in the glass of components such as thick-film components. Ceramic capacitors as well as thick-film components are basic electronic components and thus are applied in most EEE. They are thus a source of lead in almost all e-waste, even though the lead is bound in the ceramics and the glass.

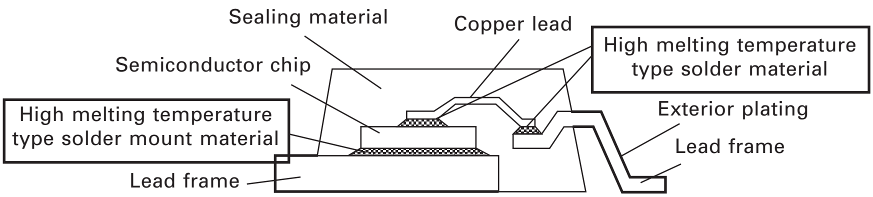
Exemption 7a is a material specific exemption deploying around 10 000 tonnes of lead in around 11 000 t of solders (Deubzer 2007) with at least 85% of lead by weight. These solders have a high melting point and hence are classified as HMP solders. The RoHS Directive (2011) does not restrict their use. As long as they contain at least 85% of lead, producers of EEE can use them wherever they want. They are mainly used in specific applications, where they cannot yet be substituted for technical reasons.

The use of lead-containing HMP solders still is indispensable in several applications, according to the producers. These solders are used to form high reliability electrical connections in large ball grid array (BGA, see Fig. 20.9) or solder column packages, as well as some discrete devices in high reliability electronics. The lead content facilitates solder joints with a high resistance to thermal fatigue and to electromigration failure.

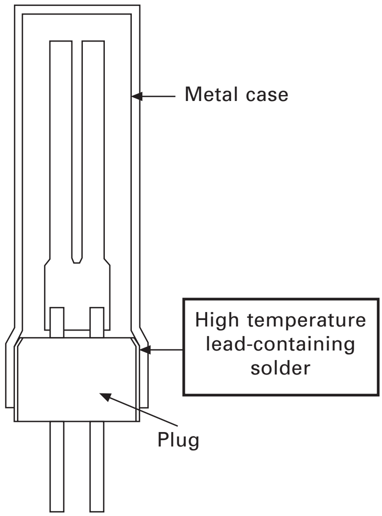
Figure 20.10 shows the use of HMP solders to form high conductivity thermal interfaces to the back of a semiconductor device, also known as die attach, in power devices and discrete semiconductors. These typically are



20.9 Ball grid array component with HMP balls (Ökoinstitut/Fraunhofer 2009).



20.10 Schematic cross-sectional view of internal semiconductor connections with die attach (Ökoinstitut/Fraunhofer 2009).

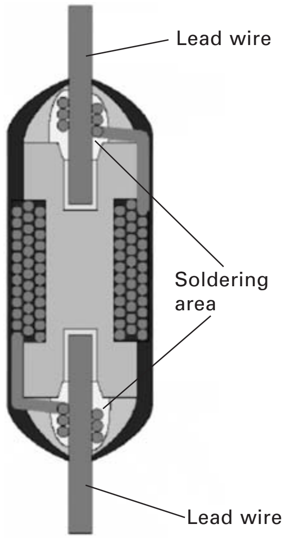


20.11 Schematic view of a crystal unit (Ökoinstitut/Fraunhofer 2009).

used in high reliability applications, such as server applications. Note that the 'Lead frame' in Fig. 20.10 does not refer to the substance 'lead', but to the function of the frame. The frame does not consist of lead! Further on, HMP solders are used as sealing substance between tubular plugs and metal cases, e.g. in crystal resonators and crystal oscillators shown in Fig. 20.11. These applications can be found in many products, including PCs and cellular phones.

Passive components may require the use of HMP solders in internal connections to withstand the high temperatures in soldering processes, especially those using lead-free solders. Figure 20.12 shows such an application. Varying lead content allows the melting point of these HMP solders to be adjusted to the requirements of the manufacturing processes.

HMP solders containing lead in the above applications are used in many types of components that are commercially available and used by most electrical and electronics sectors (Ökoinstitut/Fraunhofer 2009):



20.12 Passive component using HMP solders for internal solder joints (Ökoinstitut/Fraunhofer 2009).

- passive components such as resistors and capacitors;
- rectifiers;
- power semiconductor devices such as MOSFETS, power transistors, etc.;
- voltage regulators;
- solder joints in equipment which operates at >100 °C;
- some types of fuses;
- RF modules, attenuation modules and high frequency switches in telemetry medical devices;
- quartz crystal oscillators (some types);
- position sensor coils;
- inductor coils (some types);
- surface mount transformers.

The examples show that HMP solders are still used in a wide range of applications and thus are present in almost all EEE.

The various examples show that EEE still contains lead despite of its ban in the RoHS Directive. Collection and separate treatment of e-waste hence on the one hand are required to mitigate the environmentally adverse impacts of lead-free soldering as illustrated in Fig. 20.8. The amounts of lead still present in EEE are another environmental driver for collection and treatment of EEE to minimize emissions of lead into the environment.

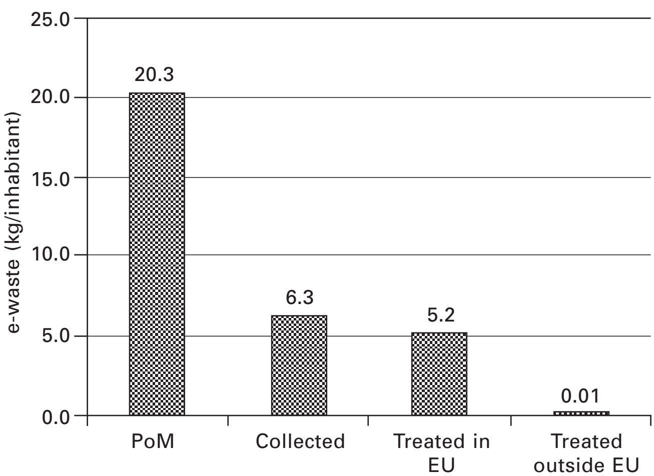
20.3.6 Collection and treatment of e-waste

Figure 20.13 illustrates the amounts of EEE put on the market (POM), collected and treated in the EU27 in the year 2008. The figures go back to the data, submitted by member states of the EU to the European Commission based on their obligations according to the WEEE Directive (2003).

As in European countries the market for most types of EEE is saturated, it can be assumed in a first approximation that EEE put on the market replaces old EEE. Figure 20.13 shows that there is a big gap of around 14 kg per year and inhabitant between POM and collection, indicating that most of the e-waste generated is not collected and treated in the official e-waste management systems installed in the EU member states based on the WEEE Directive. Eurostat (2008) confirms this trend for the years 2006 and 2007 as well. No clear information is available on the whereabouts of the rest. It may be treated outside the official e-waste management systems in the EU. Witteveen & BOS (2010) assessed that in the Netherlands in total around 80% of e-waste arising are treated, around 31% only within the official e-waste management system. Around 50% are treated outside the official system.

Consumers may dispose of part of this equipment with household waste where it must be assumed that neither the valuable nor the toxic materials in this e-waste are recycled and thus may cause damage to the environment. This applies in particular to e-waste items, which due to their small size can fit into normal household waste containers (Huisman *et al*. 2007).

Part of the e-waste is exported to developing countries and countries with market economies in transition. Sander *et al*. (2010) estimated that



20.13 E-waste reported as collected and treated in EU 27 in 2008 (Eurostat 2008).

up to 216 000 t of e-waste are exported from Germany to such countries. Espejo (2010) showed that the e-waste shipped out of the EU never enters the official e-waste management systems, but is collected and exported by a flourishing informal sector in Germany. This situation is similar in other developed countries.

Part of the exported equipment is still functional and is repaired, refurbished and reused in the countries of import (Odeyingbo 2011). Environmental, health and safety problems start once this equipment becomes obsolete.

Sepúlveda *et al*. (2009) showed that the concentrations of lead (Pb), polybrominated diphenylethers (PBDEs), polychlorinated dioxins and furans as well as polybrominated dioxins and furans (PCDD/Fs and PBDD/Fs) in air, dust, soil, water and sediments in e-waste recycling areas of China and India may exceed the pollution observed in other industrial or urban areas by several orders of magnitude. Such levels of pollution pose a serious environmental and human health threat. Improper recycling techniques of e-waste such as dumping, dismantling, inappropriate mechanical treatment, burning and acid leaching were identified as root causes of the pollution. Hence, even though the substitution of lead in solders of EEE has environmental tradeoffs, it makes sense to reduce the amounts of these hazardous substances in EEE considering the EoL situation in developing countries and countries with market economies in transition.

20.4 Differentiated approaches for the use and ban of hazardous substances

Proper treatment of e-waste can limit the impacts of hazardous substances in e-waste. The know-how and the technologies are available and are applied at least in some developed countries. Toxic heavy metals such as lead can be recycled to a certain degree or can otherwise be controlled and prevented from being released into the environment. High amounts of e-waste arising in developed countries are, however, not collected separately and thus very probably not treated according to the state of the art. Nevertheless, it can be assumed that in such countries environmental legislation setting emission limits for hazardous substances into air, soil and water at least limit the environmental and health damages even in those cases where the e-waste is not treated according to the state of the art.

Developing countries and countries with market economies in transition lack appropriate treatment technologies for e-waste. Environmental legislation is either not in place, or otherwise often poorly enforced. Hazardous substances in EEE under these circumstances cause serious environmental and health damages. At the same time, these countries have the highest growth rates for EEE. The annual increase of around 22% for information and communication equipment in China (StEP Initiative, undated) is just one example for this trend. Imports of e-waste into developing countries exacerbate the problem.

Given the fact that most EEE is produced for the global market and thus sold around the globe, conditions in the developing countries should be a main driver for the substitution or elimination of hazardous substances in EEE. As these substitutions and eliminations may cause other unwanted effects on the environment and resource consumption, and may be cost-inefficient, other possibilities should be checked nevertheless before legally restricting the use of certain hazardous substances. Technology and know-how transfer for collection and treatment of e-waste to developing countries as well as increasing its separate collection and state-of-the-art treatment in developed countries may be more appropriate, allowing the management of hazardous substances rather than their substitution. Better collection and treatment at the same time would facilitate more recycling of scarce resources such as precious metals applied in EEE and thus produce highly positive side effects of such hazardous substance management measures. In each case, the substitution or elimination of hazardous substances in EEE should be based on a risk analysis, taking into account the environmental, resource and cost effects of the substitutes and the impacts of alternative approaches.

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20.6 Appendix: abbreviations

EEE	electrical and electronic equipment
EoL	end of life
HMP solder	high melting point solder
PBB	polybrominated biphenyls
PBDE	polybrominated diphenyl ethers
PCB	polychlorinated biphenyl
PGM	platinum group metals
PM	precious metals
PWB	printed wiring board

21
Examining subsidy impacts on recycled WEEE material flows

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Abstract: Government subsidies to recycling systems can play important roles in driving or curtailing the flows of recycled items. This chapter examines the impacts of exogenous subsidies on recycled material flows in a decentralized recycling system where each entity acts according to its own interests. The chapter also discusses the issue of subsidy impact on exporting recycled items. Our findings should be useful to policy makers in creating the most efficient subsidy policy.

Key words: decentralized decision-making, recycling systems, subsidy.

21.1 Introduction

Management of recycled materials in recycling markets can have a great impact on the profitability, financial viability, and economic development of associated recycling industries. Government regulation plays an important role in recycled material flows (e.g., Waste Electrical and Electronic Equipment Directive (WEEE) and Reduction of Hazardous Substances Directive (RoHS) in the European Union). There are several legislative policies enacted and implemented in different regions or countries for electronics scrap recycling. For example, in January 2005 the California act (IWMB 2003) established an advanced recycling fee (ARF) of \$6–10 on all electronic products with certain video display devices and the ARF is used to fund electronics recycling (Gable and Shireman 2001). The California ARF was increased in January 2009, to \$8–25 depending on the screen size of the video display (SBoE 2009). In the state of Maryland, manufacturers pay fees to the state government and state funds reimburse recycling expenses for county and municipal recycling programs (ETBC 2009). Apart from the situation in the United States, take-back or recycling programs have been implemented in certain regions or countries such as the European Union, Canada, Japan, and Taiwan (Lee *et al.* 2000; Shih 2001; Hewlett-Packard 2005; Hicks *et al.* 2005; Nnorom and Osibanjo 2008; Khetriwal *et al.* 2009). These legislative developments for the recycling of electronic devices are certain to have an impact on the behavior of each entity in recycling networks for these regions.

This study aims to model and investigate the potential effects of government subsidies on recycling networks.

In this chapter, we refer to recycling systems as reverse production systems (RPS), which include the collection, sorting, demanufacturing, and refurbishment processes networked by reverse logistics operations. Many researchers have discussed reverse logistics system planning for end-of-life products in a centralized framework (e.g., Barros *et al.* 1998; Fleischmann *et al.* 2000, 2004; Ammons *et al.* 2001; Shih 2001; Guide and Harrison 2003; Realff *et al.* 2004; Sheu *et al.* 2005; Hong *et al.* 2006; Schultmann *et al.* 2006; Assavapokee *et al.* 2008; Chen and Hong 2008), where a centrally controlled planner can be seen as a local government or an organization who owns collection and processing sites in a recycling network and is capable of making decisions for the complete network.

Another approach is to view an RPS as a *decentralized system*. In a decentralized decision-making reverse supply chain system, a RPS consists of several independent entities operated by different private parties, who are unwilling to reveal their own confidential information of processing capacities or cost structures to others or the public. For such a decentralized RPS, Nagurney and Toyasaki (2005) and Hong *et al.* (2008a, 2008b) present decisions of independent decision-making participants within the network. Here we utilize the model presented in Hong *et al.* (2008a) as a planning tool to analyze and investigate the impacts on decisions in a decentralized RPS due to the government subsidy to recycling network.

Research on subsidy effects in public transportation systems, telecommunication markets, and R&D expense include Karlaftis and McCarthy (1998), Tisato (1998), Melody (2000), Sidak (2002) and Jou and Lee (2001). A variety of subsidy policies have been proposed to encourage or enhance the willingness of households, individuals, and businesses to recycle. For example, a deposit-refund system requires consumers to pay a deposit that is subsequently refunded when consumers return the reusable part of the commodity (Kulshreshtha and Sarangi 2001). The empirical results in Blomberg and Söderholm (2009), however, show subsidies might not be the most effective way to increase recycling rates in the secondary aluminum market. Other policy options to impact recycled material flows include take-back requirements and tax-subsidy schemes (Fullerton and Wu 1998; Huhtala 1999; Eichner and Runkel 2005). Very little research has focused on the analysis of government subsidies, which may cause different outcomes and impacts in a decentralized RPS, and the impact of government subsidies on recycled electronics material flows deserves further attention.

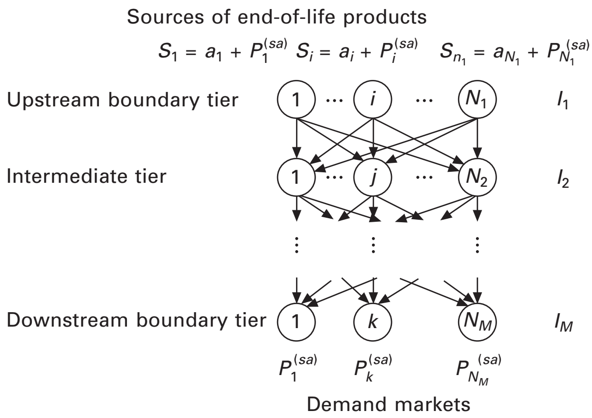
This chapter outlines a multi-tier model of the supply network from collection to end-markets for a decentralized recycling system. Agents coordinate between tiers through the use of price-flow contracts, a guarantee of the upstream tier to provide flow to the downstream tier on the basis of the prices offered. Agents within a tier compete to establish price equilibria such that no agent wishes to deviate from their price offers, or so that they are able to clear the market of material.

We investigate the impact of alternate schemes of recycling subsidies on flow decisions and the total amount collected. For the case under study, we determine that the best location of the subsidy is in the middle tier along a reverse chain. This chapter also discusses the issue of exporting recycled materials when there are no environmental regulations banning export of recycled items, and the subsidy arbitrage where the collection sites in nearby states may take advantage of the subsidy policy and transport recycled materials to the state implementing a subsidy policy. We investigate how subsidies at domestic recyclers affect the material flow in a recycling system where one recycler is assumed to be located overseas and one recycler is in another state without the subsidy policy. As expected, the material flow transported to the overseas site or nearby states decreases as the subsidy level to the domestic in-state site in the downstream tier increases, but a high subsidy level returns a low amount of recycled items collected per dollar subsidy. This finding may warn a policy maker that a high subsidy indeed results in a high domestic material percentage, but a low-efficiency subsidy scenario may result.

The remainder of this chapter is organized as follows. In Section 21.2, we describe the general multi-tiered decentralized RPS problem and summarize the solution algorithm presented in Hong *et al.* (2008a). In Section 21.3, we examine the individual entity and system behaviors for a decentralized RPS network when the government subsidizes associated participants in the network to increase consumers' willingness to recycle. Finally, we present several implications and insights drawn from a case study and draw conclusions in Section 21.4.

21.2 A multi-tiered decentralized reverse production system (RPS) problem

An RPS is a network of transportation logistics and processing functions that collect, recycle, refurbish, and demanufacture end-of-life products. In this chapter, we model the RPS as a multi-tiered network, depicted in Fig. 21.1, which consists of an upstream boundary tier, several intermediate tiers, and a downstream boundary tier. We consider N_1 independent entities in the upstream boundary tier as represented by the top tier of nodes in Fig. 21.1, $N_2,\ldots, N_{M-1}$ entities in intermediate tiers $2,\ldots, M - 1$ respectively, and N_M downstream boundary tier entities associated with the bottom tier in the network. In addition, we let sources of end-of-life products and demand markets be the two boundary exogenous tiers of the network, respectively represented as several independent and possibly geographically distinct



21.1 A general multitiered RPS network structure (Hong *et al.*, 2007; Reprinted with permission of John Wiley & Sons Inc.).

sources of end-of-life products, and demand markets for secondary used products or recovered materials.

Upstream boundary tier entities represent municipal collection sites, non-profit collection organizations, private collectors, etc. The entities in the upstream boundary tier collect recycled items from the source supply, which can include, for example, residential households, businesses, schools, or the government. The amount collected may depend upon the collection fee between the upstream boundary tier and the source. The intermediate tiers may contain several levels of entities: for example, the tier of consolidation sites, material brokers, processing sites who purchase collected materials from their preceding tier and conduct some value added processes such as sorting, or disassembly operations or simply act as an intermediary between tiers. Downstream boundary tier entities associated with nodes in the bottom tier in the network can be seen as the final stage of the entire RPS, where they purchase recycled items from their preceding tier and conduct further dismantling/mechanical fragmentation of items or refurbish end-of-life products for consumption purposes. Hence, downstream boundary tier entities may convert the recycled items into recovered materials and/or refurbished products and sell them to the specific demand markets. In summary, downstream tier entities purchase recycled items from their preceding neighbor tier; as a result, materials flow from the upstream tier to the downstream tier of entities. For simplicity, we assume that materials must move through each tier sequentially. In other words, materials cannot be transported directly across two or more tiers within the network.

We let $I_M = \{1,\ldots, j,\ldots, N_m\}$ denote the set of sites in tier m. The entities in the upstream boundary tier collect recycled items from the source, and the source supplies the upstream boundary tier site on the basis of a fee paid by the upstream boundary tier site. We let S_i denote the collection amount of a single type of recycled items in upstream boundary tier site i ŒI_1 and $p_i^{(Co)}$ be the collection fee per unit of the recycled item paid by site i ŒI_1. We characterize the collection amount for the upstream boundary tier site i Œ I_1 by a linear function $S_i = a_i + b_i p_i^{(Co)}$, where a_i and b_i are parameters and a_i, $b_i > 0$. The collection fee, $p_i^{(Co)}$, of site i ŒI_1 can be positive or negative, the latter meaning that the site charges for material. Our model can be extended to the system involving more than two types of items to be picked up or recycled if there is no interaction among them. The use of a linear function allows the analysis of the problem to be simplified. It captures a qualitative market behavior of increased flow with either an increased payment or a decreased collection fee (charged by the collection site).

At the other end of the system, we assume that the amount of raw materials resulting from the deconstruction of end-of-life products and used products is relatively small compared with the quantity in the virgin raw material and brand-new product markets. This observation leads to the assumption that the selling prices of raw materials or used products in final demand markets are fixed amounts, not affected by sales quantities. In other words, all of the entities in the downstream boundary tier are price-takers since their individual decisions in the selling quantity of raw materials or used products are not high enough to influence the price of those commodities in the final demand markets. We let $p_k^{(Sa)}$ denote the selling price obtained in downstream boundary tier site k ŒI_M. In other words, the two main exogenous information streams to the system are the source supply functions of the collected recycled item amount in the upstream boundary tier, represented by $S_i = a_i + b_i p_i^{(Co)}$ for site i ŒI_1, and the selling price obtained in the downstream boundary tier, denoted by $p_k^{(Sa)}$ for site k ŒI_M. Here, a_i, b_i, and $p_k^{(Sa)}$ are known parameters, but S_i and $p_i^{(Co)}$ are unknown variables of the system.

21.2.1 The decentralized RPS model

In the decentralized decision-making framework, each entity within the RPS concentrates on optimizing its own profit subject to its own transportation and processing capacity constraints. The decentralized RPS model is developed in detail in (Hong *et al.* 2008a). The upstream entities in one tier determine the price-flow contract, shown in eq. (21.1), which connects their subsequent downstream acquisition price information to the flow upstream entities supply. The material flow from site i ŒI_m to site j ŒI_{m+1}, denoted by $x_{ij}^{(Tr)}$, is a function of the acquisition prices, represented by p_j, j Œ I_{m+1}, to be offered by the sites in tier m+1. We let $V_{ij}^{(Tr)}$ denote the unit transportation cost from site i ŒI_m to site j ŒI_{m+1}. The format of the price-flow contract in this chapter implies that any particular arc of material flows is not only a function of the price offered by its destination downstream site, but also the relative price offers of other downstream sites. The decision variables for upstream site $i \in I_m$ are the coefficients in the material flow determination, denoted by $\alpha_{ijj'}$ from upstream site $i \in I_m$ to downstream site $j \in I_{m+1}$ affected by downstream site $j' \in I_{m+1}$. The proposed price-flow contract captures the idea that upstream site i tends to increase the flow amount on $x_{ij}^{(Tr)}$ if downstream site j offers a higher price. Meanwhile, upstream site i may decrease the amount of $x_{ij}^{(Tr)}$ to feed more flow to other arcs if other downstream sites provide more incentives in price offers.

$$x_{ij}^{(Tr)} = \sum_{j' \in I_{m+1}} \alpha_{ijj'}(p_{j'} - V_{ij'}^{(Tr)}) \quad \forall i \in I_m, j \in I_{m+1}, m = 1, \ldots, M - 1 \qquad [21.1]$$

Each upstream entity acts individually to determine the price-flow contract and then communicates the contract to its associated downstream entities in the next tier. Owing to the nature of no information sharing in the decentralized model, upstream entities do not know the exact final acquisition prices to be offered by downstream entities. Each upstream entity predicts the possible range of acquisition prices as input information for determining price-flow contracts. One way to forecast lower and upper bounds of acquisition prices is based upon the information of transportation costs and market prices. A possible lower bound on the price is the transportation cost between upstream and downstream tiers; otherwise, the upstream sites obtain a negative price offer since the net unit price paid by a downstream site (or received by an upstream entity) is the acquisition price minus the unit transportation cost. A negative unit reward is not in their interest. Therefore, we assume that the forecast acquisition prices are at least as much as the associated transportation costs in the model. Another possible lower bound is the market price since upstream sites are unwilling to sell for less than the market price. However, if downstream sites own the bargaining power, the highest market price may be a potential upper bound of the acquisition price since downstream sites are unwilling to pay more than the market price for acquiring materials from upstream sites.

The price-flow contract is determined using a robust optimization formulation that captures the idea that the upstream entity does not have exact price information from the downstream entities, and wants to minimize the worst outcome it can have. The underlying objective of each upstream is to design a price-flow contract against acquisition price ambiguity. First, each upstream entity predicts the possible range of acquisition prices as input information for determining the price-flow contract. For computational convenience, several evenly discrete points within the price range are selected to represent the whole range of the acquisition price. Then, the optimal solution is found for each upstream site for a combination of selected price points accounting for price ambiguity from downstream sites. This solution calculates the highest profit that the individual upstream site can obtain if it were to know the acquisition prices exactly. Next, each upstream site minimizes the maximum deviation of the objective function value between the 'ideal' and the 'robust' sales profit for all price combinations of the selected points. Finally, each upstream site adjusts its decision variables, α¢s, to ensure those returning the best sales profit for all tight and not-tight constraints. The price-flow contracts are independently designed by the upstream tier sites and then communicated to the subsequent downstream tier sites.

After price-flow contracts are given to the downstream tier sites, the tier entities are assumed to participate in an auction for the items from the preceding tier. The auction is assumed to persist until the participants do not wish to change their bids any further. This allows a Nash equilibrium to be reached within the tier, where no entity can be better-off by a unilateral change in its decision of the acquisition price. An algorithm for finding this equilibrium is presented in Hong *et al.* (2008a, 2008b). The algorithm respects the structure of the system by only having the previous bids of each entity available for inspection when the next bid is being determined by each independent entity. Under this framework, entities in the system reach the equilibrium of the acquisition prices. In summary, price-flow contracts are independently designed by the upstream tier sequentially from the upstream boundary tier to the second last tier. Acquisition prices are set by the downstream tier and passed back to the upstream tier sequentially from the downstream boundary tier to the first tier. As a result, the design mechanism of price-flow contracts implies that, given any two adjacent tiers, upstream entities are price-takers. In the following sections, we investigate numerical results in a decentralized RPS case study and draw several insights of examining different fee subsidizing schemes in a three-tiered RPS.

21.3 Insights from decentralized RPS case study

21.3.1 Case study overview and input data

We develop our understanding of subsidy impact by comparing results for different recycling scenarios in a realistically structured decentralized RPS. First we construct a baseline case study, and then modify it with subsidy alternatives. Our case study is based upon representative data for a particular product in the geographical region and time period of our study. Of course, these data only apply to our research case study and would be different for different products, different geographical regions, and/or different time epochs. These specific case study data are not the focus of this work and are only presented here for completeness. The reader not interested in the details of the case study data may go directly to results reported in Section 21.3.2.

This case study examines the individual behaviors of each site in a decentralized RPS that handles accumulated end-of-life laptop computers. Different sources estimate a different average weight of a laptop computer: 6 pounds per unit, 4–6 pounds per unit (CRM 2011), and 7 pounds per unit (CCG and SR 2003). In this study, we approximately estimate a laptop computer weighing 6 pounds (2.72 kg) per unit. The collected area is the state of Georgia in the United States, an area covering 57 906 square miles (149 911 km^2) with an estimated population of 9.5 million.

In this case study, we conceptually categorize the RPS into three different tiers including collection sites (tier 1), repackaging and accumulation sites (tier 2), and processing sites (tier 3). This case study considers 12 potential municipal collection sites based on service regions defined by Georgia's Department of Community Affairs in tier 1 (DCA 2003). Nine tier 2 repackaging and accumulation sites in Georgia are all commercial processing sites (Hong *et al.* 2006) which are located according to population distribution, where more than half of Georgia residents live in metropolitan Atlanta. Additionally, in tier 3 there are three processing sites, including one in the state of Georgia, one in a nearby state, Tennessee, and one is in the overseas country of Nigeria. The detailed geographical information associated with each site in each tier is shown in Table 21.1.

Table 21.1 General information for all sites

Potential site designation	State/country	County/city	Type
C_1	Georgia	Gordon	Collection sites (Tier 1 Sites)
C_2	Georgia	White	
C_3	Georgia	DeKalb	
C_4	Georgia	Meriwether	
C_5	Georgia	Oconee	
C_6	Georgia	Bibb	
C_7	Georgia	Richmond	
C_8	Georgia	Chattahoochee	
C_9	Georgia	Toombs	
C_{10}	Georgia	Dougherty	
C_{11}	Georgia	Ware	
C_{12}	Georgia	Chatham	
R_1	Georgia	Catoosa	Repackaging and accumulation sites (Tier 2 Sites)
R_2	Georgia	Carroll	
R_3	Georgia	Cobb	
R_4	Georgia	Fulton	
R_5	Georgia	DeKalb	
R_6	Georgia	Gwinnett	
R_7	Georgia	Washington	
R_8	Georgia	Baldwin	
R_9	Georgia	Richmond	
P_1	Georgia	Marietta	Processing sites (Tier 3 Sites)
P_2	Tennessee	Nashville	
P_3	Nigeria	Lagos	

Given the site locations, we next estimate the transportation costs per unit flow between sites as shown in Table 21.2. The estimation is based on the following: (1) the Retail Motor Gasoline and On-Highway Diesel Fuel Prices (EIA 2008) table listing the fuel information from 1990 to 2007 from the US Department of Energy (2008); (2) the average freight revenue of carriers (RITA-BTS 2008), which is assumed to be the average transportation cost paid by shippers; (3) the regression relationship between the average price of gasoline and the average freight revenue (see RITA-BTS 2008) obtained by running a commercial statistical package; (4) the resulting estimated number of the ground transportation cost per laptop (an average 6 pound (2.72 kg) computer) per mile of $0.000906 (equivalent to $0.000563/laptop/km).

In addition to the ground transportation cost, the ocean transportation cost for each used laptop computer is estimated. An Internet survey (Alken Murray Corporation 2008) indicates that a 40-foot container can carry 45 000 pounds (20 412 kg) and a ballpark estimate of the shipping fee quote for a 40 foot container from Savannah, Georgia, in the US to Lagos, Nigeria, based on a 40 foot container is $6000. On this basis, we estimate the ocean transportation cost per laptop computer from Savannah to Lagos is $0.8 per unit ($6000/20 412 kg × 2.72 kg) (Table 21.3).

Next we estimate end market selling prices. Processing sites 1 and 2 (P_1 and P_2) are located within the US, but P_3 is in an overseas country. We queried price information for used products (14 inch screen; 256MB memory; 40–79GB hard drive) near P_1 and P_2 site locations (eBay 2008) and took the average of the selling prices for the first ten query entries. Hence, the market selling prices at P_1 and P_2 are estimated as $321.59 and $268.97, respectively. With a similar approach, the selling price of used-laptop computers in Lagos, Nigeria (P_3) is estimated as $349.95 (CN 2008).

Table 21.2 The unit ground transportation costs between tier 1 and tier 2 sites ($/laptop)

Unit transportation cost		$j \in I_2$								
		1	2	3	4	5	6	7	8	9
$i \in I_1$	1	0.0344	0.0516	0.0444	0.0507	0.0507	0.0516	0.1459	0.1250	0.1676
	2	0.0797	0.0988	0.0707	0.0689	0.0689	0.0535	0.1169	0.1042	0.1223
	3	0.0843	0.0362	0.0082	0.0045	0.0045	0.0154	0.0969	0.0752	0.1250
	4	0.1214	0.0399	0.0498	0.0480	0.0480	0.0625	0.1006	0.0779	0.1377
	5	0.1160	0.0888	0.0598	0.0535	0.0535	0.0417	0.0634	0.0489	0.0770
	6	0.1531	0.0861	0.0761	0.0689	0.0689	0.0734	0.0462	0.0272	0.0870
	7	0.1930	0.1567	0.1323	0.1250	0.1250	0.1169	0.0417	0.0607	0.0091
	8	0.1658	0.0815	0.0951	0.0933	0.0933	0.1069	0.1123	0.0951	0.1540
	9	0.2283	0.1685	0.1549	0.1477	0.1477	0.1468	0.0553	0.0734	0.0689
	10	0.2165	0.1341	0.1413	0.1368	0.1368	0.1477	0.1133	0.1060	0.1531
	11	0.2754	0.2048	0.1975	0.1912	0.1912	0.1939	0.1105	0.1241	0.1277
	12	0.2709	0.2183	0.2011	0.1939	0.1939	0.1903	0.0960	0.1187	0.0843

Table 21.3 The unit transportation costs (ground plus ocean shipping where appropriate) between tier 2 and tier 3 sites ($/laptop)

Unit transportation cost		$k \in I_3$		
		1	2	3
$j \in I_2$	1	0.0707	0.1105	1.0818
	2	0.0362	0.1839	1.0292
	3	0.0091	0.1857	1.0120
	4	0.0136	0.1930	1.0048
	5	0.0136	0.1930	1.0048
	6	0.0172	0.1921	1.0011
	7	0.1087	0.2854	0.9069
	8	0.0870	0.2655	0.9296
	9	0.1341	0.3008	0.8942

As mentioned earlier, the source supply functions in collection sites, $i = 1,\ldots, 12$, are given by $S_i = a + b p_i^{(Co)}$. The intercept, a, can be interpreted as the amount collected in collection sites when the collection fee, $p_i^{(Co)}$, is zero and the slope, b, can be viewed as the sensitivity of the collected amount with respect to the collection fee, i.e. the increase in the collected amount per unit of the collection fee added. To estimate this for Georgia, we extrapolate from the statistical data available for California, where 184 562 698.88 pounds (83 716 232 kg) of obsolete electronics were reclaimed in 2007 without any payment to the collection sites (CIWMB 2008). This can be scaled by the relative populations in 2007 for Georgia and California, 9 544 750 and 36 553 215 people, respectively (US Census Bureau 2008). The California Integrated Waste Management Board approximates the average weight of a variety of obsolete electronic products, including portable DVDs, console or projection TVs, cathode ray tube (CRT) computer monitors, and CRT TVs, as 50 pounds (22.68 kg) (CIWMB 2008). We assume the fraction of laptops in the waste stream is 6/50 (6-pound/50-pound). As a result, intercept a for one of the 12 collection sites is estimated as follows:

$$184\,562\,698.88 \text{ lbs in California} \text{ ¥ } \frac{9\,544\,750 \text{ people in Georgia}}{36\,553\,215 \text{ people in California}}$$

$$\text{¥ } \frac{1 \text{ collection site}}{12 \text{ collection sites}} \text{ ¥ } \frac{6 \text{ lbs}}{50 \text{ lbs}} \text{ ¥ } \frac{1 \text{ unit}}{6 \text{ lbs}} = 80\,321.47 \text{ units}$$

The slope, b, of the source supply function is not straightforward to estimate owing to unavailability of data accounting for the sensitivity of the collection fee. The recycling program in California subsidizes the middle tier by $0.48 per pound ($0.217 per kilogram) of used electronics products; in a similar argument, $2.88 ($0.48 × 6 lbs) per unit of laptop computers has been placed in the second tier in our model. In the California recycling program, people bring obsolete laptop computers to collection sites and pay no collection fee. Zero payment or charge in the California recycling program implies a zero collection fee in our model. We look for parameter *b* such that our model returns a solution of the collection fee approaching zero under a subsidy scenario where the second tier is subsidized by $2.88 per unit. With this approach we estimate the value of *b* to be 603.

As mentioned earlier, the second tier is subsidized in the California case while the third tier is subsidized in the Taiwan recycling program (Lee *et al*. 2000). Different subsidy scenarios have been implemented in different geographical areas and expected subsidy impacts on recycled electronics material flows are not obvious. Our case study investigates impacts on decision variables due to different subsidy scenarios. Table 21.4 summarizes the different scenarios examined in the case study. In Scenarios I and II, we assume that the government subsidizes all entities in the first and second tiers by $1.44, $2.88, or $5.76 per unit of laptop computers, respectively. In scenario III, we assume that the state government only subsidizes P_1 in the third tier by $1.44, $2.88, or $5.76 because only P_1 is located in the state of Georgia. All of the subsidy amounts are based upon the California subsidy policy, where we take the half of, the same as, or double of the California case.

21.3.2 Case study results

We investigate the results of acquisition prices and material flows in the case study of a decentralized RPS. Materials are transported from the upstream tier to its subsequent downstream tier and are acquired by the downstream tier. Under this framework, a key issue is the set of *internal* equilibrium acquisition prices between different tiers. Hong *et al.* (2008a, 2008b) give details of the methodology to compute equilibrium acquisition prices within the network. The equilibrium acquisition prices to be offered by C_1, C_2,…, C_{12} within the first tier behave in a similar manner; in other words, the price

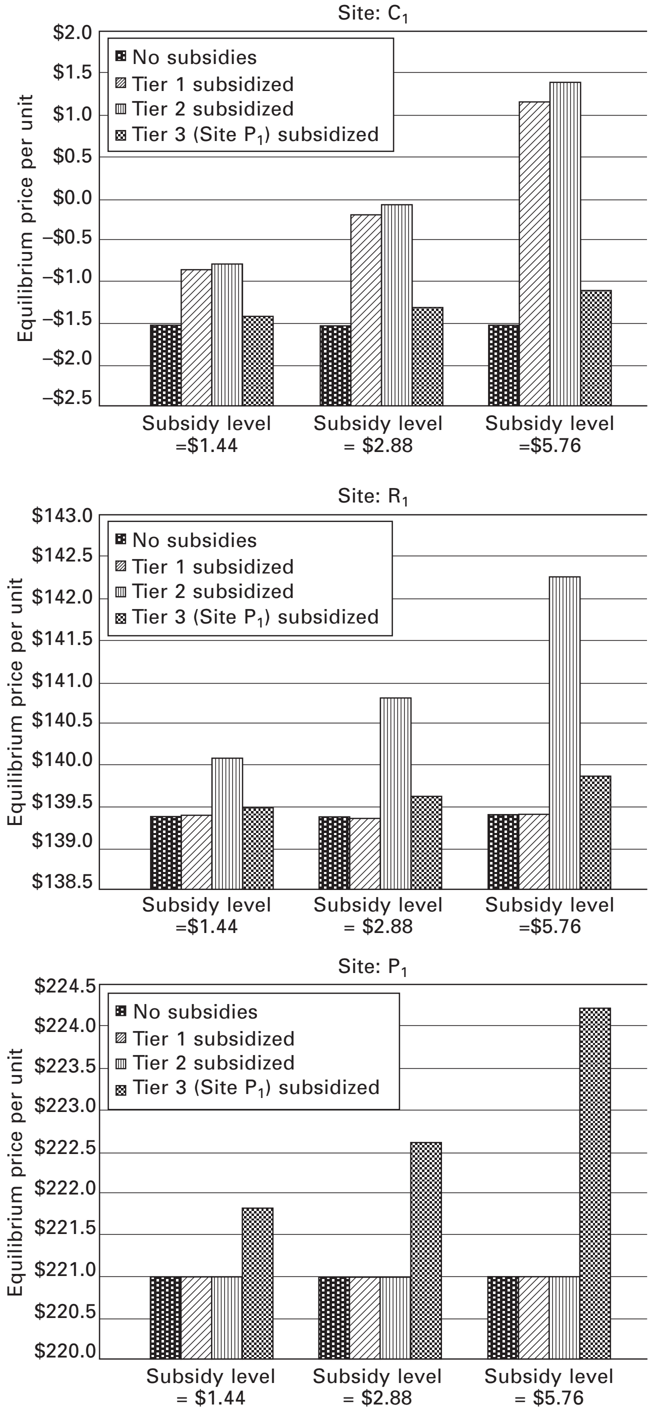
Table 21.4 Scenario descriptions of the case study

Original	The case study without any subsidy.
I-1.44	Each site in the first tier is subsidized by $1.44 per laptop.
II-1.44	Each site in the second tier is subsidized by $1.44 per laptop.
III-1.44	Only P_1 in the third tier is subsidized by $1.44 per laptop.
I-2.88	Each site in the first tier is subsidized by $2.88 per laptop.
II-2.88	Each site in the second tier is subsidized by $2.88 per laptop.
III-2.88	Only P_1 in the third tier is subsidized by $2.88 per laptop.
I-5.76	Each site in the first tier is subsidized by $5.76 per laptop.
II-5.76	Each site in the second tier is subsidized by $5.76 per laptop.
III-5.76	Only P_1 in the third tier is subsidized by $5.76 per laptop.

offered by C_1 is roughly the same as the prices offered by other sites in the first tier for each subsidy scenario. A similar outcome appears in the second tier. The equilibrium prices to be offered by P_2 and P_3 behave at roughly the same levels, which are \$200 for P_2 and \$240 for P_3 respectively, for different subsidy scenarios. We only list the equilibrium prices offered by C_1, R_1 and P_1 in Fig. 21.2 for comparison purposes. The detailed equilibrium prices offered by other sites in the first, second, and third tiers are available in Table 21.5.

The case study results show that the equilibrium acquisition prices under subsidy scenarios are higher relative to those under non-subsidy scenarios. In addition, the increment in acquisition prices increases as the subsidy level increases. For instance, the equilibrium acquisition prices per unit offered by the sites in tier 2 when all sites in tier 2 are subsidized by \$1.44, \$2.88, or \$5.76 are higher than the prices offered by those same sites without any subsidy. The increment in the acquisition price to be offered in tier 2 increases as the subsidy placed in tier 2 increases. The similar consequences can be observed in tier 3. The observation indicates that, in general, subsidizing one particular tier m or one particular site in tier m (for $m = 2$ and 3) increases the willingness of entities in tier m to offer a higher acquisition price to obtain recycled items from its preceding tier m–1 due to the competition within tier m (see the second and third figures in Fig. 21.2). Nevertheless, the acquisition prices to be offered by tier 1 when the sites in tier 1 are subsidized are less than those in other scenarios when the sites in tier 2 are subsidized (see the first figure in Fig. 21.2). There is no competition between the sites in tier 1 since the sites in tier 1 collect recycled items in distinct market segments. Thus, we conclude that subsidizing a competitive tier leads to an increased acquisition price, but subsidizing a tier without competition results in a smaller increase in willingness to acquire recycled items.

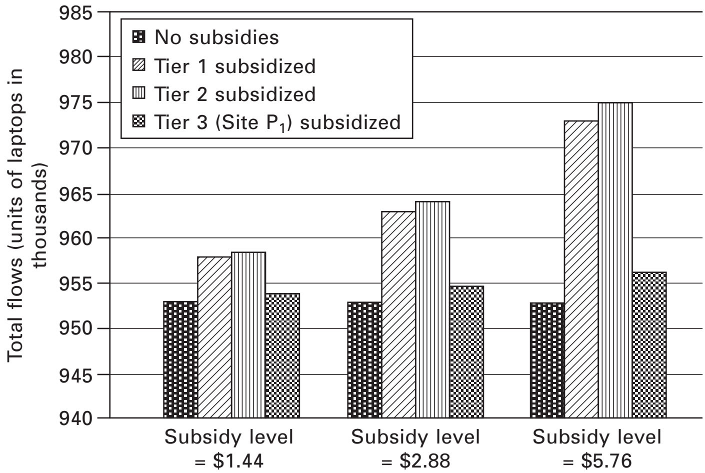
One of the reasons that the government subsidizes an individual entity in the RPS is to increase the total amount of recycled items flowing into the recycling network. Figure 21.3 compares the impact on the total source amount in the collection sites in tier 1 due to the different subsidizing scenarios. It is obvious that, no matter what subsidy level is, all subsidy scenarios (I, II, and III) increase the total amount of recycled items flowing into the entire system compared with the original scenario without any subsidy. Another intuitive finding is that the total collection amount increases as the subsidy level increases. However, it is not clear which tier in the network should be subsidized to maximize the return flow. In this case study, scenario (II), in which tier 2 is subsidized, numerically shows the highest amount of recycled items collected. For the objective of increasing the amount of recycled items, the best location of the subsidy in this case study is in the middle tier in a RPS network.



21.2 The equilibrium prices for different scenarios.

Table 21.5 The equilibrium prices for different subsidy scenarios

Scenarios	Sites																							
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	P_1	P_2	P_3
Original	1.52	1.53	1.51	1.52	1.52	1.52	1.51	1.54	1.53	1.56	1.56	1.55	139.47	139.51	139.52	139.52	139.52	139.52	139.51	139.51	139.50	221.03	200.80	239.39
(I)-1.44	0.85	0.86	0.84	0.85	0.85	0.85	0.84	0.87	0.86	0.89	0.89	0.88	139.47	139.51	139.52	139.52	139.52	139.52	139.51	139.51	139.50	221.03	200.80	239.39
(II)-1.44	0.79	0.81	0.78	0.79	0.79	0.79	0.78	0.81	0.80	0.83	0.83	0.82	140.24	140.28	140.29	140.29	140.29	140.29	140.28	140.28	140.28	221.03	200.80	239.41
(III)-1.44	1.41	1.42	1.40	1.41	1.41	1.41	1.40	1.43	1.42	1.45	1.45	1.44	139.59	139.62	139.64	139.64	139.64	139.63	139.62	139.63	139.62	221.82	201.04	239.57
(I)-2.88	0.18	0.19	0.17	0.18	0.18	0.18	0.17	0.20	0.19	0.22	0.22	0.21	139.47	139.51	139.52	139.52	139.52	139.52	139.51	139.51	139.50	221.03	200.80	239.39
(II)-2.88	0.07	0.08	0.05	0.06	0.06	0.06	0.05	0.08	0.07	0.10	0.10	0.09	141.01	141.05	141.07	141.06	141.07	141.06	141.05	141.06	141.05	221.03	200.80	239.43
(III)-2.88	1.30	1.31	1.29	1.30	1.30	1.30	1.29	1.32	1.31	1.34	1.34	1.33	139.70	139.74	139.75	139.75	139.75	139.75	139.74	139.74	139.74	222.61	201.28	239.76
(I)-5.76	1.15	1.14	1.17	1.16	1.16	1.16	1.17	1.14	1.15	1.12	1.12	1.13	139.47	139.51	139.52	139.52	139.52	139.52	139.51	139.51	139.50	221.03	200.80	239.39
(II)-5.76	1.39	1.38	1.41	1.39	1.39	1.40	1.41	1.37	1.38	1.36	1.36	1.37	142.56	142.59	142.61	142.61	142.61	142.61	142.60	142.60	142.59	221.03	200.80	239.47
(III)-5.76	1.09	1.10	1.07	1.08	1.08	1.08	1.07	1.10	1.09	1.12	1.12	1.11	139.93	139.97	139.99	139.99	139.99	139.98	139.97	139.98	139.97	224.20	201.75	240.12



21.3 The source flows of different scenarios.

21.3.3 Discussion of subsidy impact on exporting recycled items

There are a number of reasons for the existence of exporting recycled items to other countries: smaller processing costs, fewer legislative requirements, higher acquired prices, etc. In some developing countries, waste is viewed as a resource and income-generating opportunity. In addition, there is a general reluctance to pay for waste recycling and disposal services, particularly when recyclers can make money by selling old and broken appliances to developing countries (Hicks *et al.* 2005). For example, representatives within the United States' recycling industry have indicated that around 80% of the waste electrical and electronic equipment they receive is exported to Asia and Africa (Basel Action Network *et al.* 2002; Basel Action Network 2006). About two million secondhand TVs are exported from Japan annually, of which approximately 400 000 units are exported to the Philippines (Yoshida and Terazono 2010). Exporting waste may have serious environmental consequences and may expose workers to toxic chemicals in these destination countries where obsolete electronics are dismantled (Basel Action Network *et al.* 2002; MCW 2005; Liu *et al.* 2006).

As discussed earlier, there are different legislative policies enacted and implemented for an ARF on electronics, which can be used to fund the associated parties in a recycling network. However, in California recyclers or brokers who export obsolete electronics are also eligible to receive the recovery fee (Recycling Today 2003). This implies that a subsidy to upstream tiers may *encourage* exporting recycled items to the downstream sites which are located in overseas countries. Governmental agencies may feel interested in subsidy impacts on the export of recycled electronics material flows. We investigate material flows of a RPS under different subsidy scenarios where there are two downstream sites, one located in a nearby state (Tennessee), P_2, and the other in an overseas country (Nigeria), P_3. These two specific sites, of course, would not be funded by the subsidy program provided by the state government to site P_1.

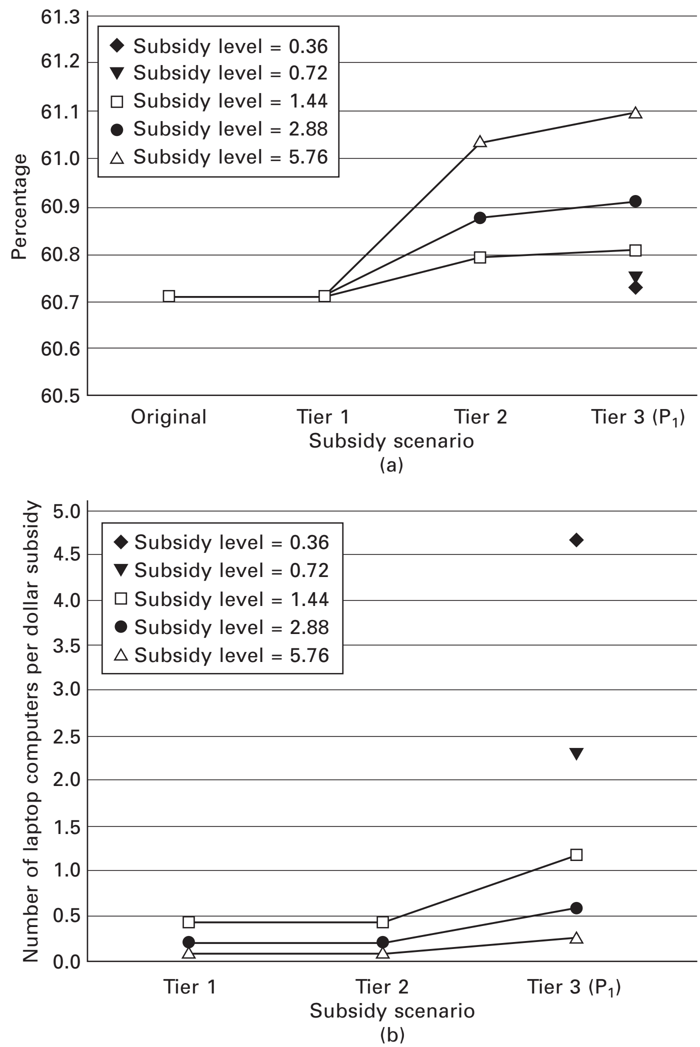
The overseas site differs from domestic sites in terms of transportation and processing costs as well as acquisition prices. In general, international transportation costs are higher relative to domestic transportation costs. However, in this case study, owing to significantly lower labor costs, P_3 becomes more cost effective for processing recycled items such as scrap electronics. This assumption ignores the externalities of pollution and worker health that could be incurred as a result of the export. Overseas recyclers may provide higher incentives to attract more recycled items from other countries if there are no regulations or laws to ban exporting or importing. Indeed, in this case study, the final selling price in Lagos, Nigeria, is much higher than the prices in P_1 and P_2.

Owing to the negative concern of exporting recycled items, one performance characteristic we investigate in the case study is the *domestic material percentage*, which we define as the portion of the flow collected and processed by domestic sites. In this case study, domestic material flows are the total flows excluding the flow transported to P_3. More specifically, the domestic material percentage can be stated as:

$$\text{Domestic material percentage} \equiv \frac{\text{the amount of materials processed in domestic sites } (P_1 \text{ and } P_2)}{\text{the total amount of recycled items}}.$$

The domestic material percentages for different subsidy scenarios are shown in Fig. 21.4(a). There are several interesting findings. For each subsidy level alternative, subsidizing the in-state site in the third tier, that is P_1, leads to the highest domestic material percentage. Another two data sets (72-cent and 36-cent subsidy per unit) have been explored to demonstrate the slight impact on an increase in the domestic material percentage due to a low subsidy level. For the same subsidy tier, a high subsidy level tends to result in a high domestic material percentage.

In addition to the domestic material percentage, we further explore the relative economic impact of subsidy levels, denoted *domestic material flow per dollar subsidy,* which is the average amount of the domestic material flow per dollar subsidy. More specifically, the domestic material flow per dollar subsidy can be stated as:



21.4 Domestic material percentage (a) and domestic material flow (b) per dollar subsidy.

$$\text{Domestic material flow per dollar subsidy} \equiv \frac{\text{the amount of materials processed in domestic sites } (P_1 \text{ and } P_2)}{\text{the total subsidy amount}}.$$

Figure 21.4(b) shows the comparison of the domestic material flow per dollar subsidy for different subsidy scenarios. In this case study, subsidizing the in-state site in the third tier is the most effective subsidy scenario, which implies it returns the highest domestic material flow per dollar subsidy. For the same subsidy tier, however, a high subsidy level returns a lower amount of recycled items collected per dollar subsidy. This observation may give a policy maker an important managerial insight: a high subsidy level tends to result in a high domestic material percentage, but in the scenario of a low domestic material flow per dollar subsidy, indicating a less efficient subsidy scenario.

Another issue faced by the state when implementing the ARF program is that the subsidy can be an incentive to attract recycled items flowing from other nearby states into the state that has implemented the subsidy program. We further discuss the portion of the flow collected and processed in the state of Georgia denoted *state material percentage*, and the economic effect of subsidy, denoted *state material flow per dollar subsidy*. More specifically,

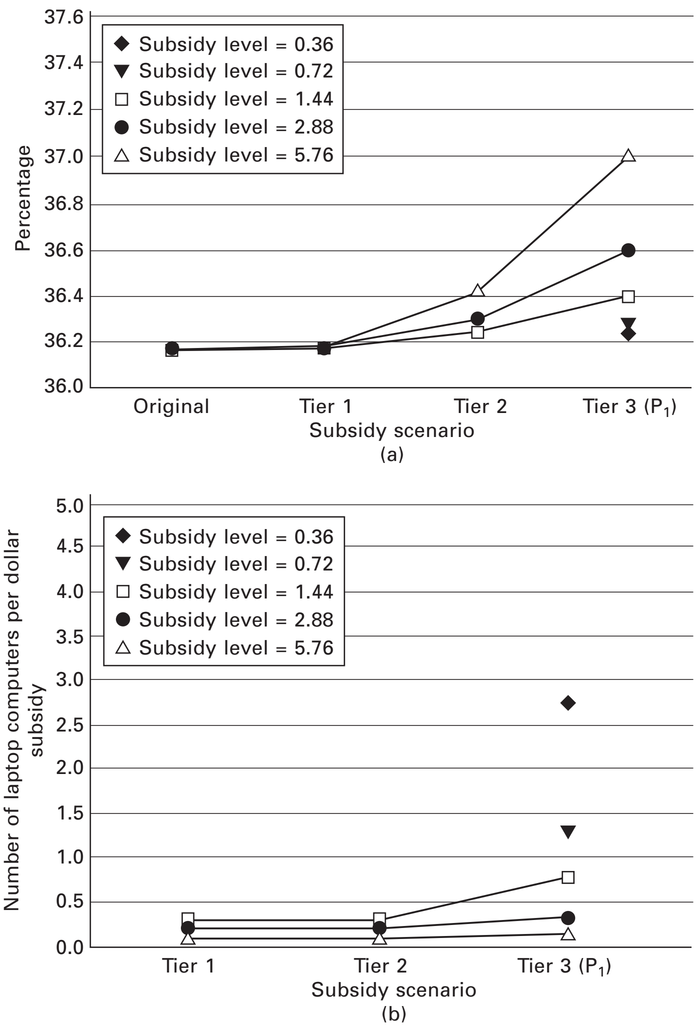
$$\text{State material percentage} \equiv \frac{\text{the amount of materials processed in Georgia } (P_1)}{\text{the total amount of recycled items}}$$

and

$$\text{State material flow per dollar subsidy} \equiv \frac{\text{the amount of materials processed in Georgia } (P_1)}{\text{the total subsidy amount}}.$$

Figure 21.5(a) shows the state material percentages for different subsidy scenarios. In this case study, we know that under the same subsidy level, subsidizing P_1 leads to the highest state material percentage, and, for the same subsidy tier, a high subsidy level results in a high state material percentage. Similarly, Fig. 21.5(b) shows the comparison of the state material flow per dollar subsidy for different subsidy scenarios. In this case study, subsidizing the in-state site in the third tier is the most effective subsidy scenario, which implies it returns the highest state material flow per dollar subsidy. For the same subsidy tier, however, a high subsidy level returns a low amount of recycled items collected in the state per dollar subsidy. This case study concludes a similar observation that a high subsidy level tends to result in a high state material percentage, but in the scenario of a low state material flow per dollar subsidy, indicating a low-efficiency subsidy scenario.

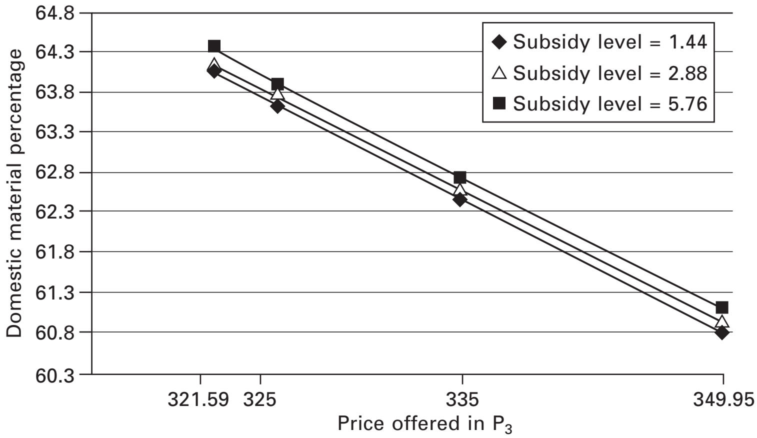
As mentioned earlier, the price offered by the overseas site (P_3) is possibly higher than that offered in the domestic sites (P_1 and P_2) due to less competition in the market from new products. We conduct the sensitivity analysis of the domestic material percentage as the incentive of the selling price to be offered in P_3 drops to the same level as the selling price offered by P_1. Figure 21.6 shows that the domestic material percentage increases



21.5 State material percentage (a) and state material flow (b) per dollar subsidy (staying in the state of Georgia).

as the attractiveness of the price offered by P_3 decreases. This observation supports the intuitive hypothesis that a low price incentive for an overseas site increases the willingness to engage in domestic recycling.

Unfortunately, for the case study the in-state subsidy scenario does not have significant impacts on increasing in the domestic or state material percentages. For instance, the domestic material percentage is increased by only 0.4% even in the highest subsidy scenario III-5.76 shown in Fig. 21.4(a). The reason for this discouraging outcome is possibly due to a relatively low

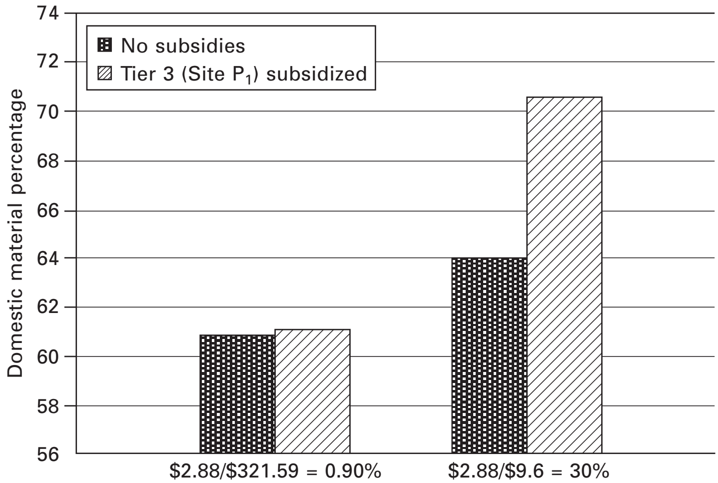


21.6 Sensitivity analysis of the domestic material percentage.

incentive of subsidy; in other words, the ratio of the subsidy level per unit of laptop computers to the final price to be offered in destination markets is relatively low. A further investigation verifies our hypothesis that a relatively high level of the ratio of the unit subsidy level to the unit price offered may increase the willingness to engage in domestic recycling. We conduct numerically the sensitivity analysis of another type of commodity, where we assume the ratio of the subsidy level to the price to be offered in the destination market is much higher than the ratio of laptop computers examined in this case study. The subsidy level per unit still remains the same at $2.88, but the price offered in the destination market (P_1 in the case study) is $9.6 so that the ratio of the subsidy level to the price offer is 30% ($2.88/$9.6) instead of 0.90% ($2.88/$321.59) of laptop computers. The domestic material percentage is significantly increased, as shown in Fig. 21.7, compared with the case of laptop computers. This observation may warn a policy maker that the type of recycled items (ratio of the subsidy level to the final price offer) plays an important role in terms of the domestic material percentage. In other words, a subsidy for a high valued commodity may only result in a slight impact on an increase in willingness to invest in domestic recycling.

21.4 Conclusions and discussions

The goal of this chapter is to explore the subsidy effect for recycled flows in a decentralized RPS where each entity independently acts according to its own interests. We investigate the individual and the system behaviors of a decentralized problem setting under several different scenarios where the government may subsidize the associated entities in a RPS. Several insights



21.7 The domestic material percentage of the high subsidy incentive commodity.

are drawn from the case study presented in this chapter. As expected, the case study results show that the tier in a decentralized RPS has higher incentives to offer a high acquisition price if subsidized. In terms of the total amount of obsolete electronics products collected in a decentralized RPS, the case study results numerically indicate that the best location of the subsidy is in the middle tier in a RPS network since placing the subsidy at the second tier in this case study returns the highest total collected amount.

In addition, this chapter discusses the export of recycled items, especially in scrap electronics, and investigates how the subsidy scenario affects the material flow in a RPS where one associated site in the boundary downstream tier is located in an overseas country. More specifically, the overseas site has high transportation costs and high acquisition prices, but low processing costs. The analysis highlights several interesting findings. As expected, the material flow transported to the overseas site decreases as the unit subsidy level to the domestic in-state site in the third tier increases. The case study indicates that placing the subsidy at the in-state site (P_1) in the third tier results in the highest domestic material flow percentage under the same subsidy level. For the same subsidy tier, a high subsidy level tends to result in a high domestic material percentage. Another indicator, the domestic material flow per dollar subsidy, shows that subsidizing the in-state site in the third tier is the most effective subsidy scenario. However, a high subsidy level returns a low amount of recycled items collected per dollar subsidy. This finding may warn a policy maker that a high subsidy indeed results in a high domestic material percentage, but a low-efficiency subsidy scenario may be incurred.

Similar observations appear for the indicators of state material percentage and state material flow per dollar subsidy.

Furthermore, we conduct the sensitivity analysis of the domestic material percentage as the incentive of the selling price to be offered in an overseas site drops to the same level as the selling price offered in a domestic site. The case study results support the hypothesis that a low price incentive by an overseas site indeed increases the desirability of domestic recycling. Unfortunately, the case study results (laptop computer case) indicate that an in-state subsidy does not have significant impact on the increase in the domestic or state material percentages. We numerically conduct the sensitivity analysis of another type of commodity with a relatively low price offer in destination markets. In this case, a high subsidy incentive indeed leads to a significant impact on an increase in domestic recycling.

In summary, this chapter makes a contribution to understanding reverse logistics by drawing attention to the effect of the subsidies on recycled flows in a decentralized RPS. We identify several interesting subsidy scenarios and investigate different indicators to compare the corresponding results of recycled flows in different subsidy scenarios. The case study results provide a policy maker with valuable managerial insights.

21.5 Acknowledgments

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22
WEEE management in Europe: learning from best practice

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Abstract: In this chapter the development of waste legislation in EU is described as an important background for the Waste Electrical and Electronic Equipment (WEEE) – and Restriction on Hazardous Substances (RoHS) – Directives which were approved in 2002. There remains a long way to go to handle WEEE in a proper and sustainable way. Currently some nations in Europe are in front. These countries are Switzerland together with the Nordic countries Norway, Sweden and Denmark. Their WEEE management systems are described, compared and analysed in this chapter. For nations having recently started to build up their WEEE management, experience from these countries can be valuable.

Key words: WEEE management, Switzerland, Norway, Sweden, Denmark, National stakeholders.

22.1 Introduction

Waste from electric and electronic equipment (WEEE or e-waste) is the fastest growing waste stream in the EU, producing 8.3 to 9.1 million tonnes in 2005, and this is expected to grow to 12.3 million tonnes in 2020. The EU, and also the rest of the world, faces enormous challenges in managing this fast-growing waste stream. Since e-waste contains a combination of recyclable and also hazardous components, a lot of attention must be paid to it in the future. Analysing the factors for moving the management of WEEE forward is, for that reason, of the highest importance.

The main objective of this chapter is to assess the status of WEEE management in the European Union countries. The history of the EU legislation from the general waste directive to the current WEEE and Restriction on Hazardous Substances (RoHS) Directives are described. The important stakeholders for the current WEEE management policies and strategies are taken into account. The extended producer's responsibility (EPR) or individual producer responsibility (IPR) principles are analysed based on the premise that tighter controls for WEEE management are necessary if we are to meet the demands of managing ever-increasing amounts of WEEE. Since Switzerland and Norway, two countries outside the EU, have both developed WEEE management systems of high quality, they are important models for developing WEEE management in the EU. In addition to Norway and Switzerland, the WEEE management systems in Sweden and Denmark are also well developed and are described in this chapter. Similarities and differences in WEEE management in these four countries are discussed on the basis of their effectiveness. The summing up can be a valuable lesson for the new EU member states where WEEE management is not yet developed.

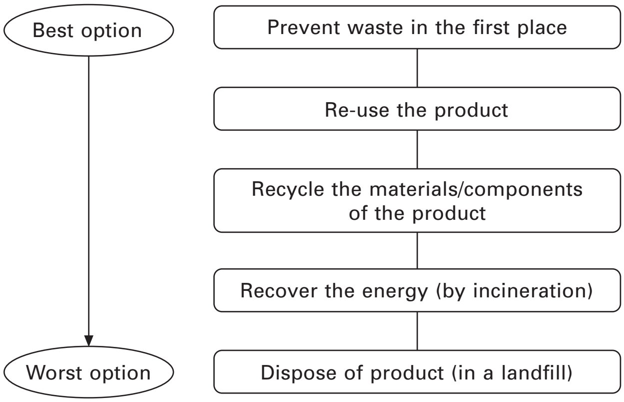
22.2 The waste strategy within the EU

European environmental policy has evolved significantly since the 1970s (European Commission 2005). Since 1970 a revolution has been going on in the way waste is managed. As a consequence, a new research area concerning all aspects around waste management and its pollution has developed. From a focus on single pollutants and their impacts, policy is now more focused on addressing the pressure on the environment, and examining different policies and behaviour patterns. In 2008, about 2.6 billion tonnes of waste was generated in the EU, of which some 101 million tonnes constituted hazardous waste. Relative to the population, the total amount of waste was over 5.3 tonnes per capita (European Commission – Eurostat 2008).

The Waste Framework Directive (Council Directive 75/442/EEC) and the Hazardous Waste Directive (Council Directive 91/689/EEC) were both adopted in 1975. They define waste and other key concepts and intend to ensure waste handling without causing damage to environment and human health. In the late 1980s a lot of environmental regulations in the developed countries led to a dramatic rise in the costs of hazardous waste disposal. Searching for cheaper ways of getting rid of hazardous waste, developed countries began shipping WEEE to less developed countries for processing or disposal. The Basel Convention 1989 was a multinational agreement addressing cleaner production, hazardous waste minimizing and control (Basel Convention 2005). The Basel Convention was a forerunner for the Waste Shipment Regulation approved in 1993 (Waste Shipment Regulation Reg. (EEC) 259/93).

The first EU directives did not specify the environmental emission parameters for the waste management options. These treatment options were landfill, incineration and recycling. The Landfill Directive was adopted in 2001 (Council Directive 1999/31/EC) and the Waste Incineration Directive (Directive 2000/76/EC) in 2002. The concept of recycling was vague and still this is one of the main problematic areas concerning WEEE since the environmental influences are substantial. The important step was to improve waste management and promote recycling, re-use and energy recovery.

During 1990 the European Commission put forward a strategy to achieve this by introducing the concept of a waste hierarchy (Fig. 22.1). In the hierarchy the treatments of putting waste in landfills, or even worse dumps,

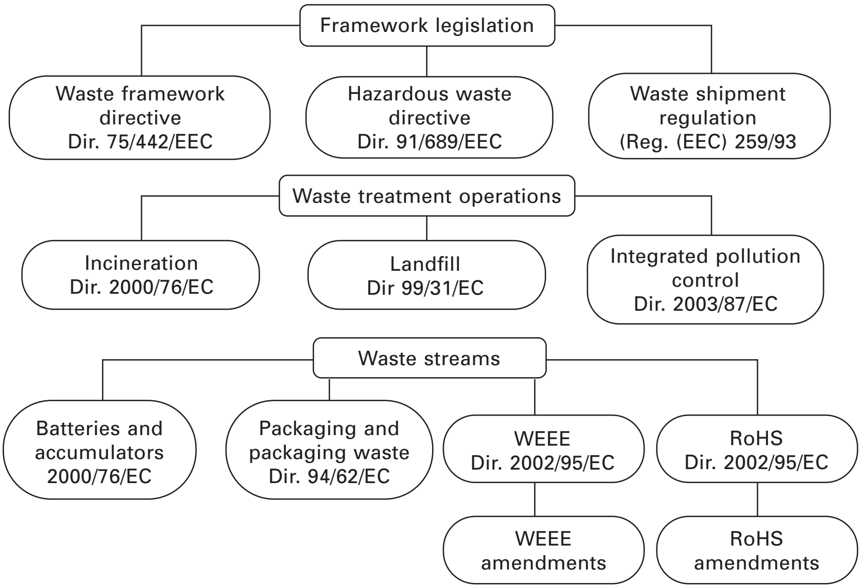


22.1 The waste treatment hierarchy. From: European Commission (2005).

was downgraded. The introduction of the '*polluter-pays*' principle (PPP) was important in order to place the overall responsibility for waste treatment with the waste producer. The concept of *waste stream* was introduced. This concept defines the different waste categories. A crude separation of waste stream is household waste and industrial waste. Household wastes can in turn be separated into new waste streams, such as food waste, paper, cardboard and hazardous waste. Within the hazardous waste stream, WEEE is a separate waste stream. Industrial waste is also a very broad waste stream and it is convenient to make a more precise definition of the industrial waste stream according to its content. The concept of waste stream was important in order to establish a common international 'waste concept language'.

The EU has developed directives, decisions and regulations for many environmentally problematic waste streams. These developments could be both due to a steady increase in the volume of waste, as with packaging waste and WEEE, or the concern over toxic compounds as for example in WEEE and end-of-life vehicles.

At the start of the new century, the EU's waste legislation system had grown from paramount requirements and definitions of waste and hazardous waste. The EU expanded the scope of the legislation to define demands on treatment options. The 'waste legislation hierarchy' is described in Fig. 22.2. On top of this hierarchy are the framework legislations – on waste, hazardous waste and also the shipment regulation. Typical 'treatment directives' are on next level. These directives comprise the directives on landfill, incineration and integrated pollution control. The different waste stream legislations are on next level. Here we find the waste streams of interest for WEEE management. Understanding this hierarchy is valuable, since directives at a lower level are founded on and refer to more fundamental and general directives at a higher level in the hierarchy.



22.2 Legislation overview. From: European Commission (2005).

Gradually the treatment directives were implemented in the EU countries. The implementation put forward environmental standards and demands on thresholds regarding emissions and gave treatment demands on these emissions (i.e. leachate and methane from landfills, ashes and emissions to air from incineration plants).

The PPP, as an overall financing system, included taxes and charges. The financing instruments were put on producers and consumers as well as the waste manager. Stricter environmental standards introduced by the landfill and incineration directives would also to a certain extent promote the diversion of waste towards material recycling. The overall policy was to move waste from landfills and also incineration over to recycling and re-use. The treatment directives on landfill and incineration and as well as the WEEE directive are all displayed 'under the Treaty 175 and Article 130' which states: 'Action to be taken to achieve the Community's environmental objectives (Article 175(1), ex Article 130 S): co-decision procedure with Economic and Social Committee and Committee of the Regions consulted'. This means that governments have to implement them but in a way best 'suited for national concern'. The directive is more a guidance than a law. The requirements are minimum ones and member states can implement them based on their actual situation. The actual situation in Eastern Europe was uncontrolled dumps. For these countries proper landfills and establishing incineration plants have been prioritized first.

The concept of producer responsibility – or EPR – was introduced in the

EU in 1996 (Gottberg *et al*. 2006). This principle provided a stable source of financing to offset the cost disadvantage of recycling versus energy recovery and landfill. In practice landfill costs grew to be an expensive waste option in most of the advanced waste treatment nations in Europe. The EPR principle is discussed more in detail in Section 22.4.

Better management of certain problematic waste streams was achieved by introducing new specific directives such as waste oil, polychlorinated biphenyls/polychlorinated terphenyls (PCB/PCT), batteries and WEEE. The concept of 'cleaner waste fractions' led the municipalities into a management regime of waste separation at source. Domestic waste management grew to be a municipal or inter-municipal responsibility. Information and campaigns resulted in education of the populations.

During the period from 2003 to 2006, the thematic strategy on the prevention and recycling of waste was under development. The main issues focused on were:

- Waste policy should focus on the environmental impacts of using resources. Waste policy should tie in with resource policy. The most important issue is not the resources scarcity, but their impacts on the environment.
- Waste policy should take a life-cycle approach. Waste policy should also tie in with the integrated product policy (IPP). IPP aims to reduce environmental impacts from products throughout their life cycle, where possible using a market-driven approach. It seeks to integrate eco-design measures and life-cycle assessments through public purchasing to producer-responsibility mechanisms in order to encourage 'greener products'.

The life-cycle and environmental impact approach was a significant feature of the amendments of the Waste Framework Directive taking place in 2006 (Directive 2006/12/EC) and 2008 (Directive 2008/98/EC). This fact is obvious when looking at the following points in Directive 2008/98/EC:

> (6) ….to <u>minimize</u> the negative effects of the generation and management of waste on human health and environment. Waste policy should also aim at reducing the use of resources and favor the practical application of the waste hierarchy. [Fig. 22.1]
> (8) ….to clarify key concepts such as definitions of waste, recovery and disposal, to strengthen the measures that must be taken in regard to waste prevention, to introduce an approach that takes into account the whole life-cycle of products and materials and not only the waste phase… Furthermore the recovery of waste and the use of recovered material should be encouraged in order to conserve natural resources.
> (19) The definitions of recovery and disposal need to be modified in order to ensure a clear distinction between the two concepts, based on genuine

differences in environmental impact through the substitution of natural resources in the economy and the recognition of the potential benefits to the environment and human health of using waste as resource.

(26) The polluter-pays principle is a guiding principle at European and international levels. The waste producer and the waste holder should manage the waste in a way that guarantees a high level of protection and human health.

(28) ….Measures aid at ensuring source separation, collection and recycling of priority waste streams.

These points have been and will be in the future the most important guidelines within the waste legislation and management of WEEE. An overall evaluation of the amendments within WEEE legislation has been going on since the first directive appeared, however the legislation fell out of step with the velocity at which the amounts of WEEE are growing.

22.3 The WEEE Directive and the RoHS framework

The trend of increasing amounts of WEEE indicated that this waste fraction should be paid considerable attention. In 1998 WEEE amounts were estimated to be 6 Mt for the EU15. For the EU27 in 2005, the amount was estimated to between 8.3 and 9.1 Mt. Forecasting assumptions predict that the total WEEE will grow annually by between 2.5 and 2.7%, reaching 12.3 Mt by 2020 (Huisman *et al.*, 2007). In the former 15 European member countries (EU15) the amount of WEEE varied between 3.3 and 3.6 kg/capita/year for the period 1990–1999 and this waste has been projected as 3.9–4.3 kg/capita/year for the period 2000–2010 (EEA, 2003). EU statistics from 2008, updated in February 2011, show that 2.7 Mt was collected from private households in the EU30 (EU members and in addition the nations Norway, Iceland and Lichtenstein) and 0.5 Mt from sources other than private households for the same period (EU WEEE statistics 2011).

There is no doubt that the directive represented a temporary break in a discussion that had been going on for over ten years (Stevels, 2007). At the same time the complementary directive on the restriction on the use of certain hazardous substances also came in force (Commission Directive 2002/95/EC).

The WEEE Directive was a key element of the EU waste policy and introduced the measures for collection, treatment, recovery and recycling of electric and electronic equipment. The complexity in this waste fraction is due to

- a wide range of products or categories of waste;
- associations of different materials and components such as printed cards, plastics, glass etc.;

- hazardous substances such as mercury, cadmium, copper, silver etc.;
- the rapid and uncontrolled increase in amount of this waste stream.

The WEEE Directive forced European countries to meet some targets concerning recovery and re-use. An important constraint on WEEE management development in Europe is that the directive is a so-called Article 175(1), which means that the requirements are minimum ones and individual member states have the option to formulate additional ones. (Stevels, 2007). As a consequence member states have interpreted the directive in a variety of ways. The management of WEEE has for that reason moved in different directions – which will be described in the next section in this article. In the StEP report 'Solving the E-waste problem' it is stated that 'having different national policies on the management of WEEE hampers the effectiveness of recycling policies' (StEP 2010, revised page 6). Article 175 should not prevent member states from maintaining or introducing more stringent protective measures.

The WEEE Directive and the RoHS framework must be looked upon as dealing with a spectrum of environmentally difficult questions. The amendments made after 2003 have documented the lack of knowledge or perhaps lack of willingness to start up a legislative system that takes real care of the environment. A total embargo on putting WEEE on landfill should solve a lot of environmental problems for the future. However, the steadily increasing amount combined with the lack of alternative and more sustainable treatment options would give member states a storing capacity problem. The problems raised since 2003 can be summed up as follows.

22.3.1 The landfill capacity problem

The waste treatment directive – the Landfill Directive adopted in 2001 (Council Directive 1999) – came almost at same time as the WEEE Directive. Even at that time problems relating to landfill capacity existed in the EU. Monitoring and treatment capacities of emissions were appalling because of a lack of systems for the collection and sorting of municipal solid waste (MSW). To introduce sorting regimes is difficult in societies where the culture and education for waste handling is totally lacking. A consequence of depositing WEEE on landfills or dumps is that hazardous elements will dissolve and come into the leachate with contents of heavy metals and brominated flame retardants escaping from these polluted sites. WEEE also contains mercury and chlorofluorocarbons (CFCs) which can evaporate from the landfills.

Huisman *et al*. (2007) document in their comprehensive evaluation of the WEEE directive in the executive summary on page iii that:

> the EU15 Member States' average collection performance is roughly half that of Switzerland and Norway… the WEEE Directive collection target can be easily met by EU15 Member States, but remains a very challenging target for the New Member States.

The situation in Central and Eastern Europe is different and landfill treatment still seems to be the most relevant treatment method in these countries. The main reason is the lack of waste-sorting systems and the municipal infrastructure for handling waste. This fact is reflected in the data concerning treatment facilities (European Commission – Eurostat 2008, 2011).

22.3.2 Handling hazardous components in WEEE

The fast growing WEEE stream with its content of hazardous components needed a separate legislation framework. The RoHS Directive on restriction of hazardous substances in electrical and electronic equipment came into force along with the WEEE Directive. According to the RoHS Directive, the way to ensure the reduction of hazardous substances in products is to substitute them for less harmful substances. Restricting use of these hazardous substances is likely to enhance the possibilities and economic profitability of recycling WEEE (Barba-Gutiérrez *et al*. 2008). They discussed in their publication how the logistic network could be improved in order to increase the re-use of WEEE. The RoHS framework was amended in 2004, 2005, 2006 and 2008 according to research documentation of the hazardous components: lead, mercury, cadmium, hexavalent chromium, polybromated biphenyls (PBB) and polybromated diphenyl ethers (PBDE). Documentation from research studies on heavy metals and environmentally toxic compounds in WEEE stressed a better system for managing WEEE (Dimitrakakis *et al*. 2009). The dispositions on landfill or in the incineration furnace give rise to environmental pollution in water, air and soil. Precautions and costs for avoiding WEEE entering these end-treatments were important to implement in the legislation. Under the same issue came the incineration treatment problem (Directive 2000/76/EC). The establishment of incineration plants to cover the EU's demand to recycle waste into energy demanded a proper collection and sorting system. Documentation shows problems with emissions due to a lack of WEEE removed from the incinerated fraction (Hu *et al*. 2011).

22.3.3 The PPP and the EPR problem

In line with the PPP, the producer or manufacturer of EEE should organize and finance a system of collection of WEEE. The term 'producers' was defined as manufacturer, re-seller or importer. Distributors of EEE manufactured outside

EU were also affected by the directives. A tax or fee introduced by member states should cover the expenses for the treatment of the WEEE in order to remove hazardous metals, plastics containing flame retardants and printed circuit boards. The directive also implemented the EPR principle. This was a vague and individual rather than collective approach, since manufacturers were responsible only for operations of their own EEE. No collective schemes were established for the producers. Therefore the individual consumers were responsible for their waste and paid a tax put on their EEE to cover collecting and recycling. In other words, the WEEE Directive was an end-of-life waste directive. The directive did not serve at all as an obligation according to law on the producer to take responsibility for the sustainability of new EEE products. Also the rapid turnover of certain EEE appliances seems to be ignored as a precautionary principle for WEEE increase.

22.3.4 Illegal export of WEEE

The Waste Shipment Regulation (Reg (EEC) 259/93) was meant to address the illegal export of WEE but this remains a problem. Uncontrolled or illegal export of WEEE to the developing world is a growing concern to the EU, and there is much debate as to how to tackle it. Global trading in waste electronics is, however, discussed in Chapter 1 and will not be discussed here.

22.3.5 WEEE management on a national level

The governmental role towards the authorities and stakeholders was important in order to succeed on national level. The WEEE Directive implemented some targets and deadlines in order to guide and put pressure on member states in their national WEEE-management. Infrastructural improvements in the WEEE management system were regarded as valuable tools in order to improve the system, make it more transparent and transferable between the EU nations.

This is stated in the following way in point 8 on page 1 of Commission Directive 2002/96/EC:

> The objective of improving the management of WEEE cannot be achieved effectively by Member States acting individually. In particular, different national applications of the producer responsibility principle may lead to substantial disparities in the financial burden on economic operators. Having different national policies on the management of WEEE hampers the effectiveness of recycling policies. For that reason the essential criteria should be laid down at Community level.

Improved WEEE management financing system

Consumers should be encouraged to return WEEE. Public collection points for private households should be set up for the return of WEEE free of charge. To finance this arrangement a fee should be put on the EEE and it should reflect the cost from the collection point covering transport and additional treatment and recycling. This point was put into force in the amendment Commission Directive 2003/108/EC of the WEEE Directive 2002/96/EC:

> By 13th August 2005 producers must provide the financing for collection, at least from the collection point, of the treatment, recovery and environmental sound disposal of WEEE.

In the case of products put on market later than 13 August 2005, each producer is responsible for providing financing with respect to its own products. When a producer places a product on the market, he must furnish a guarantee concerning the financing of the management of his waste. Financing of 'historical waste' put on the market before 13 August 2005, is to be provided by the producers existing on the market.

Information – establishment of national registers of WEEE

This demand for a national register was put into the WEEE Directive of 2002. This should be made interoperable (Europa, 2010, IP/08/1878 Brussels 3 December 2008). Yearly information from national statistics of weight or number of items of WEEE from member states and also Norway, Lichtenstein and Switzerland was a prerequisite to control WEEE management. Norway and Lichtenstein are signatories, according to the European Economic Area Agreement (content from hkdc.com) and are obliged to implement EU legislation. Switzerland, not being a signatory, has also followed up EU legislation.

Targets for collection

The WEEE Directive 2002/96/EC and the RoHS Directive 2002/95/EC had to make provisions to ensure that WEEE from private households was collected and transported to authorized treatment facilities.

> The target was set to at least 4 kg on average per inhabitant per year coming into force from 31st December 2006.

In this chapter this target makes a basis for the outline and discussion in Section 22.5.

22.4 Extended producer responsibility (EPR) and polluter pays principles and WEEE management

22.4.1 Introduction

The implementation of the WEEE Directive was perhaps expected to push product innovation in the direction of longer lifespan, ease of repair and dismantling, re-usable components and reduced complexity with regard to the amount of materials and components. However innovation has been more focused on new products rather than developing technology for re-using whole or parts of the used EEE. This fact, together with the short lifespan of some EE products (mobiles, personal computers etc.), have resulted in the steady increase in WEEE amounts. The outcome of the WEEE Directive demonstrates the complexities involved. EPR is often put forward in the numerous articles concerning WEEE management. Another principle – the precautionary principle or more precisely the PPP – is also a valuable environmental tool for analysing the current WEEE management situation.

22.4.2 EPR and PPP in current WEEE management

The EPR principle as a political strategy first appeared in an official statement by the Swedish Government in 1975 (Franklin 1997):

> The responsibility, that the waste generated during the production processes could be taken care of in a proper way, from an environmental and resource-saving point of view, should primarily be of the manufacturer. Before the manufacturing of a product is commenced it should be known how the waste which is a result of the production process should be treated, as well as how the product should be taken care of when discarded.

It was also introduced as a policy principle by Lindhquist (2000) in his doctoral thesis at University of Lund, Sweden:

> A policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially the take-back, recycling and final disposal of the product.
>
> The basis for selecting the mix of policy instruments that are to be used in the particular case: Extend Producer Responsibility (EPR) is implemented through administrative, economic and informative policy instruments.

The principle was introduced in 1994 by the Organisation for Economic Co-operation and Development's (OECD) Pollution Prevention and Control

Group (OECD 2001). EPR is an environmental principle, an idea, a mantra or a decree and not a legislation text to be obeyed. According to OECD the producer's responsibility for a products extends to the post consumer stage of its life cycle (OECD 2001). There are two related features of EPR policy:

- The shifting of responsibility upstream to the producer and away from municipalities.
- Providing incentives to producers to incorporate environmental considerations in the design of their products.

EPR seeks to integrate signals related to the environmental characteristics of product process throughout the production chain.

OECD (2001) provides in its manual a list of driving forces for waste minimization. This list is for all kind of products. For WEEE it seems to be of great interest since each of these points can be analysed and evaluated on any stakeholder level in the WEEE management system:

- Reducing the number of landfills and incinerators with their negative environmental impacts.
- Reducing the burden on municipalities for waste management.
- Focusing on recycling and re-use.
- Improving time and costs for dismantling and disassembling.
- Reducing or eliminating hazardous chemicals in products.
- Promoting cleaner production.
- Promoting more efficient use of natural resources.
- Improving relations between communities and firms.
- Encouraging more efficient and competitive manufacturing.
- Promote integrated management focus on the life cycle.
- Improve material's management.

It is obvious that the EPR principles as a mantra for the pre-production status of a new product, is difficult to obey. Economic growth is more important than environmental care. This is the most obvious reason why eco-design and recycling of components for industry still is not a strong driver in the legislation. Perhaps the situation will change when necessary resources for new EE-products start to be depleted.

The PPP was introduced by the OECD in 1974 (OECD 1975). It pervades today's legislation concerning the environment in a way that the population have accepted. Taxes for waste handling and fees put on products to cover take-back costs are both a result of the PPP's fundamental idea.

The PPP was developed as part of the precautionary principle and was laid down as an overall guiding endeavour principle as a result of the UN Conference on Environment and Development in Rio de Janeiro in June 1992 (O'Riordan and Cameron 1994). This principle states that the polluter as a stakeholder is responsible and shall pay for the harm, or pay to prevent harm to the environment.

It is relevant to compare these two principles in general and to link them up towards EEE and WEEE management. The EPR addresses the responsibility at the 'start of the production chain of a product', while the PPP addresses the responsibility at the 'end of the production chain' at the moment a product is turned into waste. The most obvious difference between the ideas or principles of EPR and PPP is that a polluter can be brought to court and be made to pay indemnification for their illegal emissions. A producer of EEE is not yet legally responsible and will not be punished if they do not take responsibility for their EEE when it turns into WEEE, is dumped or put into landfill.

The two principles have been introduced quite differently and their implementation and success in worldwide environmental precautionary legislative systems has also differed. Specific examination of WEEE management on national level shows that that the PPP has partly contributed to an improved waste situation in Europe. The EPR has not. The EPR principle is put forward in point 12 of the WEEE Directive (Commission Directive 2002/96/EC):

> (12) The establishment, by this Directive, of producer's responsibility is one of the means of encouraging the design and production of electrical and electronic equipment which take into full account and facilitate their repair, possible upgrading, reuse, disassembly and recycling.

The word *encouraging* is however too weak. Consequently the EPR was not communicated strongly enough in the legislation text towards the producers and manufacturers.

Nine years after the WEEE Directive, EPR suffers for being only words in a document. Using EPR as a guiding concept has failed in the eco-design field addressing the responsibility to the very first step on planning the design of new electrical and electronic products. The legislative system has focused on and partly succeeded in addressing EPR towards the waste management system. The precautionary principle is under-communicated in the WEEE legislative system. The most obvious result of the PPP within WEEE is indirect – the RoHS Directive demands on hazardous waste components in WEEE. WEEE legislation targets for WEEE collection are now put on end-of chain. How should measurable targets be given to the producer at the start-of-chain? This is still an unsolved challenge. As long as these operational targets are lacking in the legislation, WEEE amounts will steadily increase. Lauridsen and Jørgensen (2010) have in their analysis of the EPR principle towards WEEE Directive policy concluded that the WEEE policy is critically dependent on consistent translations and alignments between the levels of involved actors or stakeholders. The end-of life-product design must be turned to focus on the very first design step. This fits well into points 3, 4 and 11 of the EPR list of 11 points from the OECD document (OECD 2001): ‘focusing on recycling and reuse, improving time costs for dismantling and disassembling, promoting integrated management focus on the life cycle.’

It is relevant to analyse why WEEE minimization has lacked success. It is also relevant to ask why this waste fraction has not received the same attention by ordinary people. Electronic devices such as mobile telephones and flat screen TVs function as status symbols for the individual consumer. Recently, tablet PCs and mp3 players such as Apple’s iPad and iPod have appeared on the market. In Western societies, the number of personal computers and the turnover rate of mobiles, mp3 players and the newcomer tablet PCs are regarded as national competitiveness. Another aspect is that entrepreneurs in the electronic and IT world are looked upon as heroes. The huge amount of turnover and WEEE production is completely absent in today’s environmental focus. Earlier electronic production was considered to be a ‘clean’ industry, in the sense that their emissions to air and water bodies are minimal compared with traditional heavy industry. Electronic and electronic components are being introduced into other products – toys, tools, cars, kitchen utilities, hospital equipment etc. The result is an enormous amount and diversity of products, that are complex to re-use, often with short lifespan and with potentially hazardous waste components.

In their evaluation report of the WEEE Directive 2002/96 Huisman *et al.* (2007) discuss the EPR principle in relation to the WEEE Directive. They conclude that the EPR principle in fact can work counterproductively. They conclude that the most relevant environmental improvement potentials are connected to higher collection amounts and quality of treatment. Since WEEE is a social problem it demands social solution. This means that every stakeholder should contribute a positive influence on the solution side, which moves the responsibility from the WEEE manager to the EEE producer:

- Producers should remain primarily financially responsible. Producers should be given easier access to WEEE. The collection target should be higher, sorting systems more effective and differentiated, including brands and part-producers of a product.
- The logistic routes for WEEE transportation on a national and international level in Europe should be optimized.
- Member states are important stakeholders in making compliance schemes. Producers together with the official national interest group should work together to improve the sorting and collection line. Important stakeholders to be included on a national level are the authorized WEEE take-back companies. Combining incentives for an increased and a more producer-designed collection system should make a more cost-effective system.

- Better enforcement of the key provisions at EU and member state-level on all organizations and operational parts of the recycling chain to reduce illegal waste shipments.
- Key responsibilities of stakeholders should be developed and defined on a national level. The legal framework and key responsibilities should be split into operational standards.
- Consumer awareness must be increased in order to stimulate sorting and collection.

It seems reasonable that the EPR principle in some way is put into the legislative system. Since a great variety of hazardous waste components exist and for the future will exist in WEEE, EPR as a principle should be put into the RoHS Directive as Huisman *et al.* (2007) propose.

22.5 National waste recovery schemes: case studies

22.5.1 Introduction

The previous sections analysed the legislation framework in Europe established prior to the WEEE Directive. The Commission Directives – 2002/96/EC (WEEE Directive) and 2002/95/EC (RoHS Directive) – put forward some important tools or targets for the individual members in their work to obtain a more sustainable WEEE management:

- Final holders and distributors can return WEEE free of charge.
- Distributors of new products should ensure that waste of the same type of equipment can be returned to them free of charge on a one-to-one-basis.
- Producers are allowed to set up and operate individual or collective take-back systems.
- Targets to be reached by December 2006:
  - A rate of at least 4 kg on average per inhabitant per year of WEEE from private households must be achieved.
  - A rate of recovery defined by percent recovery of average weight for certain WEEE categories.
- Financing: by 13 August 2005 producers must provide the financing for collection and treatment at least from the collection point.
- Reporting: a national register should be drawn up of producers, quantities, and categories.

Since this, the so-called ‘article 175’ directive, national recovery schemes should be established out of ‘national needs’. The commission did not put very strong efforts into solving the problem of increased waste amounts. Consequently putting MSW in landfill or incinerators has been more focused on than recycling. It is reasonable that experience from already established

WEEE management systems served as measures and guided towards the decisions.

The 'national 4 kg target' is the basis for describing and analyzing the success of WEEE management on national basis. Table 22.1 gives an overview of the European countries results taken from 2006. Switzerland, Norway, Sweden and Denmark have all reached the '4 kg target' – and their WEEE management systems are for that reason described and analysed in this section. Table 22.2 shows that these four nations had established WEEE management on a national basis before the directives appeared, while Table 22.3 shows relevant data from Swiss WEEE collection. Their legislations have been revised as shown in the last column of Table 22.2.

22.5.2 WEEE management in Switzerland

Since Switzerland is not a member of the EU, the country does not contribute WEEE data to the EU statistics. The Swiss Statistic within environmental data

Table 22.1 Amounts of WEEE collected from households and other sources in the year 2006 in EU coutries and Norway. The target from the EU this year was 4 kg/capita/year. The table is grouped in decreasing order of collected kg WEEE from private households

Nation	Population 2006	Put on market (kg/capita)	Collected from private households (kg/capita)	Collected other than private households (kg/capita)	Total collected (kg/capita)
Norway	4 640 000	40.31	13.99	7.91	21.90
Sweden	9 048 000	25.05	12.75	1.63	14.38
Denmark	5 427 000	31.96	10.84	0.26	11.10
Germany	82 438 000	22.28	8.61	0.54	9.15
Luxembourg	469 000	16.93	8.14	0.06	8.20
Austria	8 254 000	19.00	7.44	0.15	7.59
Belgium	10 511 000	23.76	7.24	0.00	7.25
Finland	5 256 000	26.45	7.08	0.47	7.55
Netherlands	16 334 000	6.06	5.68	0.10	5.78
Estonia	1 345 000	13.62	4.31	0.04	4.35
Spain	43 758 000	11.71	3.64		
UK*	60 781 000	13.22	3.03	0.16	3.19
Lithuania	3 403 000	14.63	2.64	0.09	2.73
Hungary	10 077 000	13.47	2.36	0.02	2.39
Slovakia	5 389 000	9.55	1.54	0.05	1.59
France	62 999 000	23.52	0.09	0.16	0.24
Greece	11 125 000	15.81	0.86	0.16	1.02
Italy	58 752 000		0.78	0.35	1.13
Portugal	10 570 000	11.66	0.40	0.00	0.40
Romania	21 610 000	6.52	0.04	0.01	0.05

*The data from UK is from the year 2007 (data from year 2006 is lacking).
Source: EU WEEE Statistics (2011).

Table 22.2 Legislative systems established before the WEEE Directive came into force

Country	Legislation	In force/amended
Norway	1. The Product Control Act 2. Regulations regarding Scrapped Electrical and Electronic Products/2005: The Waste Regulation	1978//2000/ 2004//2005 currently under revision
Switzerland	Ordinance on the Return, Taking back and Disposal of Electrical and Electronic Equipment (ORDEE)	1998/2005
Sweden	Ordinance of producer responsibility for electrical and electronic products. Swedish Code of Statutes 2005:209. Covering both the WEEE Directive and RoHS framework	2001/2005
Denmark	1. Act No 385 of 25 May amending the Environmental Protection Act (producer liability of electronic waste etc.) 2. Statutory Order no. 664 of 27 June 2005 on management of waste electrical and electronic equipment (the WEEE order)	1998/2005/2006/ 2010

Table 22.3 Amounts of WEEE collected from households and other sources in the years 2006 and 2010 in Switzerland

Year	Population (in 1000)	Put on market (kg/ capita)[1]	Collected from private households (kg)	Collected other than private households (kg)	Total collected (kg/ capita)[2]	Total quantities collected
2006	7507	15.8	N/A	N/A	13.1	100 000
2010	7785	16.3	N/A	N/A	15.5	120 400

[1] OFEN Statistic and estimated from SWICO.
[2] OFEN Statistic: http://www.bafu.admin.ch/abfall/01517/01519/index.html?lang=en. SENS

'BAFU' has kindly provided data from Switzerland for the years 2006 and 2010 for this chapter. It is important to note the Swiss collecting system does not differentiate between the collection from private households and other sources and the data per capita is given without differentiation. The Swiss WEEE categories are only the first seven from the WEEE Directive 2002/96/ EC and categories 7 *Medical devices*, 8 *Monitoring and control instruments* and 9 *Automatic dispensers* are not included in the data provided.

The Swiss WEEE law, the '*Ordinance on the Return, the Take-Back and the Disposal of Electrical and Electronic Equipment*' ('ORDEE'), was put into force in 1998. However, the attempts to build up a system for managing WEEE started on a voluntary basis in 1990 ('Swiss e-waste competence': http://www.e-waste.ch/; Hischier *et al*. 2005, Khetriwal *et al.* 2009, Wäger *et al.* 2011). The first actors or stakeholders were in place during the period from 1991 until 1994 and the first collection points for WEEE were established in 1996.

RoHS provisions are regulated by the '*Ordinance on the Reduction of Risks from Chemicals*' ('ChemRRV'). Under the ChemRRV, on 1 July 2006 the same restrictions on the six hazardous components listed in the RoHS Directive were introduced in the ChemRRV. The legal background for ORDEE was two-sided:

1. The obligation of an owner to give back an end-of-life appliance.
2. The obligation of all retailers to take back any appliance free of charge.

The legislation did not define how the industry should carry out their responsibility to manage and finance their WEEE recycling. According to the Swiss official strategy within EPR, the actual industry decides how to establish and carry out the recycling. The 'Swiss system' is voluntary and based on the fundamental ideology that it is designed to be more flexible and cost-effective than government-run systems. The authorities' role is restricted to controlling and monitoring the results of the different stakeholders in the WEEE management system. The system is currently managed by the responsible producers, being both manufacturers and importers. They are organised in three so-called 'producer responsible organisations' (PRO's). They are all non-profit organisations. Since the consumers pay a fee – in Switzerland called the advanced recycling fee (ARF) – when they purchase the equipment, the equipment is handed back free of charge when it becomes waste. The system is differentiated according to the cost of collection and treatment of the WEEE categories. The main stakeholders in the Swiss WEEE management system are shown in Table 22.4.

Even good systems can be improved. Hischier *et al*. (2005) and Khetriwal *et al.* (2009) have summed up the Swiss WEEE system:

- The target of 4 kg/person/year cannot be sufficient for sustainable development of the WEEE.
- Life-cycle assessment (LCA) should be introduced in order to identify the most sustainable treatment action
- Detailed questions need to be asked regarding mechanical or manual dismantling
- More effective methods for treatment of plastics are needed

According to Khetriwal *et al*. (2009) history has shown that a small group of large producers is sufficient to form a critical mass for starting the system even before legislation is introduced. The system has so far been flexible and cost effective. The system does not differentiate between brands and it utilizes the retail distribution network. Reverse logistics costs are minimized through this network. The compliance between the stakeholders is necessary

Table 22.4 Swiss WEEE management system. Stakeholders' roles and responsibilities

Actor	Roles and responsibilities
Government	The federal government plays the role as overseer, framing the basic guidelines and legislation. Control authorities play a part in the overall control and monitoring in their capacity as the licensing authority for recyclers.
Manufacturers/ Importers PROs (SWICO, SENS, SLRS)	Importers carry the economic and physical responsibilities for their products. They mange the day-to-day operations of the systems, including setting the recycling fees, as well as licensing and auditing recyclers. PROs are non-profit organizations.
SWICO	Established in 1994. PRO organisation under the Swiss Association for the Information, Communication and Organizational Technologies (ICT). Handles end-of-life ICT and consumer's electronics. Guarantees that used equipment is taken back from the following sectors: informatics, office electronics, telecommunications, the graphics industry and dental industry.
SENS	Established in 1990. Foundation for Waste Management. Main activities: To supervise and monitor recycling of all WEEE, take care of white goods such as refrigerators and freezers. Currently SENS covers the following categories of WEEE (according to Annex IB the WEEE Directive 2002/96/EC): WEEE categories 1, 2, 5, 6, 7, 8, 9 and 10. SENS approve the WEEE treatment business. Holders of WEEE are free to choose their partner among these. SENS pays equal compensation to partners doing equal work – collection, transport and recycling. The system is integrated in an IT database.
IT Database	This IT database is according to Article 12 in WEEE Directive 2002/96/EC. This system is open and can be visualized to show the flow of money and material. Operated by SENS.
SLRS	Swiss Lighting Recycling Foundation. This organisation was established in 2005 by the Swiss Lighting Association. The purpose was to set up a system for the disposal of lamps and luminaries.
Distributors and retailers	Bear a part of the information responsibility of the product. Are obliged to take back products in categories they have on sale, irrespective of whether the product was sold by them, or whether the consumer purchase a similar product in replacement. Are responsible for clearly monitoring the amount of ARF in the consumer invoice.
Consumers	Are responsible, and obliged by law, to return discarded appliances to retailers or designated collection points. Bear the financial responsibility through the ARF on new products purchased.
Collection points	Collect all kinds of WEEE free of charge.
Recyclers	Must adhere to minimum standards on emission and take adequate safety measures concerning employees' health. Authorization to operate recycling facility is given from the cantonal government as well as licensed from the PROs.

to overcome free-riders. By independent control and monitoring and joint efforts between stakeholders hard legislation can be avoided. In other words, it seems like the Swiss WEEE stakeholders are proud of their effective system of managing WEEE. The EPS system is financed effectively since the cost for recovery is lower than the costs for disposal.

22.5.3 WEEE management in Norway

An overview of the Norwegian WEEE legislations and their amendments are given in Table 22.2, while the Norwegian WEEE stakeholders are summed up in Table 22.5.

Table 22.5 WEEE management in Norway: Stakeholders' roles and responsibilities

Actor	Roles and responsibilities
Department of Climate and Pollution (klif)	The government plays the role as overseer, framing the basic guidelines and legislation. Control authorities play a part in the overall control and monitoring in their capacity as the licensing authority for recyclers. Approves the take back companies. Owner and operator of the EE register.
The Customs and Excise Authorities	Provide data on import and export of EEE and WEEE to Statistics Norway.
Statistics Norway	Statistics Norway provides all their data from EEE and WEEE in addition to making national statistics within waste, provide data to the national EE-register.
EE-register	Established in 2006. Makes statistics of EEE and WEEE in Norway. May 2011: More than 4450 companies are members in one of the five authorized WEEE take-back companies.
RENAS	Established 1997. Non-profit company, owned by The Electro Association (EFO) and Electro and Energy Federation of Norwegian Industries. RENAS operate 160 collection centres and 15 treatment plants. RENAS was originally established to collect B2B-WEEE. Today they also cover consumers' WEEE.
Elretur	Established 1999. Non-profit company. Owned by the Consumer Electronics Trade Foundation, ICT Norway and Amelia. Elretur's customers are importers, or producers of electrical and electronic equipment. Operates ca 2500 collection points, mainly distributors of EEE, municipals and inter-municipal companies. Consumers can deliver WEEE free of charge to municipal collection points or to shops selling same kind of products.
Eurovironment AS Elsirk AS ERP Norway AS (European Recycling Platform)	Three business based authorized WEEE take-back companies.
Municipalities/ inter-municipal companies	Municipalities are obliged by law to collect WEEE. Common in Norway is inter-municipal companies. Municipal collecting points and stores ensures collection.

Norway created in 1976 the act which can be regarded as a forerunner to put the EPR principle into a legislative context: The Act 1976 relating to the control of product and consumer services.

The Ministry of Environment made a voluntary agreement with the Electric and Electronic Industry and Business Sector in Norway in 1999. As a result, an EPR system for WEEE financed by the manufacturers and importers was established. Norway amended the legislation the WEEE regulation in 2006 as a result of the WEEE directive**.** The major amendments in the Norwegian waste regulation within WEEE were (Román *et al*. 2008, EE registeret):

- Take-back companies handling WEEE must have an approval from the authorities.
- Producers and importers of EEE are demanded to be members of an approved waste company.
- A register of producers of EEE should be established.

The definition of WEEE is broader than the WEEE Directive and includes four new categories of the already established ten (Commission Directive 2002/96/EC, Annex IB). The last four comprise mainly WEEE from industry and business:

- (11) Automatic machines for selling beverages, food, cash points and equipment delivering automatic products.
- (12) Cables, wires,
- (13) Electronic equipment (lifts for persons and goods, moving staircases, winches).
- (14) Mounted rigid equipment for heating, air-conditioning and ventilation.

The inclusion of these four WEEE groups indicates national responsibility for taking care of WEEE from business and industry as well as consumers.

Five approved collectively-financed take-back companies collect and recycle WEEE in Norway. Two of these companies, Elretur and RENAS, are non-profit companies owned by the Electric and Electronic Industry and Business Sector. These two companies have been in the business for the last 10 years. Elretur was established in order to take care of consumers' WEEE and RENAS to take care of WEEE from the business to business industry (i.e. B2B – non-household). Currently these two companies cover all categories of WEEE. According to waste regulation, the take-back companies have to be approved by the authorities in Norway. They must ensure the free collection from enterprises, distributors and municipalities collecting WEEE. Also they have to collect and accept WEEE in equivalent geographical areas of Norway where the members of the EEE companies are located. The existence of five take-back companies ensures competition in the EEE waste branch. The country is divided into different collection areas that are managed by each logistics subcontractor.

The national database system, the EE register, ensures that WEEE is managed according to the legislation. The transporters and treatment operators are obliged by law to report the collected and treated WEEE for the database. Since Norway is not a member of EU, the total amounts of products imported and exported are recorded. The data register makes it possible to control the total amount of EEE and WEEE produced, imported and exported. The producers and importers of WEEE are obliged to be a member of one of authorized take-back companies. They pay a fee to this company, which is adjusted according to their production or their import. This fee covers the expenses of handling EEE when it turns to be WEEE. The EE register controls the membership register and takes care of free-riders (i.e. producers not being member of an approved take back-company). The system also allows for calculating the amounts of WEEE not entering the waste treatment system in Norway. The EE register has improved the information flow in Norway.

Cash flow in the form of consumer taxes ensures end-treatment. WEEE management in Norway is for that reason an example of the PPP. The resources in the WEEE are, however, not yet utilized optimally in Norway. There is still some unexplored potential for new business and reverse chain management of WEEE. WEEE collection is organized on municipal level, by inter-municipal waste companies or by stores.

A critical issue in Norway is that most WEEE treatment companies are located near the capital Oslo. Transportation of WEEE contributes to a sizeable environmental load, especially emissions to air. In addition, transportation especially in winter road conditions involves the risk of accidents.

22.5.4 WEEE management in Sweden

An overview of the Swedish WEEE legislations and their amendments are given in Table 22.2, while the Swedish WEEE stakeholders are summed up in Table 22.6. The first regulation of WEEE in Sweden was in 2001 (Sasaki 2004) and was amended in 2005 according to the WEEE Directive 2002/96/EC and the RoHS framework 2006/95/EC. The *Ordinance on producer responsibility for electrical and electronic products* (Swedish Code of Statutes 2005:209) is covering both the WEEE directive and the RoHS framework.

In Sweden El-Kretsen is the main actor in the collection and recycling of WEEE. It was established in 2001, and is owned by 21 business associations. El-Kretsen was established as a result of an agreement between municipalities, county administrations and a producers association. It is a non-profit organization and the charges paid by the affiliated members are based on their own costs. In 2011 there were 2000 members served by El-Kretsen

Table 22.6 WEEE management in Sweden: Stakeholders' roles and responsibilities

Actor	Roles and responsibilities
The Swedish Environmental Protection Agency	Department under the Ministry of Environment. Responsible for laws, regulations, guidelines, reports and information.
Producers	By obligation covers the collection and treatment of their WEEE. Must provide information to household about the collection system. Retailers are also defined as producers.
El-Kretsen	Established 2001. Non-profit organization owned by 21 business organisations. In 2011 over 2000 members paying membership to cover the collection and treatment of WEEE. Members are municipalities as well as businesses. El-Kretsen serves B2B as well as B2C.
Swedish Association of Recycling Electronic Products (EÅF)	Established 2007. Association taking care of used electronics. Members are shops selling electronics.
Municipalities	Manage collection points for household consumers.
EE-register	Operated by The Swedish Environmental Protection Agency (Naturvårdsvärket). This covers also batteries. Was established as a result of WEEE legislation 2005.

and approximately 1000 recycling facilities in operation around Swedish municipalities. Of these approximately 300 are dedicated for the business sector, the rest for municipal recycling facilities (Lehtinen *et al*. 2009). The amount of discarded electrical and electronic products collected in Sweden in 2009 was 16.3 kg per capita per year (Svensk Avfallshandtering 2010).

El-Kretsen makes contracts with municipalities (household collection) and other collecting organizations (business collecting). It is important to note that the disposal service for business is also free of charge by using a return certificate. A return certificate means that the party disposing of the object guarantees that the number of units returned corresponds with the undertaking's purchase of new equipment. At the recycling facilities, products are sorted into six different categories. El-Kretsen usually makes contracts with transportation companies and treatment plants (a recycling service provider) based on four categories: (1) fridges and freezers, (2) electrical and electronic goods, (3) large white goods and (4) straight fluorescent tubes. El-Kretsen has divided the country into different collection areas based on volume, logistics costs and location of pre-processing. There are four collection areas for fridges and freezers and ten areas for large white goods. For each collecting area a single sourced contact is made with one treatment plant.

The procurement is conducted through an open tender procedure. All tenders who meet the environmental and quality requirements have the opportunity to take part in the procurement. The transport procurement is implemented with the same manner, the transportation volume of a collecting area is divided between two to three transportation companies so that transportation routes are optimized. Each transport supplier is specialized to deal with a particular category and region. In 2007, a web-based system was introduced to disseminate and cover information. The transporters have access to stock reports that the collection facilities have submitted. The transporters plan their shipments and use handheld computers to report back. The recyclers can then see when the transporters are planning to deliver electrical and electronic waste.

The cash flow between El-Kretsen and a pre-treatment service provider is based on the material value and is totally business-based. However in the case of large white goods and television sets, when there is a negative material value, El-Kretsen pays the treatment service provider.

El-Kretsen takes care of recycling WEEE; it is not involved in re-use or remanufacturing issues. When a consumer returns the product to a collection point, the re-use possibility is checked. Those organizations responsible for collection points should also take care of re-use. The basic feature of the Swedish system is the efficient material flows; the recycling operations are centralized and transportation optimized. Large companies, such as Steno Metal AB, dominate the recycling business. Also, social enterprises have a very small role in recycling in Sweden; El-Kretsen supplied 5% of its volume from social companies in order to show social responsibility.

In 2008 the Swedish Association of Recycling Electronic Products (EÅF) was launched as a producer's organization. EÅF uses its member's shops as collection points, but since the shops are not located in all municipalities, an agreement with El-Kretsen was concluded. The agreement is a financial clearing agreement implying that EÅF will pay a fee as other members of El-Kretsen for the part of their electric waste that is collected by El-Kretsen.

22.5.5 WEEE management in Denmark

An overview of the Danish WEEE legislations and their amendments are given in Table 22.2, while the Danish WEEE-stakeholders are summed up in Table 22.7. In Denmark the first regulation for WEEE was introduced in 1998: The Statutory order on placing on the market of electrical and electronic equipment No 664 2005 (The WEEE Order). This is as an implementation of the WEEE Directive and was implemented as a part of the Danish Environmental Protection Act. The legislation has been amended in 2006 and 2010. The Danish Producers Responsibility System (undated; DPA system – Dansk Producent Ansvar) was established in 2009; the former name was 'WEEE systemet' (DPA.dk). DPA is a non-profit organization established in pursuance of The Danish Environmental Protection Act. It

Table 22.7 WEEE management in Denmark: Stakeholders' roles and responsibilities

Actor	Roles and responsibilities
DPA (Dansk Producent Ansvar – Danish Producer responsibility)	Governmental department established 2009. Independent non-profit organisation. Duty is to administrate tasks associated with the rules on producer responsibility under Danish environmental law regarding WEEE. They operate the EE register and make reports. DPA System is managed by a board appointed by the Minister for the Environment recommended by six industrial associations.
Elretur	Established 2005. Elretur is a private association established by producers and importers of EE equipment. The purpose is to assume producer responsibility for our members within WEEE and batteries. Elretur has around 1000 member companies and assumes collection of by far the largest quantity of WEEE in Denmark. Elretur covers B2B and B2C and the 10 categories of WEEE.
Municipalities/local authorities	After a local government reform in January 2007, there are 98 local authorities in Denmark. Each local authority has a number of collection sites that it registers in the DPA-System local authority database. This registration contains, for example, information on contact persons and collection equipment required.
EE-register	Operated by DPA.

covers the producer's responsibility for WEEE, batteries, cars, accumulators and end-of-life vehicles. The purpose is to operate the national EE register as well as design and operate the WEEE recycling system in Denmark. DPA calculates the statutory fees on WEEE and receives the reports on volumes collected from producers and importers, as well as other information. In Denmark EPR is not a strong environmental driver towards producers since it does not have a long legislation history.

WEEE producers have not played any role as a stakeholder within WEEE management in Denmark unlike in Switzerland, Norway and Sweden. The implementation of producer's responsibility has put forward a centralization of the WEEE recycling system in Denmark. Local authorities – the municipalities – are by law responsible for collection from households. They make agreements with WEEE recycling companies. WEEE collection companies are not required to have any approval from authority. The system in Denmark is as a consequence not so strongly regulated as it is in the other Nordic countries.

Elretur is the largest collection company in Denmark. It started operating on 1st April 2006. The environmental fee covers Elretur's administrative costs as well as the cost for operators collecting and treating WEEE in Denmark. Since EPR was implemented by law there has been an ongoing discussion in Denmark between the municipalities and the WEEE recycling companies on the economic burden laid on the municipalities. Municipalities complain that their cost for operating the waste collecting centers should be covered by more financing from the WEEE recyclers. Almost all WEEE in Denmark is collected through municipal recycling centres. Here both households and also companies can deliver all kind of waste. There are about 500 such centres in Denmark. Elretur pick-up and transport the WEEE from the municipal centres to the treatment facilities. The amount of discarded WEEE collected in Denmark in 2008 was increased to 13.94 per capita (Eurostat 2008).

22.6 Summing up and discussion

The four countries described in detail all have in common that they established WEEE regulations on national basis before the EU WEEE Directive became operative in 2002. This seems to be a consequence of an already established system for waste management. WEEE management was easily built on the basis of already smooth functioning routines of waste management in the population. The environmental taxes put on the products were known and accepted since the PPP had a fundamental place in the framework when the new regulations were established. The municipal charge for waste handling covered expenses for operating and controlling waste in a proper way. Inhabitants pay ‘double’, when they purchase an EEE device to cover costs of collection and recycling; and they also cover the expenses for the municipal operating MSW management by paying the municipal tax.

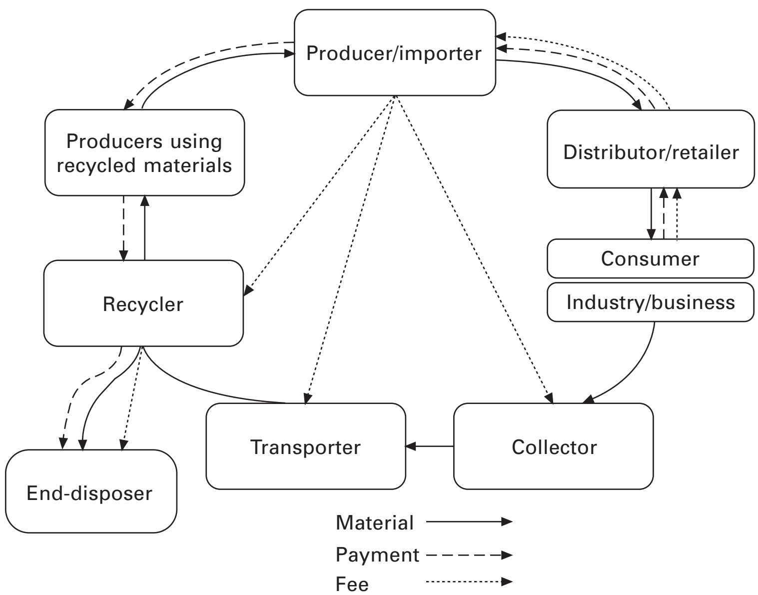
Apart from legislative decrees, the financial instruments are perhaps the most important. Effective sorting of WEEE and separate recycling treatment are not enough to establish a smooth functioning WEEE management system on national basis. The steadily increasing taxes introduced for putting waste on landfill and also incineration of waste have served as effective encouragement for introducing sorting, collection and further treatment of WEEE. Waste companies had an economic drive, perhaps overshadowing the environmental one, not to dispose of WEEE in landfills. The EU report ‘Diverting waste from landfill’ (EEA 2009) concludes that landfill taxes together with product charges can play a significant role in diverting waste from landfill. They must be designed in such a way that they regulate the behaviour of households, waste companies and producers.

The incineration directive also put very strong demands on minimizing emissions. The sorting out of WEEE from the burnable fraction would be cheaper than incineration since hazardous material in the ashes could be minimized. New incineration plants were also required to have an authorized system for the treatment of emissions.

Among the stakeholders managing WEEE, producer or industrial organizations have played an important role in Switzerland, Norway and Sweden. They have addressed the EPR demands towards their member industries for implementation. In that way they have proved to be valuable and successful promoters of good practice. SWICO, SENS and SLRS in Switzerland, RENAS and Elretur in Norway, and El-Kretsen in Sweden are all owned by different branch organizations within EEE management. The WEEE management companies established on the basis of these interest organizations are all non-profit based. Financing of their duties is carried out by their membership. Their payment is based on the volume of WEEE produced. The business and industry organizations' contribution to EPR shows that communications between stakeholders can give successful results in taking care of the environment.

Figure 22.3 gives a general overview of the WEEE management stakeholders in the four countries discussed. It is important to note that the financial system must follow the logistics route when EEE turns into WEEE. There are, however, national differences. In Norway three new business-based take-back companies are today operating together with the 10-year-old RENAS (originally B2B) and El-retur (originally B2C). The argument for putting these companies on the WEEE market was to move towards more free competition in the WEEE recycling market. In Sweden El-Kretsen was alone in the market from 2001 until EÅF was established in 2007. EÅF is constituted by the shops selling EEE and serves this segment by establishing collection points in shops and supermarkets.

In Denmark private companies operate on all levels within collection, transportation and treatment from municipalities, industry and business.



22.3 Stakeholders in the Swiss, Norwegian, Swedish and Danish WEEE take-back systems. A general overview.

Denmark puts no authorization demands on the WEEE management sector, except for the municipalities. The Swiss system is also designed to be more cost-effective and flexible without strong participation of governmental authority.

The collection points in all these countries have been moved to be nearer the consumer, from central municipal collection points to shops and supermarkets. The location of the collection points is a compromise between bringing and collection. In sparsely populated areas vans go around and people can deliver their WEEE together with other problematic waste fractions regularly. In Sweden this system has proved to be very effective.

Information and registration built into national registers was demanded in the WEEE Directive (Article 12). The national register is today a smooth functioning element in these nations having built up a sturdy WEEE management system. It is operated under different organizations but its functional duty is to monitor:

- total amounts of export and import of EEE products and WEEE;
- details of 'free-riders', i.e. producers not being members of an authorized waste company;
- total amount of collected, re-used and treated WEEE; kind of treatment;
- parts of WEEE being re-used.

Norway and Switzerland are not bound by free-trading within the EU law. Their registration of EEE and WEEE will for that reason be more comprehensive than that of member states. This is perhaps a benefit for these countries in order to control total export and import of EEE and WEEE. It is relevant to discuss the total load on the environment for the transportation of WEEE. In the Nordic countries, Norway, Sweden and also Finland, recycling companies are mainly located in the southern part of these countries. The logistic routes are mainly by trucks. Sparsely populated areas in the northern parts of these countries give relatively small amounts of WEEE. Consequently recycling in the northern part of these countries is not economically favourable. The long distance of WEEE transportation results in other environmental problems such as noise, traffic accidents, traffic jams and also large amounts of energy consumed.

The management of consumers' WEEE has been the dominating issue in the EU context. This is reflected in the ten categories list in Annex 1B and also in the target for member states to collect 4 kg per capita, per year. The EU statistics contain 'collected other sources than private households' which is supposed to be WEEE from industry, business etc. There is an uncovered area in the statistical and legislative system dealing with this large amount of WEEE.

The weak demands towards B2B's WEEE in the directive, reflect a lack of political willingness to put environmental demands on to industry. The financial system is built up to cover consumers for the cost for collection, treatment and recycling WEEE. This is not the case concerning B2B WEEE. In this case vendors and customers have to make their own arrangements (Stevels, private communication, April 2011). Among the 10 categories from the Annex IB list there is a lot of non-private WEEE. Norway is the only European country to have expanded the WEEE category list. Since the new four categories consist of valuable materials and also hazardous ones, these should be paid more attention to in amending the directive. It would also be helpful to make the logistic routes for WEEE recycling flexible without regarding the source of WEEE – private, business, industry or brand.

The national EPR driving force on WEEE management seems to be a greater influence in Switzerland, Norway and Sweden than in Denmark. The high collection rates in Denmark, however, show that other factors are a benefit for their WEEE collection. It is reasonable to assume that the logistic routes are easier and this benefits Denmark. Denmark has also a long history of waste management in general; for example it is ahead of the other Nordic counties when it comes to recycling waste into energy. This is also a benefit for central parts of Europe where large volumes of WEEE can flow in a more environmentally favourable logistic way than the Nordic countries.

22.7 Conclusions and recommendations

There is no doubt that the amount of WEEE will increase in the years to come. To deal with this inhomogeneous fraction of valuable and also hazardous components, most of the European countries still have much to do (Widmer *et al.* 2005). There are huge differences among European countries today in the way WEEE is managed. EU statistics clearly state that WEEE is managed well on a national basis in the EU15, while the new member states in general have a long way to go. This can, of course, be shortened by effectively building up the components of the system as described in this chapter.

- *The legislation framework*. It is not enough to implement the WEEE and RoHS Directives in national legislation. The Landfill and Incineration Directives are precautionary legislation instruments to be put into force in such a way that the waste stream of WEEE follows alternative recycling routes.
- *The financing systems*. The taxes put on EEE equipment are a necessary instrument to ensure that costs for collecting, transporting and recycling are cost covered by the consumers. The stream of money must follow the WEEE stream in order to ensure that the real costs for total WEEE management are covered. The taxes for putting unsorted MSW on landfill or into incineration have to be high enough. This means that

the operators of these recycling systems have an effective obstacle for end treatment of WEEE.

- *The producers' responsibilities (EPR)*. Even small groups of EEE producers can be sufficient to start EPR-run WEEE take-back system if the taxes on products are introduced and cover their costs. Municipalities are the most important stakeholder in the consumers' collecting system of WEEE and they should also be required to collect industrial WEEE.
- *The logistic system* should be as effective as possible. The system should not be built up by differentiating brands. This will minimize transportation costs. B2B and B2C collection should be integrated in the same logistic system.
- *The collection points* for WEEE must be put as near the consumer as possible.
- *Poor WEEE management systems*. In nations where WEEE management is lacking, a system for upstream and downstream WEEE handling should be planned for and established at same time. This is mainly due to the lack of storing capacity, but will also help the system of recycling become more efficient. This is, however, a question of communication between different stakeholders and can be challenging.

22.8 Acknowledgements

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22.10 Appendix: abbreviations

ARF	Advance Recycling Fee – a scrutinizing bid for recycling contracts (In Switzerland)

AENS	Swiss Foundation for Waste Management
B2B	Business to Business (non-household)
B2C	Business to Consumer (household)
ChemRRV	Abbreviation for the Swiss RoHS- law – *Ordinance on the Reduction of Risks from Chemicals*
DPA	Danish Producers Responsibility
EPR	Extended Producers Responsibility
EU15	The original EU countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom
EU25	EU15 and in addition added 1 May, 2004: Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia.
EU27	EU25 and in addition added 1 January 2007: Bulgaria and Romania
e-waste	Waste from electric and electronic equipment (e-waste and WEEE are both used in literature)
Free-riders	Those who consume a resource without paying for it, or pay less than the full cost of its production
IPP	Integrated product policy
IPR	Individual producers responsibility
LCA	Life-cycle assessment
ORDEE	Ordinance on the Return, Taking back and Disposal of Electrical and Electronic Equipment. WEEE law in Switzerland
PPP	'Polluter pays' principle
PBB	Polybromated biphenyls
PBDE	Polybromated diphenyl ethers
PROs	Producers responsibility organization in Switzerland
RoHS	Restriction of the use of certain hazardous substances in electrical and electronic equipment
SENS	Swiss Foundation for Waste Management
SLG	Swiss Organisation for Illumination
SWICO	Swiss Association for Information, Communication and Organisational Technology
Up-stream	Waste stream from waste holder to collection point
Down-stream	Waste stream from collection point to treatment or recycling site
VREG	Abbreviation for the Swiss WEEE law – *Ordinance on the Return, the Take-Back and the Waste Management of Electric and Electronic Equipment*
WEEE	Waste from electric and electronic equipment

23
WEEE management in China

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Abstract: The environmental problems caused by waste electrical and electronic equipment (WEEE) in China have aroused the attention of the Chinese government, enterprises and researchers from universities and institutions. Since 2005, some national pilot projects have been launched by the Chinese government to construct large-scale WEEE recycling infrastructures. The increasing domestic generation and illegal trans-boundary shipment of WEEE flowed into informal treatment sectors of WEEE and provided great challenges both in protecting the environment and in the large financial burden placed on the formal recycling infrastructure in the collection and treatment of WEEE. The environmental issues caused by the improper recycling of WEEE have caused concern. The Chinese government issued a series of policies and laws for the management of WEEE and environmental protection. Technologies and systematic solutions of environment problems and recycling of WEEE are being developed.

Key words: WEEE, management, China.

23.1 Introduction

China has been the largest exporter of electrical and electronic equipment (EEE) and importer of waste electrical and electronic equipment (WEEE) around the world. The environmental problems caused by WEEE in China have aroused the attention of international societies (He *et al.*, 2006; Veenstra *et al.*, 2010; Yang *et al.*, 2008). The WEEE issues in China are closely related to both the environmental situation and the development of the economy and society (Osibanjo and Nnorom, 2007; Shinkuma and Huong, 2009).

The Chinese government has been adopting positive measures to prevent and control the environmental pollution of WEEE. A series of important administrative measures and regulations about the treatment and disposal of WEEE have been promulgated in recent years (Ni and Zeng, 2009; Sinha-Khetriwal *et al.*, 2006; Yang, 2008): for example, the Regulations for the Management of the Disposal of Waste Electrical and Electronic Products ('China WEEE' or 'Regulations') signed by Chinese Premier Wen Jiabao on 25 February 2009, which came into effect on 1 January 2011. The regulations provide the details needed to establish a national regulatory 'baseline' to minimize local government variations in WEEE regulation (Y. Wang *et al.*, 2010). Meanwhile, another incentive policy called 'the home appliances traded-in policy', which was implemented in 2009, has had a profound impact on the WEEE management system (Z. Wang *et al.*, 2010).

In China, WEEE has become the fastest growing waste stream in most cities and one of the largest sources of heavy metals and organic pollutants in municipal waste (Widmer *et al.*, 2005; Xing *et al.*, 2009). Furthermore, according to a report from the State Environmental Protection Administration of China, 70% of worldwide WEEE has been sent to China by legal or illegal channels, which will lead WEEE management into embarrassment and increase environmental risk (Yu *et al.*, 2010). In addition, research has shown that high concentration of heavy metals and persistent organic pollutants (POPs) originating from WEEE have been detected in the air, soil and river and also in the living organisms such as infants, fish, leaves etc. (Bai *et al.*, 2011; Li and Zhang, 2010; Liu *et al.*, 2011; Qiu *et al.*, 2010; Wong *et al.*, 2007). Therefore the construction of formal treatment facilities using environmentally sound technology is urgently needed to reduce the environmental pollution of WEEE. In fact, the Chinese government has made great efforts to introduce advanced WEEE treatment technologies and management experience from Western countries to try to build a domestic integrated WEEE management system.

23.2 Infrastructure: collecting, processing, recycling facilities

23.2.1 Pilot projects

In 2005, four national pilot projects of Hangzhou Dadi, Beijing Huaxing, Qingdao Haier and Tianjin Datong were launched by the Chinese government to construct large-scale WEEE recycling infrastructures. Several big formal WEEE recyclers have emerged since then. For the formal recyclers of the national pilot project, technologies and equipment from developed countries are preferred and imported, but they are not totally appropriate for the Chinese local situation. The inability to collect sufficient WEEE from consumers has brought much economic burden for these recyclers to sustain daily operation and capital flow.

Several international and national WEEE pilot projects have been completed in China. Among them, Swiss-Sino cooperation pilot project was the first large-scale scheme in China dedicated to establish WEEE recycling facilities in four target cities across China since 2004 (Anon., 2009). A project of the United Nations University about solving the e-waste problem (UNU/StEP) is now exploring how to adapt the eco-efficient recycling approach to the Chinese local situation. However, formal infrastructures such as pyrometallurgical smelters for printed wire boards (PWBs) recycling, high-standard landfill for hazardous waste and incineration plants for specific waste streams have not been fully installed yet.

23.2.2 Recycling industrial parks

The increasing domestic generation and illegal trans-boundary shipment of WEEE have created great challenges to the environment and formal recycling infrastructure. The international and domestic attention given to the processing of WEEE in southern and eastern China has drawn responses from the central and local authorities in China. The Chinese government is taking measures to manage and improve the industrial parks for environmental protection and waste recycling processes. The import of WEEE by these professional parks may be permitted because of their environmentally sound dismantling techniques and further treatment (J. H. Li *et al.*, 2006).

In Taizhou and Guiyu, the local authorities have attempted to regulate and control WEEE processing enterprises, and asserted that they had made significant progress in controlling the illegal import of WEEE. According to a report by the Pollution Control Division of the Taizhou Environmental Protection Bureau (EPB) (Shen, 2005), the processing of imported waste and domestically produced WEEE is moving towards a system of 'fixed-point processing parks'. These are government-established industrial parks where processing enterprises can set up regulated recycling and disposal businesses. The Taizhou EPB stated that Taizhou had 42 fixed-point waste processing enterprises capable of processing waste including WEEE (Hicks *et al.*, 2005).

23.3 Informal and formal recycling

23.3.1 Informal recyclers in China

The concept of an 'informal sector' originates from studies embedded in the context of the so-called 'Third World', and has, since the late 1950s, become increasingly recognized as important. The informal recyclers in China did not develop overnight, but rather gradually developed together with the development of the local economy. In the late 1970s, many farmers left their farmlands and started to pick out the valuables from the miscellaneous wastes discarded by households to make money by recycling. Since the production of primary metals and energy were constantly controlled by the central government on account of the economic pattern at that time, recycling of secondary material from waste became a reasonable target for these private recyclers and has shaped the spatial pattern of China's recycling industry (Chi *et al.*, 2011; Wang, 2008).

In the early 1990s, the initial used EEE importation stimulated the early development of the informal WEEE recycling sector. During the following years, a booming increase of domestic EEE consumption alongside the country's rapid industrialization and urbanization quickly enlarged the local demand of second-hand components and refurbished appliances, the most common outputs of informal recyclers.

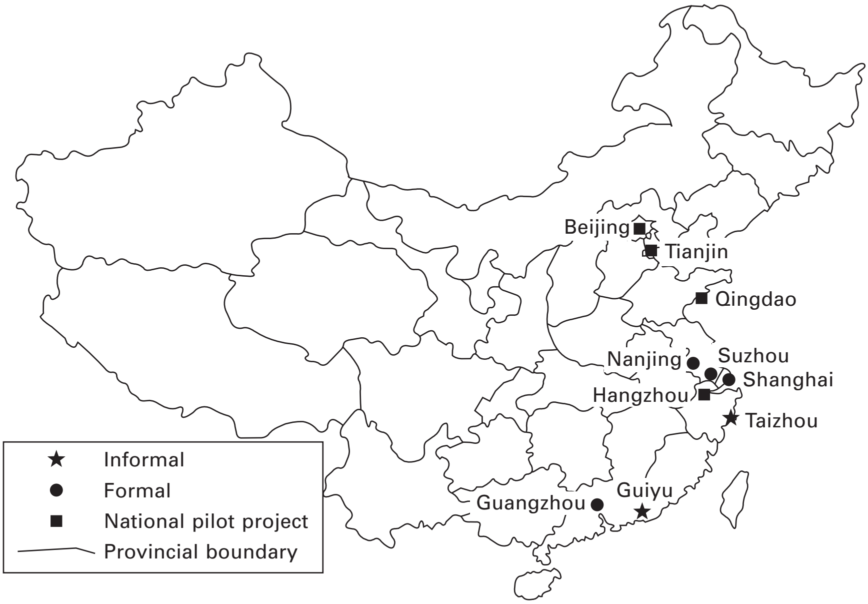
Informal recycling is currently the prevalent WEEE recycling practice in China, especially in some coastal regions. These small or medium-scale recyclers always undertake the recycling activities in their backyard or private factories without any legal licenses, toxicity prevention or health protection measures. The reasons underlying the present low-end management of WEEE and the existence of informal recycling sectors in China include:

- unwillingness of consumers to return and pay for disposal of their old EEE;
- uncoordinated high levels of importation of WEEE as second-hand devices;
- lack of awareness among consumers, collectors and recyclers about the potential hazards of WEEE;
- lack of funds and investment to finance improvements in WEEE recycling;
- absence of recycling infrastructure or appropriate management of WEEE;
- absence of effective take-back programs for end-of-life EEE;
- lack of interest/incentive in WEEE management by multinational IT companies;
- absence and/or lax implementation of WEEE specific legislation.

Spatial distribution of informal recyclers across China

The main centralized clusters of the informal recyclers in China are Guiyu of Guangdong province and Taizhou of Zhejiang province (Fig. 23.1). The main reasons that informal WEEE recyclers converged on these two regions are as follows.

- These regions are geographically adjacent to large ports, and thus logistically convenient for the illegal transboundary import of WEEE.
- The economies in these regions are highly engaged in the manufacturing industries like EEE, toys and electrical machines.
- Emergent evolution of local markets for recycling materials has attracted the WEEE flows from the other parts of China to these regions, which turned them into the trading center for the WEEE recycling.



23.1 Distribution of the major formal and informal WEEE recycling sites and national pilot project sites in China (from Chi *et al.*, 2011).

Recycling techniques of informal recyclers

In informal recycling process, components and devices of WEEE were firstly dismantled for re-use as recovery of function. Then material-specific recovery processes were applied, as recovery of material. Generally these processes show low recovery efficiency and do not abate environmental emissions. Examples of such crude techniques worth mentioning are:

- Physical dismantling by using tools such as hammers, chisels, screwdrivers and bare hands to separate different materials (Wen *et al.*, 2006).
- Removing components from printed circuit boards by heating over coal-fired grills (Puckett *et al.*, 2002).
- Stripping of metals in open-pit acid baths to recover gold and other metals (Wong *et al.*, 2007).
- Chipping and melting plastics without proper ventilation (Wong *et al.*, 2007).
- Burning cables to recover copper, and burning unwanted materials in open air (Wong *et al.*, 2007).
- Disposing of unsalvageable materials in fields and riverbanks (Wong *et al.*, 2007).
- Refilling of toner cartridges (Puckett *et al.*, 2002).

23.3.2 Formal recyclers in China

Formal recycler literally stands for the recycler who is officially recognized and authorized by the government to recycle WEEE. Along with the execution of policies and regulations for WEEE recycling, many official pilot projects have been undertaken by the Chinese National Development and Reform Commission in different provinces. Four national pilot projects were launched sequentially since 2004 in order to gain practical experiences in collection network design, WEEE management standards, and regulations and recycling technologies (Yang *et al.*, 2008).

To improve WEEE recycling technology, the Haier Group and Tsinghua University created a research group using financial support from the government project budget and in-kind funds from Haier (Li and Li, 2007). The main technologies employed in the recycling center are manual disassembly and mechanical recycling methods. Four disassembly lines for waste refrigerators, washing machines, TVs and air conditioners, installed in 2006, had dealt with 8000 home appliances by May 2007. Treatment equipment for waste printed circuit boards is currently under construction and is expected to be in operation soon (Yu *et al.*, 2010).

Since 2009, China's Ministry of Commerce has been piloting a home appliance replacement scheme whereby consumers receive a subsidy worth 10% of the price of five types of new appliances, namely: TVs, refrigerators, washing machines, air conditioners and computers. In June 2010, the scheme was expanded to 19 new cities and provinces in addition to the original nine existing pilot areas (Table 23.1). A total of 14 million home appliances had been sold in the old-for-new home appliance pilot scheme by the end of May 2010 (Ongondo *et al.*, 2011).

Two other types of practice for collection and recycling of WEEE in China, besides the National pilot projects, were United Nations Environment Program (UNEP) project and companies' WEEE reclamation campaigns. In 2006, a UNEP project was launched in Suzhou, Jiangsu Province. The project involved the establishment of several WEEE recycling companies, such as Suzhou Weixiang WEEE Recycling Ltd. With advanced recycling technology and highly efficient air and water purification equipment, this firm has the capacity to recycle more than 5000 tons of computer motherboards, Li-ion batteries and CRTs annually, which is equivalent to around 100 000 computers (Li and Li, 2007).

To encourage consumers and enterprises to give their waste electronic products to formal recycling sectors instead of informal peddlers, UNEP began a WEEE collection pilot project in Suzhou in September 2008. The pilot project encourages electronics manufacturers to take social and environmental responsibility for WEEE recycling, schools to help guide green electronics consumption through propaganda and education, and residents to take environmental responsibility by giving their WEEE to formal recyclers

Table 23.1 Main certified WEEE recycling companies in China

Region	Number of electronics retail outlets	Recycling companies	Dismantling companies
Beijing	23	25	2
Tianjin	22	19	4
Shanghai	62	31	3
Jiangsu	97	97	5
Zhejiang	84	83	5
Shandong	17	19	2
Guangdong	48	43	3
Fuzhou	36	36	1
Changsha	40	20	1
Hebei	40	40	3
Liaoning	15	14	3
Heilongjiang	26	27	2
Jilin	19	19	5
Shanxi	14	14	1
Anhui	30	30	5
Fujian	2	5	1
Jiangxi	44	42	4
Henan	80	89	4
Hubei	28	36	7
Chongqing	24	20	3
Hunan	69	65	4
Sichuan	15	15	4
Guizhou	15	15	2
ShanXi	13	19	1
Gansu	14	14	2
Qinghai	13	12	1
Dalian	11	4	1
Xiamen	15	16	1

Source: China Ministry of Commerce.

instead of informal peddlers. Two communities are the demonstration collection points for the pilot project, which encourages residents to hand over their waste home appliances on their own initiative (Yu *et al.*, 2010).

The UN-based StEP Initiative is initiated by United Nations University with the purpose of forming a neutral arena to enhance and synthesize various efforts around the world for the recycling chain of WEEE. With prominent members from industry, governments, international organizations, non-governmental organizations (NGOs) and universities actively participating, StEP initiates and facilitates approaches towards the sustainable handling of WEEE around the world. Under the task force 4 'recycling' the 'Best of 2 Worlds' (Bo2W) project is initiated and includes the participation of TU Delft, Chinese Academy of Sciences, Umicore, Swiss Materials Science and Technology Institution (EMPA) and Taizhou Chiho Tiande (a large Chinese recycling plant for electric engines) and Philips (Wang, 2008). The Bo2W relies on the initial fact that the Province Zhejiang grants permission to Taizhou Chiho Tiande to recycle 500 000 tons of WEEE. The aim of this project is to research the development of recycling infrastructure in China by realizing high-level disassembly operations for discarded electronics. It is expected that manual disassembly of discarded (domestic) electronic products will lead to a much better separation of materials and components in purer fractions compared with shredding and separation technologies. However, the environmental performance of such industrialized recycling approaches in China will depend, among other factors, on optimizing the environmental and economic value recovery of the resulting material streams. Besides the need for a suitable political framework, this would enable the gradual conversion of the current uncontrolled informal sector into better controlled recycling operations and would increasingly meet global demand for materials in an eco-efficient way.

One of the first voluntary reclamation campaigns for WEEE in China was an initiative jointly launched by Sony, HP, Electrolux and Brant to establish an inter-firm platform for materials procurement, transportation and WEEE recycling. This campaign gave rise to a series of collective WEEE reclamation campaigns between various companies. Subsequently, Dell, HP, Lenovo, Siemens, Motorola and Nokia engaged in all kinds of WEEE collection schemes.

In 2005, Nokia and Motorola jointly initiated the 'Green Box' program with China Mobile (a major telecom operator in China) to collect consumers' obsolete cell phones and accessories in 40 cities across China. Another six cell phone producers including LG, Lenovo and NEC also joined the program in April of 2006, making the 'Green Box' one of the most influential WEEE take-back organizations in China now. In the same year, Dell and Lenovo both introduced free take-back services for their computers sold in China (Chi *et al.*, 2011).

The characteristics of formal and informed recyclers are listed in Table 23.2

23.4 Contamination from landfill and incineration

Landfill and incineration are the two main methods for treating municipal wastes, which are also widely used for WEEE treatment. Conventional landfill and incineration are generating more and more environmental pollution that affects both ecosystems and the people living within or near the areas.

23.4.1 Contamination from landfill

In China, it is rare to find WEEE in landfills. Local authorities do not regard WEEE as a major factor in the increase of waste, and WEEE is generally

Table 23.2 Typical features for formal and informal recyclers in China

Aspects	Formal recyclers	Informal recyclers
Economic	– Initial big-scale investment in construction/equipments – High operation cost and fixed cost – Internalize the environmental cost – Poor availability and costly purchasing on WEEE – Heavily subsidized by the government	– Low investment in facility and equipment construction – Low operation cost and fixed cost – Externalize the environmental cost – Easy and cheap approach to WEEE stream – High revenue from critical material recycling and component reuse – Lack of subsidies
Technical	– Combination of hand disassembly, shredding, detoxification measures, incineration and refinery – Western technology and equipment are preferred	– Labor-intensive hand disassembly – Simple tools and equipments – Primitive and hazardous processes to further recover materials
Environmental	– Controlled measures for detoxification and final disposal – Fine health protection	– No measures for detoxification and waste disposal, direct discharge toxics into the water body, atmosphere, and land – No health or safety protection
Social	– Decrease the employment opportunity for informal sectors	– Numerous unskilled rural and suburban people involved, and their income and living totally rely on the recycling business
Legislative	– Authorized by MEP – Easy to track and monitor	– Officially banned by MEP – Distributed and flexible, hard to regulate
Market/ Network	– Incomplete business network – Lack of support from formal collectors and channels, logistic system, management panels etc. – Creating new market and channels – Poor involvement into the existing market and informal sectors	– Emergent market evolved by simple trade between individuals – Deep coupled with informal collectors, secondary material dealers and consumers – Features of complexity: diversity, emergence, robustness, adaptiveness, non-linearity – Flexible toward external uncertainties
Cultural	– 'Big investment and western high-tech can always solve problem easily' – 'Rigid law can perish the informal sectors overnight'	– Hand dismantling is the current mainstream of recycling methods, and have been providing livelihood to the unskilled mass for over 30 years

Source: Schlummer *et al*. (2006)

traded at a positive value. If the discarded electronic items cannot be repaired, they are dismantled for spare parts and recyclable materials, and only the leftover parts are then brought to landfills (Kojima *et al.*, 2009). The two main pollutants of the landfill are landfill gas and leachate, which could have negative effects on the environment, in particular, polluting surface water, groundwater, soil and air.

The landfill gas contains up to 55% methane (CH_4) and 45% carbon dioxide (CO_2), which are both greenhouse gases contributing to global warming. Although CO_2 is used as the main indicator in discussions about carbon footprints, studies have shown that CH_4 has between 20 and 60 times the global warming potential of CO_2. On the other hand, the flammability of the landfill gas is another concern because of the possibility of its causing an explosion.

Since most landfills in China are open dump sites, hazardous substances contained in WEEE are more likely to dissolve into leachate. The leachate is produced as water percolates through the waste within a landfill site. The water extracts soluble chemicals and products of decomposition. Organic compounds and heavy metals are the main pollutants. Metals from the discarded electrical equipment can lead to mercury (Hg), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn) and cadmium (Cd) being present in landfill leachate which contaminates the local water supplies and soils in surrounding areas (Hester and Harrison, 2009).

23.4.2 Contamination from incineration

Incineration is the most basic form of thermal treatment of WEEE. However, if the waste was not sorted or segregated prior to incineration, the outputs from the combustion process would often be toxic stack emissions and ash containing heavy-metal residues. Open burning of coated wire, heating of printed circuit boards to remove integrated circuit (IC) chips are widely used during the informal recycling process of WEEE in China. There are a number of substances produced during the incineration process, some of which have a direct effect on human health, and others an indirect effect by damaging the local and global environment. The combustion of WEEE can bring emissions of acid gas, CO_2, heavy metals (Pb and Hg from circuit boards and liquid crystal displays) and organics such as dioxins (polyvinyl chloride (PVC) combustion), fluorinated compounds (LCDs and plastics). All of these substances could increase the concentration of contaminants in the air.

Studies showed that in the ambient air of the informal recycling area, Cd, Cr, Cu, Ni, Pb, Zn, Mn and As were detected in 29 air samples of total suspended particles (TSP, particles less than 30–60 μm) and 30 samples of particles with an aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$). Similar to metals, organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/Fs), polybrominated dibenzo-p-dioxins/dibenzofurans (PBDDs/Fs) were also detected in high concentrations (Tsydenova and Bengtsson, 2011).

Fly and bottom ashes from burning activities are another hazardous emission from incineration and are considered as a further potential risk factor for environmental and human health in the WEEE incineration locations. The flue gas consists primarily of Cu, Pb and antimony, which are above the regulatory limits (Stewart and Lemieux, 2003).

23.5 Environmental impacts

Serious adverse impacts on the environment and human health from WEEE recycling occurred in the past and continue to occur in China due to a lack of effective national management. At present, the processing and recycling of WEEE in China is mostly managed by informal recycling businesses. This sector runs a considerable risk of causing environmental and occupational hazards (Streicher-Porte and Yang, 2007).

23.5.1 Environmental impacts of formal recycling

The main environmental impacts of the formal collection system come from vehicle emissions during the collection process. Large numbers of motor-driven vehicles are used to collect the dispersive WEEE, which results in high energy consumption and more waste gas emission.

The formal recycling industries in China comply with national environmental standards. They already exist for the recycling of materials which do not require very specific treatment of WEEE in order to avoid negative impacts on the environment. For example, the recovery of copper and aluminum from car shredder residues is done in an environmentally sound manner without any specific treatment of the waste (Liu *et al.*, 2006).

23.5.2 Environmental impacts of informal recycling

In spite of the great effort in developing WEEE regulation in China, a formal governance system has still not been established and official statistics on collection rates do not exist. Currently, there is anecdotal evidence that much of the WEEE flows into informal recycling channels such as the secondhand market and manual recycling workshops (Veenstra *et al.*, 2010). With simple recycling methods and no environmental pollution control measures, WEEE is recycled informally in these sectors (e.g. Guiyu, Guangdong; Taizhou, Zhejiang; Yu *et al.*, 2009). Taking little account of effects on the environment, recycling in China is actually an activity that generates considerable pollution.

Private individual collectors form the main channel for WEEE collection. However, it must be noted that there are also semi-organized collection networks which exist even though they do not exclusively collect WEEE. There are also some secondhand appliance markets as well. The collection of WEEE by small peddlers is a good example of a low cost collection system, without any significant environmental impacts (Liu *et al.*, 2006). The main environmental problems from informal WEEE recycling are energy consumption and secondary pollution.

The majority of WEEE in China is processed in small workshops using basic methods such as manual disassembly, open burning and acid baths with residues leaking into the soil, air and water. In general, disassembly and dismantling are done by hand or using very simple tools. Pollution occurs when crude methods are applied, such as open burning of wire and cable, open melting of a motor's rotor to extract aluminum and copper, as well as disassembling transformers without preventing oil from leaching into the water and soil. Open melting of aluminum and copper from disassembled WEEE to cast it into ingots causes air pollution and damages the health of workers. In general, illegal treatment of imported WEEE by burning or extracting metals in acid baths is toxic to workers directly and results in serious water and air pollution in the local vicinity. Such unregulated salvaging operations and optional dumping of the residual waste, result in loss of resources, energy wastage, severe and complex contamination of the land, air and water by POPs such as PCDD/Fs, PAHs and polychlorinated biphenyls (PCBs), which have caused severe pollution in air, dust, soil, river water and sediment (Yu *et al.*, 2009).

More attention must be paid to the treatment of residues from the recycling process, which are presently sent directly to a landfill site for municipal waste or dumped elsewhere. Heavy metals, like Pb, Hg and Cr, are leaching into the groundwater, which may lead to toxic impacts on the local environment in the long term. Air pollution and leaching liquids from landfill sites have also threatened public health and the local environment (Zheng and Gao, 2009).

The most prominent areas for the small-scale, unlicensed processing of WEEE are in southern Guangdong Province, and around the city of Taizhou, in eastern Zhejiang Province. The town of Guiyu, in Guangdong, is an established WEEE recycling centre, made up of many small-scale enterprises (Yang *et al.*, 2008). There are several studies on environmental and health impacts of WEEE recycling in Guiyu, where a large portion of the recovery of copper, lead and precious metals is carried out. Long-term informal recycling of WEEEs in Guiyu appeared to have adverse impacts on the environment and the health of the people working/living there (Zheng and Gao, 2009).

Studies at Guiyu revealed high levels of environmental pollution from crude recycling activities. The levels of PAHs, PCBs and PBDEs were detected in environmental samples up to 593,733 and 2196 mg kg^{-1}, respectively (Hicks *et al.*, 2005). Heavy metals Cu, Pb and Zn were also determined at levels up to 711,190 and 242 mg kg^{-1}, respectively. Similar investigation by the Basel Action Network (BAN) indicated alarming levels of heavy metals that correspond very directly with those metals commonly found in computers. Surface water, sediments and soil samples revealed alarming levels of chromium, tin and barium which were found at levels 1388, 152 and 10 times (respectively) higher than the Environment Protection Agency (EPA) threshold for environmental risk in the soil (Leung *et al.*, 2004).

Leachates from bottom ashes, informal dump sites and toxic liquids from acid and cyanide leaching activities have been identified as the other important source for the contamination of environmental compartments and an increased human exposure through affected natural resources such as soils, crops, drinking water, livestock, fish and shellfish (Roman and Puckett, 2002).

About 65% of Pb, Cd and Cr are likely to accumulate in the edible part of rice, the endosperm (Sepulveda *et al.*, 2010). High concentrations of PBDEs in soils of rice fields of Guiyu indicate that, as these compounds are persistent in soils and vegetation, slow uptake may be occurring over extended timescales, so that levels in biota may increase with time. Total PCDD concentrations reported for soils of acid leaching sites, rice crops and a forested reservoir in Guiyu far exceed ecological screening levels. The homolog dioxin and furan profiles in soils of Guiyu were dominated by TCDDs, TCDFs, pentachlorodibenzo furans (PeCDFs), hexachlorodibenzofurans (HxCDFs) and Octa chlorodibenzodioxins (OCDDs). Among these kinds of dioxins and furans, the TCDDs and TCDFs pose the highest toxicity. As food consumption is one of the most important sources of human exposure to PBDEs, PCDD/Fs and PBDD/Fs (contributing more than 90% of total exposure in the case of dioxins and furans with fish and other animal products accounting for approximately 80%), bioaccumulation of these substances in red meat, milk, eggs, fish and shellfish must be considered as a matter of high concern in the places studied. The consumption of foods, origin from animal, especially crab meat and eggs, are the main dietary exposure to dioxins at a WEEE recycling site in China (Taizhou). Owing to the high levels of heavy metal pollution of surface water and groundwater in the town, Guiyu's drinking water has been delivered from a nearby town since approximately 1 year after the appearance of the WEEE industry over a decade ago (Hicks *et al.*, 2005).

The data on effects of hazardous substances released from WEEE during informal recycling operations in Guiyu suggests a cause and effect relationship between the release of Pb, PBDEs and dioxins/furans and the determined concentrations in environmental components (e.g. soil and air), biota and humans. It clearly indicated an urgent need for better monitoring and control of the informal recycling sector in China. However, since the livelihoods of large population groups depend on the income from recycling activities, it is paramount to include the informal sector into formal WEEE recycling systems instead of trying to eliminate the informal sector (Wang *et al.*, 2001).

23.6 Management of hazardous materials

23.6.1 Policies and legislations concerning WEEE

Proper treatment of WEEE is of great importance not only because of the hazardous materials WEEE contains, but also because it enables recovery of valuable resources and alleviates the landfill shortage problem. In order to resolve WEEE problems, the Chinese government has implemented some laws, regulations, standards, technical guidance and norms related to electronic product production and WEEE management. There are general environmental laws that are applicable to WEEE management, such as the General Environmental Law (National People's Congress, NPC, amended in 1989), the Clean Production Promotion Law and the Solid Waste Pollution Control Law. Various government agencies have been involved in enacting better-targeted policies and laws regarding WEEE (Yang *et al.*, 2008). Many specific and pertinent laws and regulations have been issued in the last decade, and the most important are described below.

The Circular on Strengthening the Environmental Management of Waste Electrical and Electronic Equipment (Ministry of Environmental Protection (MEP), 2003) aims to prohibit the environmentally harmful processing of WEEE. However, there is no specific licensing system for WEEE recycling and treatment in this regulation.

The Technical Policy for the Prevention of Pollution from Waste Electrical and Electronic Equipment aims to reduce the overall volume of WEEE, to increase the re-utilization rate and to increase standards for WEEE recycling (Guo *et al.*, 2005). It sets forth the overall guiding principles of 'Reduce, Reuse and Recycle (3R)' and 'polluter pays' (i.e. shared responsibility of producers, retailers and consumers), and stipulates the general provisions of eco-design and the information disclosure of products about any toxic substances contained, as well as provision for the environmentally sound collection, reuse, recycling and disposal of WEEE. It also lists the technologies and equipment for WEEE recycling and the associated national policies and standards needed to be encouraged and developed in the future (Hicks *et al.*, 2005).

The Ordinance on the Management of Prevention and Control of Pollution from Electronic Information Products (EIPs) (MIIT, 2006) aims to reduce the utilization of hazardous and toxic substances in electronic appliances as well as the pollution generated in the manufacture, recycling and disposal of these products (Streicher-Porte and Yang, 2007). It is the counterpart of the EU RoHS directive, including: requirements for eco-design; restrictions on the use of six hazardous substances (i.e. Pb, Hg, Cd, Cr^{6+}, PBB or PBDE) in EIPs; requirements for producers to provide information on the components and hazardous substances present in their products as well as the period of safe use and the potential for recycling. Under this law, the control of poisonous and deleterious materials will be implemented in two stages. In stage 1, all electronic information products which enter the market shall disclose environmental protection-related information, e.g. name, content, period of usage of the hazardous materials as well as whether the product can be recycled at the time of disposal. In stage 2, China will implement strict supervision of the EIPs listed in the Key Management Catalogs. Along with China's RoHS regulation and the relevant Catalogues, detailed standards and implementation rules have been or will be enacted. As at the time of writing, the Requirements for concentration limits for certain hazardous substances in EIPs (SJ/T 11363-2006), marking for control of pollution caused by EIPs (SJ/T 11364-2006) and Examination Approaches for Poisonous and Deleterious Materials contained in EIPs ('Examination Approaches', SJ/T 11365-2006) have been enacted on 6 November 2006. More relevant standards, such as the General Guidelines of Environment-Friendly Use Period of EIPs and the Key Management Catalogues for EIPs are being drafted.

The Administrative Measure on Pollution Prevention of Waste Electrical and Electronic Equipment (MEP, 2007) intends to prevent the pollution caused by the disassembly, recycling and disposal of WEEE as well as pollution by production and storage of WEEE. The responsibilities of relevant parties and the licensed scheme for WEEE recycling companies are specified, and it is stipulated that MEP shall take the responsibility of supervising the pollution prevention of WEEE.

Regulations on the management of recycling and disposal of WEEE are the counterparts of the EU WEEE Directive and are very important for the establishment of an entire management framework for WEEE recycling in China (Liu *et al.*, 2006). It is stipulated that WEEE should be collected by multiple channels and recycled intensively. A special fund should be set up, and producers and importers of electronic products shall perform their duty in making contributions to fund for WEEE recycling. After the ordinance comes into effect, the government of every province will be required to make a local plan for the recycling and disposal of WEEE (Li *et al.*, 2008; MEP, 2009). A standards and certification system for WEEE recycling and disposal enterprises should be established to ensure safe processing of WEEE.

In order to deal with the illegal import of WEEE, many regulations have been issued, including the Notification on Importation of the Seventh Category Waste (MEP, 2000), the List of Goods Prohibited to be Imported (the first list, issued on 30 December 2001), the List of Goods Prohibited to be Imported (the fourth list, issued on 25 August 2002), the List of Goods Prohibited to be Imported (the fifth list, issued on 3 July 2002), and the Prohibited Goods Catalog for Processing and Trade (issued in 2004) (J. Li *et al.*, 2006). However, both because of the large profits to be made in international WEEE trading and because of the lack of a central management system for WEEE recycling, neither foreign companies nor importers want to give up their business. In addition, these regulations lack effective enforcement and monitoring mechanisms. As a result, illegal WEEE imports still exist despite the ban (Eugster *et al.,* 2008).

23.6.2 Techniques to deal with hazardous materials

WEEE could contain a large number of hazardous substances, including heavy metals (mercury, cadmium, lead, etc.), flame retardants (pentabromophenol, PBDEs, tetrabromobisphenol-A (TBBPA), etc.) and other substances. Owing to the presence of these substances, WEEE is generally considered as hazardous waste, which, if improperly managed, may pose significant human and environmental health risks (Tsydenova and Bengtsson, 2011).

As for formal recycling facilities, there are two types of facility engaged in the recycling chain according to the nature of the methods involved (Chancerel *et al.*, 2009). The first group comprises the facilities that are principally engaged in the dismantling and mechanical processing of WEEE for the recovery of raw materials. The second group comprises the facilities employing metallurgical processes to recover metals.

Brominated flame retardants (BFR) are mainly present in printed circuit boards, plastics which might contain banned PBDEs or toxic PBDD/F (Schlummer *et al.,* 2006). In some formal recycling facilities, the primary treatment route for printed circuit boards is as follows: first they are mechanically shredded and crushed, after size reduction, the metals are sent for recovery of copper by using physical airflow separating methods, and the non-metal materials are sent for incineration or landfilling. This type of method is considered to be low cost and easy to implement in China considering its economic benefit. But the BFRs which are embedded in electrical and electronic equipment will be released into the ambient environment during shredding. Furthermore, the incineration treatment may lead to the formation of mixed halogenated dioxins and furans.

The precious metals are mainly found in printed circuit boards, and the concentrations of the precious metals contained in the boards are usually higher than those in ore, so hydrometallurgical treatment is desirable in precious metal recovery. The main steps involve acid or caustic leaching of solid material. From the solutions, the metals of interest are then isolated and concentrated. Leaching solvents are mainly sulfuric acid and hydrogen peroxide, aqua regia, thiourea, cyanide leach solutions, nitric acid, sodium hydroxide, hydrogen chloride, etc.

Pyrometallurgical processes, particularly smelting, are widely practised for metal recovery from WEEE. Hazards associated with the pyrometallurgical processes are possible emissions of fumes of metals, particularly the low melting point metals such as copper, cadmium and lead. Cathode ray tubes are the biggest WEEE flow in China, and generally, the closed-loop recycling for manufacturing is preferred. However, with the CRT market shrinking the CRT glass manufacturers do not have the capacity to utilize the increasing amount of CRT glass. According to our investigation, at present only three CRTs manufacturers (IRICO, Shanxi; ANFEI, Henan; ANCAI, Henan) have the capacity to accept the volume of 100 000 tons of the recycled glass every year. A large amount of CRT glass is sent to copper or lead smelters as silicate flux or raw materials and a great amount remains as solid wastes waiting for treatment.

From the investigation of Chinese WEEE recycling infrastructure, formal infrastructures like pyrometallurgical smelters for PWB recycling, high-standard landfill for hazardous waste and incineration plants for specific waste streams are not fully installed. In some small or medium scale pilot projects the technologies for dismantling, sorting and recovery of valuable materials still lags behind the developed countries. Therefore the formal recyclers of the national pilot projects prefer to import technologies and equipment from the developed countries.

23.7 Knowledge centers of excellence

WEEE is still a new topic in emerging economies as this waste stream began to be integrated into the recycling industry only a few years ago. Because of this, innovation hubs and centres of excellence have not been established yet. However, a few local organizations have existed, which are building up their WEEE competence based on national or international cooperation projects. This includes a few small businesses who took early action in the local development of (low-tech) recycling technologies.

The following organizations have the potential to develop into innovation hubs and centres of excellence:

- University and research institutes: Tongji University, Tsinghua University, China Academy of Science, Shanghai Jiaotong University, Shantou University, China University of Mining and Technology, Hong Kong Baptist University, East China University of Science and Technology, China Household Electric Appliances Research Institute.

- Governmental departments: Ministry of Environment Protection (MEP); National Development and Reform Commission (NDRC), The Ministry of Industry and Information Technology (MIIT).
- NGOs: Basel Convention Coordinating Center for Asia and the Pacific (Beijing). Greenpeace (Hong Kong).

For the research sector in China, the focus is mainly put on the technology and equipment, which could be used to recycle and detoxify various types of WEEE. There is a great deal of interest in the hydrometallurgical recycling of precious metal from PWB. However, the limits of this technology regarding the recovery and management of toxics have as yet been insufficiently addressed. Limited research is concentrating on the toxicology of the hazards from WEEE recycling and the potential policy instrument for WEEE management in China.

Thanks to the activities and campaigns of Basel Action Network (BAN), Greenpeace and others, enormous global attention has been drawn to the WEEE problem in China, especially in the regions around Guiyu and Taizhou. There are global initiatives being executed in China in order to ease the tension. For example, the project 'Best of 2 Worlds', which is being carried out by UNU/StEP Initiative conducted in cooperation with Chiho-Tiande Metal Co. Ltd, aims to seek an eco-efficient recycling approach. The idea is to combine the benefit of deep level manual dismantling of WEEE in China and local end-processing of less complex (metallic) fractions (Cu, Al, ferrous metals, plastics) with treatment of critical fractions like circuit boards in state-of-the-art integrated smelters abroad. The Swiss government and Empa have been working closely with the Chinese government to facilitate the development of national pilot projects.

Comprehensively speaking, the slow process of political decision making and creating a national WEEE directive has a negative effect on the diffusion of sustainable innovation in China. Without the restriction of the legislation and with the absence of proper subsidies and financial schemes, actions and responsibilities normally taken by the consumers and producers have become suspended, which consequentially prevent the survival and sustainability of current formal recyclers. Stimulation from both political intervention and market instruments are essential to environmentally close the loop of WEEE recycling in China. More concern and research will focus on the social and economic impact of various WEEE management scenarios, as well as exploring alternative political instruments and management tools for effective operation of WEEE recycling across China.

Innovation hubs and centers of excellence have not been established yet; but some organizations are currently establishing their WEEE competence and have a great potential to develop into innovation hubs. Multilateral institutions, mainly National Cleaner Production Centres and Basel Convention Regional Centers can develop into knowledge hubs for WEEE management in some countries. Crucial instruments and framework conditions for the development of innovation hubs include the possibility of participating in international knowledge partnership programmes. It also has been observed that without a clear legal framework and the active participation of the government, the development of innovative technologies is hampered. The future success of technological innovation in environments with strong informal participation strongly depends on alternative business models with financial incentives, which allow the informal sector to still participate with 'safe' recycling processes, while hazardous operations are transferred to state-of-the-art formal recyclers. There is also a need to establish a fair competitive environment with common rules, clearly favoring the development and application of innovative technologies.

23.8 Future trends

In general, the Chinese government has accelerated the process of decision making and developing a national WEEE directive, which will have a positive effect on the diffusion of a sustainable innovation in China. As far as China is concerned, legislation, proper subsidies and financial schemes, actions and responsibilities are the key point for the survival and sustainability of current formal recyclers.

With regard to system innovation, the Chinese government hopes to adopt efficient policies that conform to the domestic conditions, just like 'the home appliances traded-in policy', to repair deficiencies that have emerged from the process of WEEE management. Advanced management experiences and successful management cases from western countries were usually used as a source of reference for making or revising relevant policies, regulations, rules etc. Typically, the Circular Economy Promotion Law of the People's Republic of China, which came into force on 1 January 2009, has referred to the concept of the producer responsibility system and design for the environment. Besides, regulations about import of WEEE are being revised in order to forbid illegal cross-boundary movement and also construct legal areas for the centralized treatment of imported WEEE. Meanwhile, the government will focus on establishing a practical and operational standard system of WEEE management.

Technology innovation refers to the innovation of management technology and production technology. At the national level, the Chinese government encouraged leading research groups and relevant enterprises to engage in technology innovation for WEEE treatment for the first time during the China 11th five year plan (2005–2010), which belonged to the 'national science-technology support plan'. In fact, some research results from this work have now been applied to daily WEEE management and production practice. During the 12th five years (2011–2015), the government will still carry out research projects to solve the outstanding issues emerging in WEEE management. In addition, more and more WEEE treatment enterprises devote themselves to technology innovation independently, which should promote technology innovation in WEEE management in China.

23.9 Sources of further information and advice

Some useful information about relevant functional departments, institutes, non-governmental organizations, enterprises and website are provided in Table 23.3. Readers may refer to them for further valuable information and advice about WEEE management.

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Table 23.3 The list of stakeholders of WEEE management in China

Functional departments	National Development and Reform Commission/NDRC, Ministry of Environment Protection/MEP (Department of Pollution Control), Ministry of Science and Technology, Ministry of Commerce, Ministry of industry and information technology.
Institutes	Tsinghua University, Tongji University, China Academy of Science, Hong Kong Baptist University, East China University of Science and Technology, Shanghai Jiaotong University, Shantou University, Donghua University, Nankai University, University of Science & Technology Beijing, Chongqing Technology and Business University, Jiangxi Academy of Science, China Household Electric Appliance Research Institute, Tianjin University of Technology, Shanghai Electric Cable Research Institute, China National Electric Apparatus Research Institute, Peking University, North University of China, General Research Institute for Nonferrous Metals, Jiangsu Teachers University of Technology, Qingdao University of Science & Technology, People’s Liberation Army Armored Force Engineering Institute, China National Institute of Standardization, Central South University, China University of Mining and Technology, Yangzhou University, Anhui University of Architecture, South China University of Technology, Fudan University, Chang’an University, Huazhong University of Science & Technology, Hefei University of Technology, Beijing University of Chemical Technology, Zhejiang University, Guangdong University of Technology, Shanghai Second Polytechnic University etc.
NGOs	Basel Convention Coordinating Center for Asia and the Pacific (Beijing), Greenpeace (Hong Kong), China Resource Recycling Association, China Association of Resource Comprehensive Utilization, China Plastics Processing Industry Association etc.

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24
WEEE management in the USA and India: research and education for a responsible approach to managing WEEE

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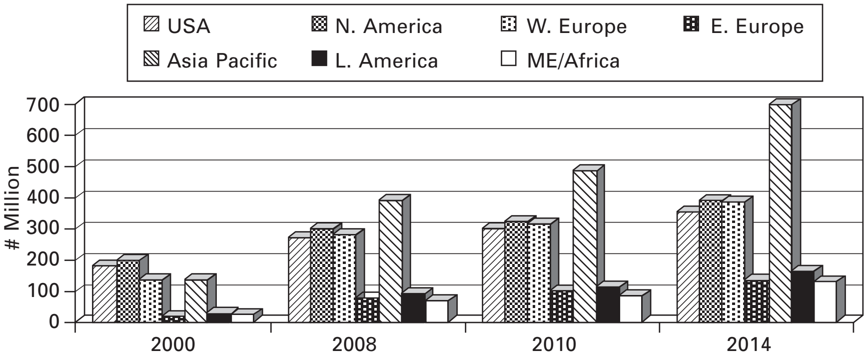
Abstract: Global and local situational analyses show that electronic waste recycling is a global issue. Consumers, designers and manufacturers play key roles in ensuring that electronics are reused, recycled and diverted from being dumped in landfills. Recyclers play an important role in ensuring that recycling meets accepted standards, dismantling maximizes precious metal recovery, damage to environment and human health is minimal and the process creates jobs. Education about safer electronic waste recycling using videos and posters could help increase participation among citizens and change their attitudes. Using an educational toolkit to train workers could help them safeguard health and retain their productivity.

Key words: e-waste or electronic waste, dismantling, recycling, education, training.

24.1 Introduction

With the rapid increase in the manufacture and use of electronic products (Fig. 24.1) and their subsequent disposal because of manufacture-induced obsolescence and marketing-induced consumer preferences, electrical and electronic waste (e-waste) recycling is emerging as an intransigent issue,



24.1 Growth of usage of electronic products worldwide.

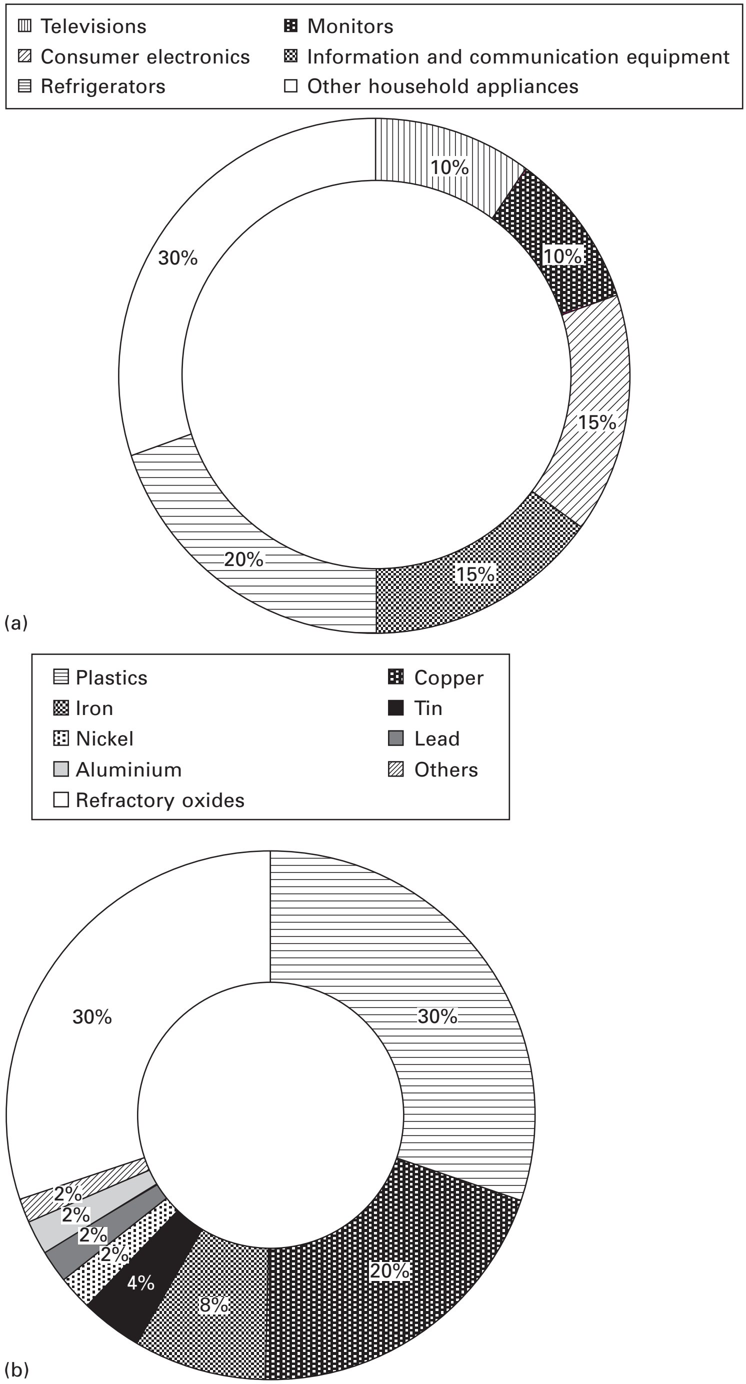
posing grave danger and threats to the lives of people and the ecosystems on which they depend.

According to United Nations Environment Program (UNEP), every year 20 to 50 million tons of electrical and electronic waste are generated worldwide, which could bring significant risks to human health and the environment (Schwarzer *et al.*, 2005). While in 1998, 6 million tons of e-waste was generated, which was 4% of the municipal waste stream (Arensman, 2000), it is presently close to 40 million tons, which is 5% of the municipal waste stream (UNEP, 2006). Of the millions of computers purchased around the world (183 million in 2004) (UNEP, 2006), only about 14% are recovered for recycling. In 2008 about 430 000 tons of electronics (13.5% of e-waste) were recovered in the US compared with 32% for other categories of municipal waste recovered (USEPA, 2009a). In the US, 14 to 20 million tons of PCs are discarded every year, and a similar number are discarded in the EU, with a growth rate of 3–5% every year. According to the United States Environmental Protection Agency (USEPA), e-waste is the fastest growing municipal waste stream in the US; 3.16 million tons was produced in 2008, 5% more than in 2007 (USEPA, 2009a). Of these 65 000 tons are cellular phones (130 million handsets), which makes cellular phones one of the largest components of the e-waste stream (BAN, 2004). In Japan 610 million cellular phones were discarded in 2010 (Uryu *et al.*, 2003). Developing countries have also tripled e-waste generation (UNEP, 2006).

Today's e-waste – including used computers – is mainly generated by industrialized countries which already have a high number of personal computers. But in the near future, a large quantity of waste will be generated from countries in economic transition such as Zimbabwe, China, Sri Lanka, India and Eastern European countries.

While global e-waste generation is 40 million tons per year, India's annual generation of e-waste is expected to reach 800 000 tons by 2012 (Palkhiwala, 2011). In addition, nearly 50 000 to 80 000 tons of e-waste gets exported to India from various developed countries (MAIT-gtz, 2007). It is estimated that nearly 200 000 workers in the informal sector and about 20 000 in the formal e-waste recycling sector are exposed daily to heavy metals, solvents and brominated flame retardants (BFRs) while recycling e-waste. Only those in the formal sector, 10–12% of the workers, have access to personal protective equipment (PPE) – not others.

Electronic devices contain a mixture of compounds, including some which are toxic with a high potential for pollution (Fig. 24.2). While mercury (Asari *et al.*, 2008), lead, cadmium and chromium are the major toxics in e-waste, beryllium, cesium, selenium, indium, gallium (Uryu *et al.*, 2003) and BFRs like polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDEs) (Oros *et al.*, 2005) can also cause health and environmental problems in humans and animals. The plastics in the outer covering or housing of



24.2 Percentage of various electronics and composition of materials: (a) e-waste by type; (b) e-waste by composition.

the electronic devices too, have toxic chemicals, which accumulate in the bodies of dismantlers (Chan *et al.*, 2007). Circuit boards contain about 16% copper, 4% solder and 2% nickel along with iron, silver, gold, palladium and tantalum. Approximately 90% of the value of most scrap board is in gold and palladium content. Traditional reprocessing of circuit board has focused on the recovery of metals (Palkhiwala, 2011).

The main issue of the e-waste recycling industry is that e-waste is not only being generated in large quantities all over the world but is being exported for recycling throughout the world (Toxics Link, 2004). Rich countries send their old devices to developing countries as donations but since the obsolescence rate is so high, these donated devices quickly become unusable and end up for recycling in slums and suburbs, where they are unsustainably dismantled and disassembled, endangering the lives of those involved (Schwarzer *et al.*, 2005).

In a study conducted by non-profit organizations, it was estimated that e-waste is exported from industrialized nations like the US and Europe, which are the largest consumers of electronic goods, to the underdeveloped and developing countries in Asia and Africa (Fig. 24.3). The preliminary study concluded that 12.75 million computer units went to the recyclers in US in 2002 of which 80% were shipped off-shore to Asia, which amounted to 10.2 million units (BAN/SVTC, 2002). This problem is now spreading

24.3 A typical E-scrapping dismantling operation: 100 000 such migrant workers labour in Guiyu breaking down imported computers in hundreds of small operations like this one in a four-village area surrounding the Lianjiang River. Guiyu, China. December 2001. © 2006 Basel Action Network (BAN).

to Africa with evidence of workers in Kenya (UNEP, 2010), Côte d'Ivoire (Green, 2011) and many other places suffering the consequences of e-waste export (Fig. 24.4).

The issue of e-waste recycling is becoming more important with increased manufacture and use of electronic products in the developing countries as well. A number of studies have been carried out on e-waste generation and

(a)

(b)

24.4 Informal e-waste recycling site in Accra, Ghana: (a) a man breaking a cathode ray tube from a computer monitor with a hammer; (b) recyclers burning wires from computers; (c) the e-waste dumpsite in Accra with open fires for processing e-waste. As with operations in Guiyu, China, this creates a range of health hazards for workers who are exposed to highly toxic phosphor dust from CRTs and environmental damage as lead leaches into the surrounding groundwater. Source: Mike Anane, SVTC, 2010.

(c)

24.4 Continued

its recycling in different geographical locations of India. According to the studies carried out by the Central Pollution Control Board (CPCB) in 2005 it was estimated that about 146,180 tons of e-waste is generated annually in India which is expected to exceed 800 000 tons by 2012 (CPCB, 2011).

According to the UNEP website, the electronics industry in the developed countries had not developed automated, sophisticated e-waste recycling plants in 2001, and hence was sending their waste to unknown sites. 'Electronics 'recycling' is a misleading characterization of many disparate practices, including de-manufacturing, dismantling, shredding, burning or exporting. Recycling is mostly unregulated and often creates additional hazards itself' laments the UNEP website (UNEP, 2006), which has also been struggling to regulate e-waste recycling and illegal export of e-waste to developing countries.

Furthermore, a lot of the e-waste also ends up in landfill (Table 24.1). The USEPA estimates that 29.9 million desktops and 12 million laptops were discarded in 2007 in the US, which is over 112 000 computers discarded per day. The EPA report estimates that 31.9 million computer monitors were discarded in 2007 – both flat panel and cathode ray tubes (CRTs), of which hardly 18% was recycled in the US (USEPA, 2008). The Rest of the e-waste was either shipped abroad or dumped in landfill (Fig. 24.5). Similar issues are seen in different parts of the world.

The UNEP *Alert Bulletin* also warns that the best of landfills leak and heavy metals and hazardous chemicals find their way into water and soil. The vaporization of metallic mercury and dimethylene mercury is also of concern. Uncontrolled fires may begin at such landfills, posing additional health and environmental risks (Tech-Edge, 2002).

Table 24.1 US e-waste in 2007: was it trashed or recycled?

Products	Total disposed** (million of units)	Trashed (million of units)	Recycled (million of units)	Recycling rate (by weight)
Televisions	26.9	20.6	6.3	18%
Computer products*	205.5	157.3	48.2	18%
Cell phones	140.3	126.3	14	10%

*Computer products include CPUs, monitors, notebooks, keyboards, mice, and ‘hard copy peripherals’, which are printers, copiers, multifunctional devices and faxes.
**These totals do not include products that are no longer used, but stored.
Source: EPA (2008).

24.5 Automobile shredder in a landfill in Washington State, USA. Source: Alex Stone, WA Department of Ecology.

A river water sample from the Lianjiang river near a Chinese ‘recycling village’ revealed lead levels that were 2400 times higher than World Health Organization Drinking Water Guidelines. Sediment samples there showed lead levels 212 times higher than what would be treated as hazardous waste had it been dredged from the bottom of the River Rhine in the Netherlands (BAN/SVTC, 2002). A Basel Action Network (BAN) investigator took soil samples along riverside where circuit boards were treated with acid and burned openly (Fig. 24.6). Massive amounts of dumping of imported computer waste takes place along the riverways in Guiyu, China.

The Basel Convention on the Control of the Trans-boundary Movement of Hazardous Waste and their Disposal was adopted in 1989 and entered into force in 1992. It was created to prevent the economically motivated dumping of hazardous wastes from richer to poorer countries. The Basel Ban Amendment, adopted in 1995, prohibits all exports of hazardous wastes from parties that are member states of the European Union (EU), the Organization of Economic Co-operation and Development (OECD) and Liechtenstein to all other Parties to the Convention. However, the Ban Amendment has not been enforced uniformly. The United States is the only OECD country not having ratified the original Basel Convention, nor the Basel Ban Amendment. Thus, the export of e-waste as has been witnessed in China, India and Pakistan is in violation of the Basel Convention and the Basel Ban Amendment (UNEP, 2004).

Health concerns regarding the effects of BFRs, which are added to electronics, both as reactive chemicals in the printed circuit boards and in the housing of devices and the plastics, have begun to emerge. One concern is the possible association between BFRs and childhood autism. The Childhood Autism Risk from Genetics and the Environment (CHARGE) is a UC Davis study addressing a wide spectrum of environmental exposures, endogenous

24.6 BAN investigator Clement Lam taking a soil sample along the riverside where circuit boards were treated with acid and burned openly. Massive amounts of dumping of imported computer waste takes place along the riverways. The groundwater in Guiyu is completely contaminated to the point where fresh water is trucked in constantly for drinking purposes. Guiyu, China. December 2001. © 2006 Basel Action Network (BAN).

susceptibility factors, and interplay between these two (Hertz-Picciotto, *et al.*, 2006). As yet there is no conclusive evidence of an association between BFRs and childhood autism (Hertz-Picciotto *et al.*, 2006). According to a new study led by researchers at the University of California, Berkeley, pregnant women with higher blood levels of a common flame retardant show altered thyroid hormone levels, a result that could have implications for fetal health. The study did not find a statistically significant effect of flame retardants polybrominated diphenyl ethers (PBDE) concentrations on thyroxine, a hormone responsible for brain development in children. However, with one exception, all the women in the study showed signs of subclinical hyperthyroidism. The study found that odds of subclinical hyperthyroidism were increased 1.9 times for each tenfold increase in PBDE concentrations (Chevrier *et al.*, 2010).

Although the above studies may not be conclusive, based on animal and human research, BFRs have been linked to behavioral problems, neurodevelopment and attention deficit hyperactivity disorders (ADD/ADHD) in children, depression and schizophrenia in adults, besides abnormal gonadal development, reduced ovarian follicles, reduced sperm count, decreased memory, learning deficits, altered motor behavior, and endocrine disorders like obesity and diabetes (Danon-Schaffer, 2011). Therefore, using the precautionary principle, the European Union has banned some PBDE compounds through the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH, 2007; Messer, 2010).

The USEPA, under the Toxic Substances Control Act (TSCA), regulates various chemicals and their standards and notifies the industries to comply with the standards. The standards for the e-waste recycling industries include antimony, arsenic, barium, beryllium, cadmium, chromium, lead, selenium (Table 24.2). However, in a document published in December 2009, the USEPA expressed concern over the bio-accumulative and toxic nature of flame retardants especially PBDEs and proposed a Significant New Use Rule (SNUR) by the TSCA in 2010 (USEPA, 2009b). PBDEs are yet to

Table 24.2 Toxic characteristics leaching procedure (TCLP) standards regulated by USEPA

Antimony	1 mg/l
Arsenic	5 mg/l
Barium	100 mg/l
Beryllium	0.007 mg/l
Cadmium	1 mg/l
Chromium	5 mg/l
Lead	5 mg/l
Selenium	1 mg/l

Sources: BAN (2009), USEPA (2010)

be regulated by USEPA. Table 24.3 lists the substances banned under the TSCA.

24.2 Local situational analysis of health and safety monitoring practices in WEEE recycling facilities in the US

The objective of the study described and discussed here was to examine the global and local situations and recommend methods to change our behavior through education and action so that we understand the dangers of indiscriminate disposal of electronic devices and learn to become more eco-friendly and responsible, both globally and locally.

The Silicon Valley Toxics Coalition (SVTC) is an organization in the US working to keep the myriad of toxic chemicals found in electronics from damaging the health of workers, communities and the environment. In partnership with national and international non-governmental organizations, SVTC is striving to keep electronics from being exported abroad or sent to US prisons for 'recycling' and is advocating for the reduction and eventual elimination of noxious chemicals in electronics (SVTC, 2011). Since I was analyzing the local situation in and around the Silicon Valley, I took help from SVTC to conduct the local situation analysis and to gain access to an e-waste recycling facility to understand the situation.

Before coming to the US, as the Project Coordinator for the Waste Management component of the Action Plan Support Facility (APSF) project, an EU-supported project in India for policy changes in the 'e-waste recycling' and 'improving contaminated sites' sectors, I organized dialogs and conferences

Table 24.3 Substances banned under TSCA, USEPA

	Year banned
Hexavalent chromium used in water treatement in comfort cooling towers	1990
Asbestos	1989
Dioxin in certain wastes	1980
Polychlorinated biphenyls (PCBs) in response to congressional mandate	1979
Halogenated chlorofluoroalkanes used as aerosol propellants	1978

Source: Richard A, Denison, 'Ten essential elements in TSCA reform', *Environmental Law Reporter* (January 2009); Government Accountability Office, chemical regulation; options exist to improve EPA's ability to assess health risks and manage its chemical review program,' GAO-05-458 (2005).

along with Euroconsult Mott McDonald between formal, informal e-waste recyclers, central and state government officials, electronics manufacturers and several experts from different countries in Europe. Concrete recommendations for encouraging non-formal and semi-formal e-waste recyclers in India to become formalized were made (Mani, 2010). India now has e-waste rules which have become effective from 1 May 2012. The 23 registered recycling facilities and several e-waste collectors and transporters registered with the CPCB will be formalizing their facilities if not already formalized and will be adopting best practices through upgrading of technology, education and training. Although informal recycling has not been eliminated in India, formal e-waste recycling is a growing industry. After dismantling, separated and slightly shredded printed circuit boards are still sent to Belgium, Japan etc. for precious metal recovery. A couple of facilities are also coming up in India for copper and gold recovery from e-waste (Palkhiwala, 2011). To strengthen this trend and make the formal facilities sustainable, I decided to study the health and safety monitoring practices in the US e-waste recycling facilities and adapt them for India. The toolkit I am developing for training would help workers primarily in India.

According to the best practices for needs assessment, situational analysis is an important function of an external agent, which helps the person in making an accurate assessment of a country or region where he/she intends to develop an educational program. 'The situational analysis process is essential in determining the need of individuals and communities' (Forest, 1998). In this study, further best practices of the situational analysis methodology were incorporated such as clear focus, directed purpose, time, location, and needs of clientele. Furthermore, to avoid bias, groups and individuals representative of the target audience were involved.

Applying the best practices of the Situational Analysis Methodology, the following steps were decided and implemented:

- Global situational analysis was conducted by doing a literature review, by having detailed discussions with experts, non-governmental organizations (NGOs) officials of USEPA, and reviewing documents and information from US and international organizations.
- Local situational analysis was conducted by visiting
  - a local e-waste recycling facility in California, discussing with the owner/CEO and other officials at the facility,
  - a local e-waste drop-off cum repair center, interviewing experts,
  - local NGOs; and
  - citizens in the Bay area, California.
- It was also decided that the process of visiting the facility, talking to the officials, experts, NGOs, and citizens would be filmed on video (with their consent), which would be used for both making a video for

raising citizen awareness and for situational analysis purposes. This was executed as planned.

- It was decided that, based on discussions, analyses and needs, a poster on e-waste recycling would be designed which would be used as a discussion point with all the stakeholders, and their perception of their individual and collective roles would be recorded. The poster was drafted and used.
- Furthermore, it was decided that a booklet with specific instructions and illustrations and in the language of the workers, would be developed which would give a clear understanding of the subject as well as motivate the workers to adopt best practices for their health and safety and the environment. This would soon be ready.
- It was decided that exposure monitoring assessment would be conducted through visits and observation, interviews and environmental monitoring within three facilities as permission was obtained through help from the Basel Action Network (BAN). Photography and filming which were also permitted were used for conducting the observational study. This was executed as planned.

The list of persons interviewed and the questions posed to them are given in the Appendix.

The global situational analysis addressed the questions

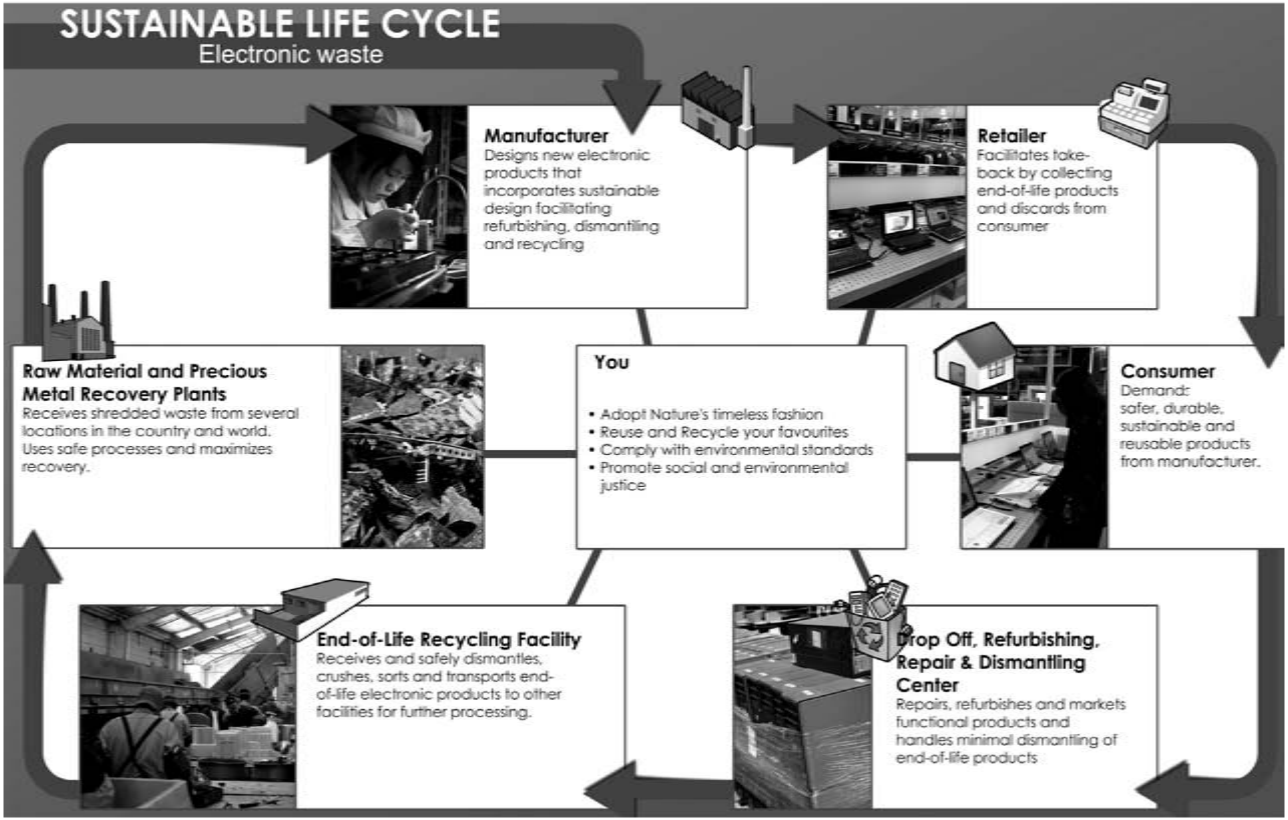
- Is electronic waste recycling a global issue?
- What is the role of the designer/and or manufacturer of consumer products?
- Do consumers have a role?
- Who is a green citizen?
- What is sustainable e-waste recycling?

Through literature review and discussions with persons like Ms Sheila Davis, Executive Director of SVTC, Ms Sarah Westervelt, Director of e-stewards program at BAN, Dr Arlene Blum, Fellow at UC Berkeley and Director of Green Science Policy Institute, officials at USEPA Region 9 and Cal EPA and documents from SVTC, BAN, USEPA and Waste and Resource Management (WaRM) group of Centre for Environment Education (CEE), India, the following answers were recorded:

- Is e-waste recycling a global issue?
  - Yes, it is, because electronic products are used everywhere in the world.
  - Although a lot of the designing happens in the developed countries, most of the manufacturing happens in the emerging economies.

  - A lot of the end-of-life processing happens in both developed and developing countries.
  - E-waste is a multidimensional global issue because (a) many precious metals and other metals, plastics, glass and oil are being recovered from e-waste, (b) e-waste recycling is hazardous, with the potential for toxic chemicals to be released when products are broken open and (c) recovery of resources from e-waste generates jobs in the formal and informal sectors but are plagued by many health and safety and environmental issues.
- What is the role of Designer-Manufacturer?
  - The designer can play an important role in designing to reduce obsolescence and increase durability.
  - Good design helps to replace, dismantle end-of-life products easily, enabling greater reuse and safer recycling.
  - A green manufacturer uses recycled raw material in manufacture of new products, introduces buy-back, practises extended producers' responsibility (EPR) and facilitates recycling.
  - The present scenario is that too much and too many types of electronic devices are in the market and hence all are sent for shredding.
- Do consumers have a role?
  - The consumer is key in setting a trend and creating the demand.
  - Aware consumers can reduce the burden on recycling by shifting priorities, showing preference for durable and safe products and participating in buy-back and drop-off schemes.
- Who is a green citizen?
  - One who uses electronic products responsibly.
  - One who stores them safely after use.
  - One who (a) makes an effort to give it to someone who can use it for some more time (b) then deposits it at location like a drop-off cum repair center, where they would repair and reuse or (c) send it to a facility to be dismantled and recycled.

To answer the question 'what is sustainable e-waste recycling' a draft poster was used as a discussion point for getting the perspective of the stakeholders on individual and collective responsibilities. A full-fledged trial could not be conducted using the poster since it required a lot of work in terms of putting better illustrations and reducing the text. This has been done since. However, the initial responses were to suggest improvements in the poster so that it could try to represent the intercontinental nature of the process of electronic products design, manufacture and recycling. Many of the non-profit organizations such as SVTC, BAN and greencitizen along with e-waste recyclers and other NGOs suggested that the poster should be addressed to the general consumer as well as workers, to pictorially represent the global



24.7 A draft poster: Sustainable e-waste recycling poster which resulted from interaction with the stakeholders.

nature of the life cycle of electronics from conception of new products to design, manufacture, assembly, marketing, distribution, use, reuse, refurbish and recycle. The shortage and recovery of precious metals need to be shown so that people understand why safer electronic waste reprocessing is important. I also interviewed Mr Jagdeesh Belani from an organization in Silicon Valley, California, dealing with semi-conductor packaging to learn about what materials are required, whether there is any shortage of materials, how important recycling is for meeting this demand and the cost of doing so. The poster is now completed (see Figure 24.7).

24.3 What are the issues for the WEEE recyclers?

An interview with the CEO/President of ECS Refining, an e-waste recycling facility at Santa Clara, and another at Stockton, both in California was conducted in his office which was simultaneously recorded on video. As a recycler, the President of ECS Refining, Mr James Taggart felt that his company has to face many challenges concerning the volume, a wide variety of devices and materials, toxics especially in batteries, like nickel, cadmium and lithium, data security in hard drives, profitability, health and safety of workers and environmental regulations of e-waste recycling. He felt that the e-steward program of which he and others are founders along with the BAN is a good program that helps to motivate recyclers to recycle e-waste in accordance with the rules and do so domestically within the US.

24.4 What do recycling workers expect from this job?

Although I did not interview any workers, since I was not encouraged to do so, this question was posed to the Operations Manager at ECS Refining who listed the needs of workers to be good working conditions, health and safety and a good compensation.

24.5 What were the observations at the ECS Refining WEEE treatment site?

There are several e-waste recycling companies in California which are medium to large and which receive tons of e-waste from various sources including consumers, collection facilities and large manufacturers and retailers. One of the facilities in California is a company ECS Refining, which receives nearly 1.5 to 2 million lbs (i.e. nearly 680–907 metric tons) of e-waste per month (Fig. 24.8). It is in the process of receiving e-steward certification and claims to be compliant to USEPA and Occupational Safety and Health Administration (OSHA) of the US Department of Labor OSHA standards.

The workers dismantle e-waste both manually and using shredders in northern California and they send the dismantled and shredded material like plastics, metal, shredded CRT tubes, mercury bulbs, batteries, oil, capacitors and others to either their own facilities in Texas, Arizona, Georgia or to other firms in Canada, specialists in extracting the precious metals, for processing. The leaded glass from CRTs are, however shipped to a company called M/S Videocon Industries (Videocon Narmada Glass Division) in Bharuch, Gujarat, India via Thomson Displays Mexicana, Mexico for recycling. Alternatives

(a)

(b)

24.8 Photo-documentation of visit to ECS Refining and observations: (a) CRT Monitors Recycling warehouse at ECS Refining (Source: SVTC, November 2010); (b) Worker holding silver ingot recovered from photographic waste, Santa Clara, CA, USA (Source: author, March 2011); (c) worker at ECS checking for wires and batteries before shredding at ECS Refining, Santa Clara, CA, USA; (d) miscellaneous electronic items on conveyor (Source: author, March 2011); (e) materials going into the shredder; (f) materials coming out of the shredder – metals and plastics are still mixed after shredding; ECS Refining, Santa Clara, CA, USA (Source: author, March 2011); (g) Dismantling electronic equipment at ECS Refining, Santa Clara, CA, USA – a safer and eco-friendly option (Source: author, March 2011).

(c)

(d)

(e)

24.8 Continued

(f)

(g)

24.8 Continued

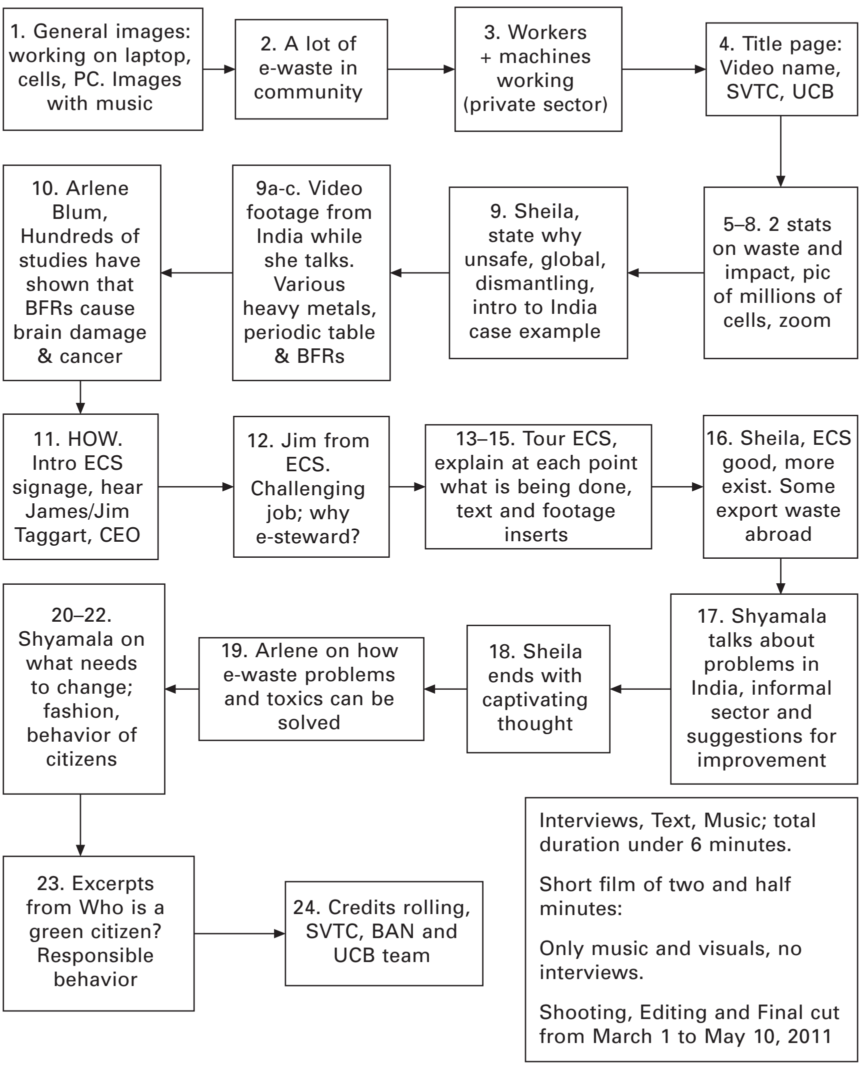
to this are now being examined by ECS after appealing to them that this would cause excessive lead pollution in the area.

In the process of dismantling, ECS uses shredders, manual breaking equipment like hammers and removal and extraction special equipment. Shredders and manual breaking stations are the areas where there will be dust and aerosols with lead and flame retardants. After conducting air monitoring for PBDEs at ECS Santa Clara, ECS Stockton and Onsite Industry at Stockton, I was able to confirm that dust and BFRs were highest near the manual dismantling sites and shredders (Mani and Hammond, 2012).

What are the consequences of hammering and shredding cathode ray tubes (CRTs) at site?

- Shredding of hazardous parts such as cathode ray tubes (CRTs) having lead, cesium and phosphors causes dispersal of lead and cesium in ambient air.
- Mechanical shredding of CRT causes generation of fine dust which spreads in the ambient environment and necessitates use of respirators.

SVTC and BAN throughout the US, Canada and some European countries are trying to establish better standards for e-waste recycling by creating awareness, pressing for regulations and promoting compliance through advocacy and incentivization (e.g. e-steward certification) (BAN, 2011). The author (s.m.) is at present volunteering with BAN and the University of California, Berkeley (UCB) to conduct a pilot project in three e-waste facilities in the US to establish a method for capturing and analyzing PBDEs in dust and vapor phases so that guidelines for the method can be used in the e-steward certification process in the US by BAN and also adopted by regulatory bodies in India for recommending standards for Indian facilities. Figure 24.9 shows a story board of an e-waste recycling film which was produced and published by UCB in May 2011.



24.9 A story board of an e-waste recycling film.

24.6 Discussion and implications

E-waste recycling technology needs to improve globally and this will be possible only if better designs are applied and manufacturers make the devices so that they can be easily taken apart. Newer technologies need to be introduced which are less hazardous and toxic, while methods used to dismantle, remove material inside are less damaging to health and the environment.

The Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry (ATSDR), CDC, USA, September 2004 says that

> PBDEs can occur during the production of commercial PBDE mixtures and of PBDE-containing plastic products. Workers involved in recycling plastic products, or who repair computers in confined workspaces can also be exposed to PBDEs. If you are exposed to PBDEs while at work, you may carry them home on your clothes or body. Your occupational health and safety officer at work can tell you whether the products you work with contain PBDEs and whether those are likely to be carried home. If this is the case, you should shower and change clothing before leaving work. Your work clothes should be kept separate from other clothes and laundered separately. (ATSDR, 2004)

Most people in e-waste recycling facilities do strictly adhere to this recommendation of the ATSDR but some may not because of lack of awareness. Education helps us understand the importance of doing a task without compromising safety or productivity. Training helps us achieve it.

24.7 Recommendations to ECS Refining and similar facilities elsewhere in the US and India for tackling WEEE recycling issues

- Develop equipment which reduces manual hammering of the housing of computers.
- Do not shatter CRTs in shredders, which permanently mixes leaded and non-leaded parts of the CRT or export leaded glass to developing countries.
- Use vacuum chambers for cutting CRTs and removing the dust directly into dry dust scrubbers, as many formal recyclers are beginning to do in US and India.
- Do not allow office personnel or workers without respirators to walk in and out of areas with high levels of dust, heavy metal and toxic vapor exposures.

- Improve workers training for putting on and removing respirators and PPE according to Centers for Disease Control and Prevention (CDC)'s National Institute of Occupational Safety and Health (NIOSH) standards

The public health significance of this project is that e-waste recycling is an activity that cannot be wished away or hidden under the carpet. It has huge health, environmental and economic significance. Hence, whether in developing or developed countries, we have to educate the stakeholders and only then can we protect the workers, consumers and the communities.

As stated in the introduction, it is estimated that nearly 200 000 workers in the informal sector and about 20 000 in the formal e-waste recycling sector in India are exposed daily to heavy metals, solvents and BFRs while recycling e-waste. Since only 10–12% of the workers are in the formal sector, they have access to PPE but not the others. However, since technologies adopted in India are based on separation of hazardous components followed by baling, dismantling and finally shredding, leading to recovery of reusable parts, plastics, metals and printed circuit boards for recovery of precious metals, the industry is sustainable and supports the promotion of PPEs and training for workers as has been demonstrated by some of the early formal facilities in India – E-Parisara, Trishiraya, Ecoreco and others.

The educational toolkit comprising a film, a poster and a booklet (translated in local languages) on safer electronic waste recycling or e-mining, as I would like to call it, will help workers in formal and informal sectors adopt best practices and safeguard their health and the environment. The educational toolkit would also be useful for training workers at e-waste recycling facilities such as the ECS in the US. There are over 200 facilities in the US and at least 10 000 workers who are engaged in e-waste recycling in addition to at least another 10 000 workers in industries connected with further processing. The poster would help all stakeholders to understand their individual and collective responsibilities. While the video film 'Who is a green citizen?' is targeted at an average citizen and the consumer, the video 'Eternal waste' is targeted to educate consumers, manufacturers, recyclers and decision makers. The booklet in the workers' languages, English, Spanish, Hindi or any other language is targeted at the industry. The efficacy of the toolkit can be known only after it is finalized, tested and evaluated.

24.8 Conclusions

E-waste recycling is at present being implemented worldwide as a 'necessary evil'. However, with participation from the industry, especially the designers, manufacturers and those who market and sell the products, consumers and the regulators, it is possible to turn it into a safer and a more lucrative industry for all. This would not only increase recycling which would help us recover precious resources but also safeguard the environment and health of the workers. Thus 'e-mining', meaning recovery of depleted resources through intelligent recycling of electronic waste, can be used for tackling an intransigent problem in a sustainable manner.

24.9 Sources of further information and advice

For further information on SVTC, visit www.svtc.org and for information on BAN, visit www.BAN.org

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24.12 Appendix: interview question list

Sheila Davis, Executive Director, Silicon Valley Toxics Coalition (SVTC), CA, USA

1. Your position, name.
2. What is SVTC's aim regarding electronic waste?
3. Can you define e-waste and e-mining?
4. Why is e-waste/e-mining unsafe?
5. What is the problem in the process of dismantling? (if didn't already state)
6. Please tell us the situation in Silicon Valley and the US in general regarding e-waste/recycling.
7. What is the problem in the developing countries?
8. If you can give one message to NGOs and advocates in India and the US, what would it be?
9. Do you have anything you would like to add that we didn't touch upon?

Shyamala Mani, Programme Director, Waste and Resource Management, Centre for Environment Education, New Delhi, India

1. Your position, name.
2. Please describe the situation in India regarding electronic waste.
3. Why do you think this is a problem?

4. How do you think India can solve this problem? (e-mining applicable to India)
5. What is the future challenge in India?
6. Do you have anything you would like to add that we didn't touch upon?

James Taggart, CEO, ECS Refining, CA, USA

1. Your position, name
2. Can you please give a brief description of ECS, its history and mission?
3. What is the difference between ECS and others?
4. Please tell us ECS's challenge and accomplishment in your company's history.
5. What does an e-steward certification mean for a company?
6. Why did ECS decide to get an e-steward certification?
7. What is the future challenge at ECS and how do you see ECS overcoming it?
8. Do you have anything you would like to add that we didn't touch upon?

Arlene Blum, Executive Director, Green Science Policy Institute, CA, USA

1. Your position, name.
2. What are you currently researching or focusing on?
3. What is your concern regarding electronic waste?
4. Currently are there standards for PBDEs or other flame retardants in electronic waste recycling? If yes, what are they? If no, why do you think there are no standards for flame retardants in electronic waste recycling?
5. How do you think flame retardants from e-waste recycling harm us?
6. What should be done about the problem?
7. What else do you think can be done about the electronic waste problem?
8. Do you have anything you would like to add that we didn't touch upon?

Joshua Rego, Manager, Greencitizen (a non-profit organization collecting used electronic products for reuse and recycling), CA, USA

1. Your position, name
2. What is the role of Greencitizen in e-waste recycling?
3. What material do you accept and what you don't? Reasons?
4. What do you do when you receive material which are in working condition?

5. How much does a citizen have to pay for depositing electronic devices/ e-waste at your center? Which are the ones which are free?
6. What do you do with devices that don't work or cannot be repaired?
7. Who is a green citizen?

Jayant Rao, Mountainview, CA, USA

1. Your name
2. What electronic devices do you use every day?
3. What happens to older electronic devices once you buy a newer model or don't need what you had?
4. How do you store these devices? Where?
5. Are you aware of what you need to do with electronic devices once you have finished using them?
6. Are you aware that electronic devices have toxic components?
7. Do you think it is important to find the right way to deposit them at a safe place for reuse or recycling?
8. Who is a green citizen?

25
WEEE management in Japan

F. YOSHIDA, Hokkaido University, Japan and
H. YOSHIDA, Sapporo University, Japan

Abstract: This review considers how Japan manages the recycling of consumer appliances, PCs and cellular phones through an overview of their current collection and treatment systems for WEEE (waste electronic and electrical equipment). Costs, performance and quality of recycling are considered, as well as the role of each of the individual actors in the system. The problems occasioned by the practice of cross-border recycling are also discussed. On the basis of its findings this chapter offers recommendations for the improvement of these systems.

Key words: WEEE, collection, treatment, generation, recycling.

25.1 Introduction

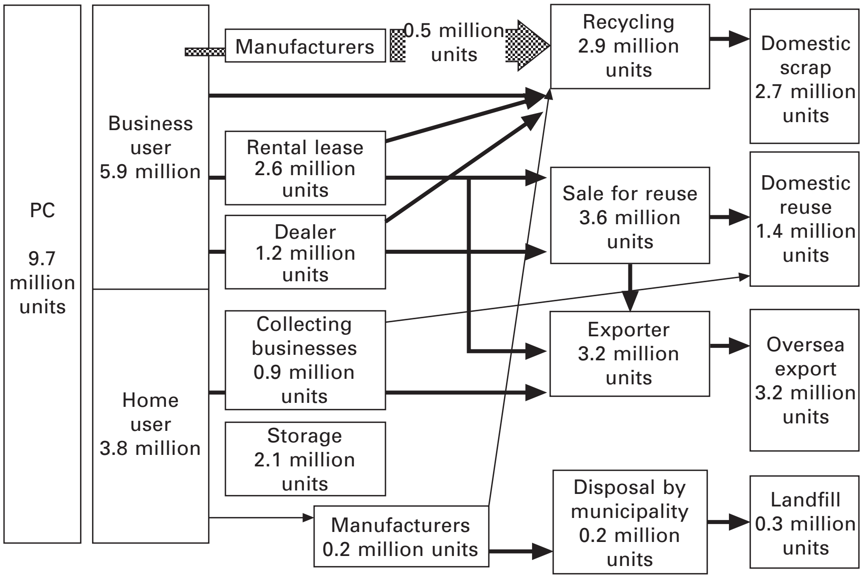
The acronym WEEE (waste electronic and electrical equipment) signifies a relatively new category of waste type (waste electrical and electronic equipment), a category that includes precious metals as well as such toxic substances as lead (Pb) and polybrominated biphenyls (PBBs), and one whose components require separate sorting and special treatment for waste management. The cost of processing discarded WEEE is probably the motivating factor in shipping it to countries where the labour is cheaper and health and safety regulations are not stringently enforced. If the treatment process is not supervised under proper safety conditions, it may ultimately cause serious air pollution, contamination of the soil and groundwater pollution, as when, for instance, strong acids are used for metal extraction and burn used wire (BAN/SVTC 2002; Yoshida and Yoshida, 2008; Zheng *et al.*, 2008). To tackle such problems as these, the OECD (Organization for Economic Cooperation and Development) has proposed that countries should adopt the EPR (extended producers responsibility) principle, and the EU, for one, has implemented the WEEE and RoHS (Restriction of Hazardous Substances) Directives to collect WEEE separately from other municipal solid waste (MSW) and to manage it with the participation of producers (financially and/or physically). Between 2001 and 2005, countries such as Japan and the member countries of the EU, introduced the EPR principle into their WEEE recycling systems. The purpose of this chapter is to draw lessons from the ways in which developed countries, in this case Japan, are managing to deal with WEEE. Japan launched its own WEEE recycling system in 2001, and 5 years later the Japanese government conducted a review of how the system was working; it released its final report, based on documents submitted by Japan's Home Appliance Recycling System Review Council, in February, 2008.

The present authors were able to conduct a study of Japan as developed countries with respect to the achievements and challenges of their WEEE recycling systems: we focused on three dimensions: (1) material flow analysis, (2) regime-actor analysis, and (3) economic analysis, which the study of circular economy requires (see Yoshida, 2005). Previous studies of WEEE have focused in the main upon aspects of the material flow (Jofre and Morioka, 2005; Tasaki, 2006; Terazono *et al*., 2006) or on an analysis of the economic features (Hosoda, 2007). Here, we attempt to analyse the WEEE recycling system through a focus on a combination of four interrelated issues: (1) the need to improve the collection rate of WEEE, (2) questions of the cost and the quality of recycling, (3) the problems of cross-border recycling, and (4) economic aspects of urban mining related to WEEE.

This review looks at, in order: (1) the systemic character of WEEE recycling in Japan, (2) the collection rate, (3) the cost and the quality of the recycling, (4) the problems raised by the export of WEEE, and (5) the urban mining agenda.

25.2 Japan's home appliance recycling system: purpose and background

Japan's consumer equipment recycling system requires that consumers pay a recycling fee when discarding any one of four equipment types (TVs, air conditioners, refrigerators and washing machines), that retailers take them back, and that producers recycle them. Two problems were the basis for the successful creation of Japan's home appliance recycling system: the shortage of landfill space and the need for the recovery and use of resources. A characteristic of the system is that Japanese municipalities do not, as is the case in some other countries, themselves perform the collection and processing operations for recycling. The recycling fee and fund is managed by the Association for Electric Home Appliances (AEHA, 2009), while collection and processing are carried out under a producer partnership system that is divided between Group A (Panasonic, Toshiba and other) and Group B (Mitsubishi, Hitachi and other). Although the government sets the recycling rate for the four items that are to be collected, PCs, on the other hand, are supposed to be collected and recycled under the Law for the Promotion of the Utilization of Recycled Resources. Unfortunately, the collection rate achieved by the manufactures is not even 10% of the PCs that are presumed to be discarded, whereas many of these PCs are shipped abroad (Fig. 25.1).



25.1 Japan main material flow of used PCs (2006) (Source: JEITA, 2008, Table 2-6).

In the case of cellular phones, the take-back rate in 2009 was estimated at about 22% (6.92 million per 31 million).

By contrast, the EU regulations (1) cover a broad range of products, (2) assign responsibility and costs to producers, (3) establish collection targets and recycling rates, and (4) limit the use of hazardous substances. Their purpose is to build a system that, by these means, recovers WEEE separately rather than disposing of it as municipal solid waste (OKOPOL/IIIEE/RPA, 2007). The municipality is an important actor or stakeholder in the WEEE recycling system and the recovery of resources is not the main target in the EU.

25.3 The collection rate

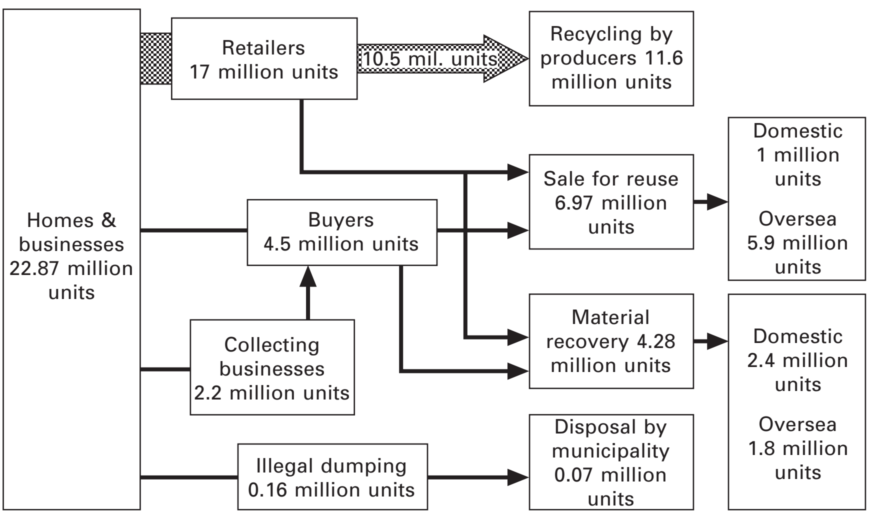
What has Japan achieved so far? Previously, only valuable metals were recovered from discarded household appliances, and the great majority was then land-filled; now, under the new system, introduced in 2001, about half of all discarded appliances are treated after collection. Newest data in 2009 are:

- Amounts collected and treated: 17.5 million units treatment per year, 0.64 million tonnes treatment per year, about 5.1 kg per capita of the four items. The numbers of collected units started in 2001 increased from 8.3 million units and 0.32 million tonnes to 17.5 million units and 0.64

million tonnes in 2009, in particular collected CRT-TV is increasing because of the obsolescence of CRT-TV caused by the end of the old analogue broadcasting system.

- Material recovered: 0.54 million tonnes per year; this does not include payment to recyclers for accepting waste.
- Effects on the environment: reduction of landfill (extended for the remaining years from 12.8 year in 2001 to 14.8 year in 2006), recovery and treatment of chlorofluorocarbons (CFCs) (about 4287 tons in 2009), management of hazardous substances.
- Design for the environment: long-life design, design for easy disassembly and for the recovery of plastics (Aizawa *et al.*, 2008; Joint Meeting, 2008a).

Reviews of the Japanese systems have found that increasing the collection rate is a vital requirement. In Japan, 17.2 million of an estimated 22 million units are taken back by retail stores, of which, 11 million units are recycled by their producers, while the rest disappear in an 'invisible flow'; and while the primary collection rate at retail stores is 75%, the final processing rate drops to 50%. The main reason is that of the 17.2 million units taken back by retailers, as many as 6.65 million discarded appliances enter channels outside the system (according to the new estimation in 2008, 13 million of 18 million discarded units are taken back by retailers, of which 12 million are recycled by their producers; Joint Meeting, 2009). No recycling fees have been paid for these appliances, and they are not taken to the processing facilities of producers or other parties (see Fig. 25.2). Furthermore, because Japan's



25.2 Japan main material flow of home appliances (2005) (Source: Joint Meeting, 2008a).

WEEE recycling system is built around recycling, there is no place in its policy for reuse. Because another underlying factor is the high recycling fee that consumers must pay when turning in an appliance, the authorities, fearful that these conditions would lead to illegal dumping, have considered switching to a system for advance fee payment (AFP). According to a recent survey carried out during April and June 2008 (Joint Meeting, 2008b) of retailers' take-back of the four used items (home appliances) comprising 1.9 million units (covering about one-third of the four items generated domestically), only 1% were taken back without payment or with payment by the retailers. Items taken back free of charge go abroad, whereas items that are paid for enter the domestic used market. Although this means that the route from the retailers to points of sale for domestic reuse is decreasing dramatically, Consequently, the route taken by the buyers seems to play a major role in determining reuse or material recovery. Also the amount of collected CRT-TV is increasing but, because there are no CRT-TV production facilities in Japan, Japan is exporting collected CRT-TV to Malaysia and Korea. However there is not so much need for recycled cullet in the world.

As for the Japanese system, more positive options that would serve to raise the collection rate are: (1) free take-back when a product is discarded, (2) the use by municipalities of the agreed collection channels, and, (3) paying for the collection. By combining (1) and (2), Korea has achieved a higher collection rate than Japan, as well as including a wider range of categories among the collected items.

25.4 Cost and recycling quality

Although some have claimed that the high cost of Japan's recycling process can in part be explained by the recycling fees customers must pay when turning in an old piece of equipment, the producers, who are responsible for WEEE processing, seek to rebut this criticism with the counterclaim that the quality of recycling is also high. Nevertheless, the problems caused by the high cost of recycling could lead to recycling outside the formal scheme and thus encourage the export of WEEE abroad. We must therefore continue to ask the question, is Japan's recycling cost truly high, and, if so, why? Let us examine this issue through a comparison with the EU.

Although the direct costs incurred in recycling household appliances are not publicly released, Japan's Recycling System Review Council has issued a report, 'On the Transparency of Recycling Fees' (Joint Meeting, 2007; Table 25.1), and each year the AEHA publishes the recycling amounts collected and the number of units recycled, whereas information on WEEE in the EU comes from estimates by type of product based on cost data collected by the WEEE Forum and other bodies (UNU, 2007; Table 25.2). Calculations based on this information show that in 2005 Japan's costs were 20–60% higher

Table 25.1 Recycling cost of television, refrigerator and air conditioner in Japan

	TV	Refrigerator	Air conditioner
Group A per unit	3128JPY	5885JPY	3535JPY
Group B per unit	3239JPY	6382JPY	3878JPY
Reported treatment units	3852000	2807000	1990000
Reported treatment weights	108000 tonnes	162000 tonnes	86000 tonnes
Units per ton	36	17	23

Group A and Group B in 2005 JPY per 1 unit.
Source: Joint Meeting (2007).

Table 25.2 Total cost per tonne of recycling in 2005 for Japan and the European Union (1 euro = 137 JPY)

	TV (1t = 36 units)	Refrigerator (1t = 17 units)	Air conditioner (1t = 23 units)
Japan			
Group A	112608 JPY (1024 USD)	100045 JPY (909 USD)	81305 JPY (744 USD)
Group B	116604 JPY (1059 USD)	108494 JPY (1067 USD)	89194 JPY (748 USD)
EU			
	TV	Refrigerator and air conditioner	
EU average	72336 JPY (658 USD)	75409 JPY (685 USD)	
Maximum	85077 JPY (773 USD)	111107 JPY (1010 USD)	

Sources: AEHA (2009), UNU (2007).

than those in the EU (see Table 25.2). In the context of Japan's Household Appliance Recycling Law, one therefore cannot overlook the fact that, at the least, nearly 20 billion JPY (20 million USD) in tax money has been invested in this task.

We offer the following reasons to explain why Japan's recycling costs are higher than those of the EU. In the first place, the system's very structure makes it costly. Because consumers are required to pay recycling fees when they turn in an old appliance, management costs, which are processed through a manifest system, are levied to ensure the traceability of each item. Although the collection management cost in the EU is about 40% of total costs, in Japan, the collection management cost is nearly 50%.

One of the EU countries, the Netherlands, has done well by charging visible fees to provide the initial investments for setting up the recycling infrastructure, such as facilities for recovery and processing, whereas, in Japan, the two Groups, A and B (see above), which are partnerships entered into by the manufacturers, conduct collection management and processing independently of each other, and the redundant investment prevents economies of scale. A further reason is that the heavy involvement of Japanese producers in the task of recycling makes capital investment that much higher. Furthermore, just at a time when the EU is mechanizing its operations to lower costs, Japan is still relying on manual disassembly as well as mechanization to raise the recycling rate. Whereas the EU limits manual disassembly mainly to the removal of hazardous items, Japan has made considerable investments in actually expanding manual disassembly processes to raise the plastic recycling rate, and in the development of technologies and facilities for plastic sorting. Yet, when we examined how recovered plastic is used by Japanese producers, we found that its use in new products is restricted, because even if there is no problem with quality, it would be likely to hamper product sales. Consequently, recovered plastic is only used when, for example, it is mixed, in quantities of about 20%, with virgin materials, and only in parts that are not externally obvious, or for those internal parts of refrigerators that do not come into contact with food. In the EU, on the other hand, even plastic that is incinerated is counted toward the recovery rate.

A third issue concerns the matter of recycling quality and cost. Because Japan's regulations guarantee the recycling charge, manufacturers ask for higher recycling rates without needing to indulge in price competition, thus making the actual rate higher than that legally required. The legal and actual rates are, respectively, 70 and 88% for air conditioners, 55 and 86% for TVs, 60 and 75% for refrigerators, and 65 and 85% for washing machines (2009). Some observers believe that because of the heavy involvement of producers in processing, Japan is demonstrating its strong design for environment (DfE) feedback, and it is true that there has been a certain degree of progress in this area, particularly in terms of ease of dismantlement and the aforementioned recovery and in the use of plastic; but design has a lower priority than the need for energy-saving performance and the avoidance of hazardous substances, and this is a drawback.

In the EU, on the other hand, producers are not directly concerned with the business of recycling itself. Instead, individual producers or members of the joint scheme enter into individual contracts with specialized recycling companies. Although, under this arrangement, the principle of cost competition works reasonably well, the feedback to DfE and the like is rather weak. More meaningful in terms of DfE are such different schemes as the hazardous substance regulations (RoHS) and the energy-using product (EuP) directives. Yet, although the regulations have led to an increase in the amounts of collected waste and processors have benefited from the larger scale, producers have been inclined to hold down processing costs because high-quality discarded equipment is hard to find, and some experts observe that the current recycling quality has actually tended to be lower than before the directive was implemented (Svensson *et al.*, 2005).

In response to this weakness, Sony, HP and Elecrolux set up the European Recycling Platform, and certainly, in the case of office machinery, individual producer responsibility (IPR) can be feasible and can contribute to the DfE achieved by these companies; in the case of many consumer appliances, however, this model is still not capable of working well. Even so, producers are checking and controlling the processors' management procedures more rigorously and are working within the terms of the environmental regulations more than in the past (Kheitriwal *et al.*, 2009). In view of all this, we need to reconsider the cost of recycling and its possible benefits, in terms of both the environment and the economy. Now, in response to a report submitted by Japan's Home Appliance Recycling System Review Council, and against the backdrop of recent steep price increases for natural resources, consumer appliance/electronics makers are leaning toward the lowering of recycling fees, down in the case of air conditioners, for example, as much as 17%.

25.5 Export problems

Both Japan and the EU have serious problems with the dispatch of WEEE to other countries. In Japan, newly issued trade statistics reveals that used CRT-TV (HS code: 8528.72–990) exported in 2009 accounted for 2 290 717 units, to the value of 1 888 333 000JPY, at an average price of 824JPY per unit. The chief importing countries are Vietnam (794 201 units), Philippines (481 698 units), China (22 285 units) and Indonesia (91 245 units). As about 9 213 000 units are formally recycled in 2009, we reckon that, compared to the amounts recycled domestically, about 25% are exported (Table 25.3).

In the case of used PCs, research carried out in 2008 by JEITA (Japan Electronics and Information Technology Industries Association) estimated that the number of discarded PCs in 2006 had been about 9.08 million units, of which 0.68 million units were recycled by manufacturer recycling facilities, 0.14 million units by municipalities, 2.60 million units by independent waste management companies, while 1.34 million units were sold domestically, 1.24 million units were exported for reuse and 1.85 units were exported for scrap (see Fig. 25.1). This means that the formal collecting system (manufacturers and municipalities) covers only about 10% of used PCs.

Table 25.3 Export of used color television from Japan in 2009

Country (units)	Value (1000JPY)	Average unit value (JPY)
Vietnam 794 201	566 047	712
Philippines 481 698	525 043	1089
Indonesia 91 245	82 188	900
China 22 285	12 928	580

Source: Japan Trade Statistics.

Economic principles dictate that as long as discarded PCs have market value and the domestic used PC market is saturated, and even if reuse is encouraged and a domestic take-back system is created, it will naturally follow that discarded PCs will be exported rather than enter the domestic recycling/reuse channels, whereas, at the same time and because of wide income differences between countries and areas, PCs will be widely subjected to cascade use.

In Thailand, for example, where used PCs from the country's own domestic market do not satisfy the demand among the middle- and low-income class buyers, the supply of imported PCs are subjected to reuse and are rebuilt. The chief concern, however, centres on what happens to those PCs after the importing countries have, in their turn, discarded them. If ICT for environment is to be promulgated, then, quite apart from taking care of the WEEE, the business style for the original mass production and mass sales of electrical goods has to be changed.

In Japan, there is no effective regulation on companies that lease equipment, despite the large amount of WEEE that they generate, and this oversight, so it is supposed, contributes largely to the drain of WEEE overseas. Additionally, Japanese recycling plants sometimes export compressors and other hard-to-process parts as scrap.

Although the EU has approved the Basel Convention amendments, which virtually ban exports of WEEE, Japan has yet to follow suit. Unfortunately, the reality of international resource cycling practices, which lack any specific controls, entails that the industrialized countries cannot process their hazardous wastes at home, and so, by making the developing countries take the responsibility for dealing with it, they are themselves responsible for damaging human health as well as the environment (BAN/SVTC, 2002). Because the EU Review Report recommends banning illegal shipments of exported waste, it obviously needs to strengthen its export controls on scrapped consumer equipment when these violate the Basel Convention: at the same time, when a developing country such as China, which has environmental problems but also a great demand for resources and a need for imported goods, has installed building facilities for imported scrap disassembly and appropriate processing under the supervision of customs and environmental protection agencies, it becomes necessary to consider the creation of institutions under whose umbrella producers are able to engage in active cooperation and involvement in construction and operation.

Although the technologies developed under the recycling systems of Japan and the EU need to be transferred to developing countries, the high-cost constitution of Japan's recycling technologies will remain a stumbling block, and the appropriate domestic treatment of WEEE will be the duty of the developed countries (Yoshida and Yoshida, 2008).

25.6 Economic analysis for urban mining

According to the estimation carried out by the National Institute of Material Science (released on 11 January 2008), of the quantity of metals that had accumulated in Japan to be recycled (in short, the content of the man-made 'urban mining'), gold amounts to about 6800 tonnes (16% of world's reserves), silver comes to 60 000 tonnes (22%), indium (16%), tin (11%) and tantalum (10%). Although many of these metals exceed more than 10% of the world reserves, they have not yet been collected. Instead, they are stored and some of them are shipped to other countries. The research conducted by the National Institute of Material Science has not confirmed the location of all the collections of recyclable material that have been designated as constituting 'urban mining', and although the data has been estimated on the basis of governmental trade or production statistics, it is still not clear whether it is the fate of the metals to be scattered in the air, oxidized, or buried in the waste landfill. Nor is the grade of urban mining at all clear. Consequently, it remains necessary to clarify the form in which they at present exist (Halada *et al.*, 2009).

As to the electronics products, the generated amount of WEEE is estimated to be 2 500 000 tonnes/year (19.4 kg per capita). Among them, the smaller items of electrical equipment amount to around 500 000 tonnes/year, while the quantity of metals included in such small WEEE is estimated to be in the order of some 1000 tonnes to 10 000 tonnes as to base metals like copper and lead, and around 10 tonnes for precious metal in a scattered condition (Shiratori and Nakamura 2007).

The main material of the non-ferrous metal industry consists of industrial by-products, termed industrial waste, and this is enough to keep it in operation and the quality homogeneous. For example, the quantity of materials input in the TSL (top submerged lance) furnace at DOWA's Kosaka refinery, opened in 2007, is sufficient to keep the furnace operational and the quality of the input stable. The main materials are waste-water sludge, electronics scrap, metal plate waste solution, used mercury oxide cells, lead frames, control boards, PCs and connector boards. Throughout Japan, the waste electronics material constitutes only 4% of the recycling material of the non-ferrous metal industry (Kozan, 2009).

We thus see that the non-ferrous metal industries are carrying on their business by unifying the collection of metal and the treatment of waste, and that, within the total amount of WEEE that constitutes the mass of 'urban mining', the scrap that is to be mined, the percentage by weight of mobile phones is very small. According to the report published by the Ministry of Public Management, Home Affairs, Post and Telecommunications (2009), the metal price recoverable from one mobile phone is about 100JPY (in case of gold, 0.03 g ¥ 2920JPY/g = 87.6JPY). The recycling cost is therefore reduced, and the real price of one phone is some 1–10JPY. On the basis of this estimation, we can predict that if mobile phones were to be collected from each of the 120 million people living in Japan, the amount of gold they contained would be worth about 10 billion JPY. (For comparison, we note that in 2008 DOWA's annual sales came to 350 billion JPY.)

The reason why we focus attention on mobiles and PCs as types of 'urban mining', however, is the expanding and high speed of technological innovation of high-tech products on the one hand and supply restrictions on the other. In order to obtain a better picture of the collection and recycling of rare metals, the Japanese Ministry of Environment and the Ministry of Economy and Trade and Industry set up a research committee, and since 2009 it has been carrying out a model business in Japan. (DOWA and three other entities are cooperating in the project.) The model business has already published its first results: the mobile phone has had the highest collection rate, about 14% (collection units per potential collection units), while the average collection rate of a total of 9 items (game machines, DVDs, digital cameras, etc.) has reached 10.9%. Although the estimated total of the 9 items (84 million units per year) will contain 353 tonnes of rare metals per year, this figure accounts for only 0.2% of the total quantity of imported rare metals. Since the recovery rate at the smelter is about 60%, this means that if the collection of rare metal, combined with the recovery of the base metal and precious metal, is only of the order of 30%, then the B/C (benefit per cost) ratio will become 1. This means that the economic conditions of the rare metal collection business are very severe, and that a high collection rate of over 30% and the development of a more sophisticated extraction technology are therefore indispensable.

When we consider the collection cost per unit, we may conclude that the methods of collection, recovery and recycling of WEEE and end-of-life vehicle (ELV) offer a possible solution, for as well as an effective system of collection of WEEE and ELV, the research and development technology for dismantling and sorting plays a role of critical importance. For example, Shin-etsu Chemicals, one of the Japanese producers of the Nd-Fe-B permanent magnet, has developed recovery and recycling technology for extracting neodymium and dysprosium from motors in the compressors of used air conditioners. It is estimated that if 70% of the air conditioners and washing machines in use in Japan are recycled, the amounts of rare metal magnet can, by 2030, amount to 410 tonnes. But it is necessary to further develop the dismantling and recycling technology (Arai, 2010).

The Japanese government is planning to set up the recycling system for small home appliances to recover and recycle rare metals in 2012. Targets may be mobile phone, game machine, digital camera, video camera, DVD player and electric wave range etc. Municipalities have to collect them and also retailers have to set collection box. After collection and special treatment of private information, recyclers recover rare metals from them. However, problems of who has to pay and each actor's role are not yet decided.

On the basis of these analyses, we can summarize the economic conditions of urban mining under three headings. The first concerns the *system of collection*. WEEE is both diffusely scattered and movable, despite its potential accumulation, and the creation of a collection system for WEEE is an important condition for enabling the items to be recycled. The four items (TV, washing machines, refrigerator, air conditioner) are regulated and collected by Japan's Home Appliance Recycling Law, while the Law for the Promoting Effective Use of Resources permits PCs to be taken back without charge. Nevertheless, the collection rate is not sufficiently high since used PCs have their own market value.

At the same time, municipalities have collected and disposed small electronics appliances as municipal solid waste, despite the difficulty of treating them, and this creates problems for both proper treatment of waste and resource usage. If the range of the collected objects regulated by Japan's Home Appliance Recycling Law is extended to include the smaller items of WEEE, consumers will have to pay the recycling cost at the time of disposal, which induces the storage or illegal dumping of such small pieces of WEEE. Yet without role sharing and cost bearing, the project for the collection of small items WEEE that is now being carried out in Japan, an experiment aimed at the collection and treatment, is bound to be limited. Although the business has facilities for both the proper treatment of waste and the recovery of resources, resource recovery only is stressed.

The second condition is the *development of technology* by individual private companies. Our examples show that non-ferrous metal recycling companies must have high-level technological and R&D capability in unifying the waste treatment and the resource recovery, and technology for the appropriate analysis of WEEE that contains complex materials becomes the base for the evaluation of the metals and the cost of their treatment. The TSL furnace of DOWA and Mitsui's lithium ion battery recycling are instances of companies responding within the current regulations to the development and deployment of new technologies of R&D. We also require both the recovery of precious metals in general and special metals such as mercury and cadmium in particular (Hagellueken, 2009). The collection and treatment of liquid crystal displays (LCD), video players and new type batteries becomes new business opportunities for companies.

At the same time, not only do the Japanese companies' environmental technology, management systems and human development projects–which are designed to cope with serious mining pollution–compare well with those of other countries, but they have also acquired a good social reputation and many customers in and out of Japan, while being favorably noted for strong international competitiveness.

The third condition concerns the *demand-side problem of metals*. In the countries that we have studied, price fluctuations for virgin resources constitute a major influence upon the recycling of resources. The price of virgin materials affects the fluctuation of foreign exchange, and excludes such external costs as environmental disruption, the need for subsidies, all in competition with the recycled material (Yoshida, 2004).

The economic condition will depend on the costs incurred for collection, decomposition and disposal, as compared with the prices of virgin resources. Consequently, it may be possible to focus on economically valuable resources and the application of appropriate technology for the disposal of complicated ores. Since 2008, when metal market prices fell sharply because of the world financial crisis, this has become more necessary than ever. It is essential that the non-ferrous metal industry should succeed in stabilizing the diversity of the input material and the prices of the output product (metal). It is vitally important to raise the recovery rate of precious metal so as to cope with the dangerous fluctuations in the ultimate prices of finished goods.

25.7 Conclusions

Our analysis of the distinctive WEEE recycling systems operated by Japan has shown that, in the light of the systems' purposes and contexts, we need to reconsider cost and performance as well as the role of each of the individual actors. We consider that neither system is obviously better than the other, and that they face similar challenges to the achievement of their ultimate goals. Those challenges include the raising of collection rates, the allocation of costs, the involvement of municipalities, recycling cost/benefits, the relationship between EPR and DfE, and the drain of WEEE exports to developing countries. In particular, the key to the raising of the collection rate lies in providing an incentive for proper collection and in making it convenient for the consumer to abide by the adopted scheme. If municipalities are involved, the collection cost has to be paid. Our findings have also revealed that the retailer's role is particularly important. The payment of a recycling fee at the time of discarding curbs the collection rate, which must be the real target. The visible fee, or the advance fee payment, does not curb the purchasing power and can contribute to the construction of the infrastructure. In the case of many home appliances, EPR cannot work well, and the appropriate domestic treatment of WEEE will be the duty of the developed countries. Our findings lead us to make the following recommendations:

- If Japan hopes to increase its collection rate of WEEE to any substantial degree, it has to change its system from one where payment is made at the time of disposal to one where payment is made in advance.
- Because the consumers have to pay at the time of disposal, the cost and the quality of recycling within the Japanese system is too expensive and must be reduced.

- To oversee and amend the problems occasioned by the cross-border problems of WEEE, Japan need a common agenda and the framework to set up a fund that will enable them to cooperate in the collection and treatment of cross-border recycling.
- The regulations that forbid mixing small WEEE with MSW will contribute not only to environmental protection but also to the business opportunities and green employment. Thus, to build the collection system and to raise the collection rate of the specified four items and PCs, we need to improve the collection system by involving the participation of producers, retailers, consumers and waste treatment businesses, and by introducing such incentive systems as the deposit.

In the context of the quite unprecedented changes that are now afflicting the global economy, these questions take on a new and disturbing urgency. Instead of simply organizing a WEEE recycling system meant to clean up after the consequences of mass production, mass consumption and mass disposal, we now need a far more painstaking and balanced assessment of the issues that will cover all their environmental, economic and social aspects, especially as they relate to each other, for if we hope to see worldwide sustainable development, it is essential that governments design systems that are meant to mitigate environmental and social burdens and reduce the consumption of natural resources by a far more effective management of WEEE.

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26
WEEE management in Africa

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Abstract: This chapter discusses the problem of waste electrical and electronic equipment (WEEE) management in Africa based on recent experiences from Ghana, Nigeria, Morocco, South Africa, Tanzania and Uganda. The analysis includes a quantitative review regarding imports of EEE, installed base and WEEE generated. Furthermore, current recycling practices and their environmental and socio-economic impacts are described and an overview of the current developments on policy and legislation is given. The chapter concludes the analysis by pointing out the main challenges and recommendations.

Key words: Africa, import of used EEE, WEEE generated, informal recycling, WEEE legislation.

26.1 Introduction

The problem of waste electrical and electronic equipment (WEEE) management in Africa came to public awareness only a few years ago. The term 'e-waste', often used instead of WEEE, was mostly unknown and often misunderstood as virtual trash produced in the Internet, rather than as a physical waste stream. This perception changed in 2005 when the Basel Action Network documented illegal export of e-waste to Nigeria and the subsequent informal recycling and dumping (Puckett *et al*. 2005). A milestone for more awareness was marked by the 'Nairobi Declaration on e-Waste', which was adopted at the eighth meeting of the Conference of the Parties (COP8) to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes in 2006 (UNEP 2006). Since then WEEE appeared more often on the political agenda in and for Africa.

As a result African governments started to move WEEE up in their priority list of environmental issues, which need special legislative attention. In addition, various international cooperation projects were launched, the first one being the Swiss e-Waste Programme from 2003 to 2009 in South Africa. At that time this programme was a pioneering initiative, launched by the Swiss State Secretariat of Economic affairs as part of a larger effort to build 'global knowledge partnerships in e-waste recycling' including China, India and South Africa (Widmer *et al*. 2005, 2008). Between 2007 and 2010 various projects were launched by multilateral organizations, producers from the information and communications technology (ICT) industry, non-governmental organisations (NGOs) and governmental organizations. As an outcome of some of these projects the involved African and international stakeholders drafted suggestions for the way forward in Africa in the so-called 'Durban Declaration on e-Waste Management in Africa' (WasteCon 2008).

Still, Africa in general is lacking infrastructure for e-waste recycling. Only in South Africa has an e-waste recycling industry evolved over the last years. A few other countries see some entrepreneurs and investors trying to build e-waste businesses, such as in Egypt, Ghana, Kenya, Morocco and Nigeria. However in the absence of national e-waste management systems, economically viable e-waste fractions get recycled at best. There are no sustainable solutions available for the appropriate treatment of hazardous fractions on the continent. Experiences show that informal activities mainly occur on the level of collection and recovery of copper, aluminium and steel through dismantling, sorting and burning. Activities are partially organized, though resulting impacts are still not as dramatic compared with highly organized informal sectors such as in China and India (Schluep *et al*. 2009). However, for a few years it has been observed that the informal sector is growing in African countries as well. Examples can be found especially in Western African countries, such as Nigeria (Puckett *et al.* 2005) and Ghana (Brigden *et al*. 2008; Kuper & Hojsik 2008). Triggered through a prosperous trade of used electrical and electronic equipment (EEE) from industrialized countries, the associated illegal transboundary shipment of e-waste, as well as an increased domestic consumption of electronics, there is a severe risk that informal activities start to rule the whole sector.

Although Africa in general saw a rapid growth in electronics consumption, the e-waste situation is very heterogeneous. This is illustrated in this chapter based on recent experiences from Ghana, Nigeria, Morocco, South Africa, Tanzania and Uganda.

26.2 Volumes of WEEE imported and generated in African countries

The amount of EEE consumed in Africa might seem negligible compared with the rest of the world. Estimations of the African share of global consumption point towards approximately 1.5% in the case of personal computers (Mueller *et al.* 2009; Schluep 2009). Still, a comparatively low share of EEE can produce a relevant amount of WEEE. On top of WEEE generated out of domestic consumption, a considerable amount is – intentionally or unintentionally – imported via the trade of used EEE (Schmidt 2006). In addition, various studies have shown that Africa's consumption of EEE is growing fast, hence increasing also the amount of WEEE generated in the future (see Table 26.1 for references). Developing countries in general have a steep increase in consumption of EEE and WEEE generation, hence

Table 26.1 Quantitative data for computers in Ghana, Nigeria, Morocco, South Africa, Tanzania and Ghana related to imports, installed base and WEEE generated

Country	Year	Population (millions)	Imports		installed base		WEEE generated	
			Units/year	Thereof used EEE (%)	Units	Units per 1000 inhabitants	Units/year	Tonnes/year
Ghana	2008	23.8	750 000	70	2 000 000	84	475 000	11 000
Nigeria	2009	154.7	2 200 000	35–70	21 000 000	134	5 250 000	70 000
Morocco	2009	32	900 000	<11	4 000 000	125	900 000	15 000
South Africa	2007	47.6	1 900 000	8	5 900 000	124	1 100 000	20 000
Tanzania	2009	42.5	120 000	13	850 000	20	200 000	4 000
Uganda	2007	28.8	29 000	14	300 000	10	53 000	1 000

Note: The data presented is based on the e-waste country assessment reports of the respective countries: Ghana (Amoyaw-Osei *et al.* 2011), Nigeria (Ogungbuyi *et al.* 2011), Morocco (Laissaoui & Rochat 2008; GIZ 2010), South Africa (Finlay & Liechti 2008), Tanzania (Magashi & Schluep 2011), Uganda (Wasswa & Schluep 2008).

producing their own waste challenges despite imported problems via the trade of used EEE (Schluep *et al*. 2009; Yu *et al*. 2010).

26.2.1 Imports of used and new EEE

Most of the consumed EEE is imported into Africa, while there are only a few local manufacturers in, for example, South Africa (Finlay & Liechti 2008), and some assembling companies in, for example, Nigeria (Ogungbuyi *et al*. 2011). Quantitative data for computers is summarized in Table 26.1 based on the respective e-waste country assessment reports. Since national and international import statistics do not distinguish between new and used EEE imports, special field investigations were conducted, such as the study commissioned by the Secretariat of the Basel Convention for West Africa, which concentrated on assessing the import flow of used and end-of-life EEE into West Africa.

The studies for Ghana (Amoyaw-Osei *et al*. 2011) revealed that in 2009 around 70% of all imports were used EEE. Some 30% of the second-hand imports was estimated to be non-functioning, whereas about half of this fraction was repaired locally and sold to consumers. The other half, or 15% of all imported 'used EEE', was unrepairable and hence correctly has to be defined as import of e-waste. In the case of Ghana this was about 20 000 tonnes of e-waste in 2010. A field investigation in Nigerian ports (Ogungbuyi *et al*. 2011) shows that the share of used EEE imports is about half of what was found in Ghana (35%). However this data was gathered at a time when stronger enforcement by the Nigerian government made it less attractive to import used EEE. Hence it is thought that the share of used EEE imports could have been in a similar range as in Ghana in the years before. Rough estimations for computer imports from other countries indicate a much lower share of used EEE, between 8% and 15% (see Table 26.1). These numbers suggest that West Africa serves as the major trading route of used EEE into the African continent, with Nigeria being the dominant hub, followed by Ghana.

26.2.2 Installed base of EEE

The use of ICT equipment is still low in Africa compared with other countries in the world, but it is growing at a staggering pace. According to World Bank (World Bank 2010) and ITU data (ITU 2008), in the last decade, for instance, the penetration rate of personal computers has increased by a factor of 10, and the number of mobile phone subscribers by a factor of 100. For the years 2007–2009, the per capita installed base of computer units in the selected countries varied between 10 and 134 per 1000 inhabitants. From Table 26.1 it can be seen that the less developed countries such as Tanzania and Uganda have the lowest penetration rate, while the more developed countries such as Morocco and South Africa have the highest. It is interesting to note that Ghana and Nigeria have a penetration rate as high as Morocco and South Africa, although their development status is similar to Tanzania and Uganda. This is an indication that owing to the intense trade of used EEE, people in those two countries have better access to lower priced ICT equipment. From this perspective the import and trade of used EEE is in support of the UN millennium goals for development as a means to foster ICT for development.

In Ghana the total installed base of computers is estimated at 2 million units in 2008, which corresponds to approx. 34 000 tonnes (using a conversation factor of 17 kg/unit, representing a theoretical average weight of a mix of desktop computers with CRT or flat screens and laptops). As the total amount of EEE installed in Ghana was estimated at around 1 million tonnes (Amoyaw-Osei *et al*. 2011), the weight-based share of IT equipment is around 3-4%. This range is a few percentage points lower than in Europe (Huisman *et al*. 2008), but in a similar range to those estimated for South Africa (Finlay & Liechti 2008) and Nigeria (Ogungbuyi *et al*. 2011). A recent market survey from Nigeria (Ogungbuyi *et al*. 2011) suggests that on a weight base large household appliances account for more than 50% of the EEE in use for private consumers. ICT equipment is the dominant category with institutional (government) and corporate (industry) consumers and represents about 73% of the EEE in use. It was also observed in Nigeria that the vast amount of the installed EEE (category 1–4) is held by private consumers (95% of the weight). Looking at ICT equipment only, the distribution shifts to 70% for private and 30% for institutional and corporate consumers.

26.2.3 WEEE generated

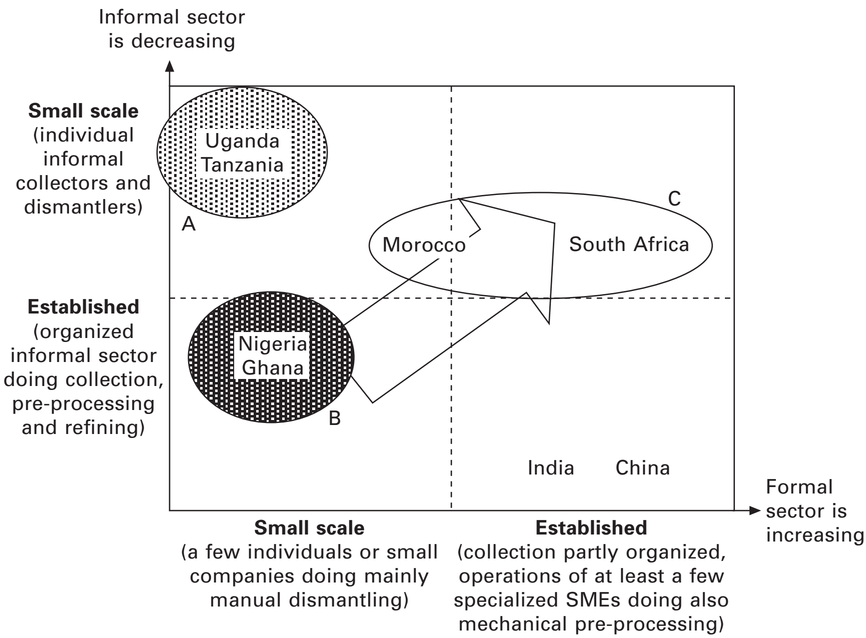
Estimations for computer waste generated in the selected countries are given in Table 26.1. Countries with high imports of used EEE, such as Ghana and Nigeria, generate relatively high volumes of WEEE. This is due to the direct import of non-functioning and non-repairable used EEE and the usually lower lifespan of (functioning) used EEE compared with new EEE. Referring to the study from Ghana (Amoyaw-Osei *et al*. 2011), where total WEEE generated was estimated at 180 000 tonnes, it can be concluded that computer waste corresponds to approximately 6% of total WEEE generated. The same number was confirmed in the Nigerian study (Ogungbuyi *et al*. 2011), where the amount of computer waste is 15 000 tonnes of the 1 100 000 tonnes total WEEE generated. The higher share in the waste stream compared with the installed base is due to the fact that computers have a clearly shorter lifespan than other appliances, such as white goods. Out of the 180 000 tonnes of WEEE generated in Ghana, almost 95% or 170 000 tonnes were collected and reached the informal recycling sector. As stated earlier, out of this volume, approx. 20 000 tonnes of non-functional and non-repairable equipment were collected directly from the trade of used EEE, i.e. around 15% of WEEE reaching the informal recycling sector in Ghana originated from the (illegal) trade of used EEE, with its origin in developed countries. Applying the share of 30% new versus 70% used EEE imports on the remaining 150 000 tonnes, it can be roughly estimated that at least another 60% was WEEE generated out of EEE imported and consequently sold in Ghana as used products. As used EEE has a shorter lifespan than new EEE and hence enters the waste stream earlier, its share was most probably even higher than 60%. This leaves less than 25% or 42 000 tonnes of WEEE generated from equipment, which originally was bought as new products in Ghana.

The high collection rate in Ghana is due to the large informal sector being very active in WEEE recycling, which is triggered through the high volumes of traded used EEE. This pattern can also be observed in Nigeria, where the importance of the informal sector is comparable. In the other countries however, where no similar informal e-waste sector is present, the situation is different. Only 10–25% of WEEE generated gets collected. Most of the equipment was thought to be in storage in consumers' homes. In Tanzania and Uganda, where EEE penetration rate is low and neither informal nor formal activities build a large sector, the collection rates were rather at the lower end, but more than 10%. In Morocco and South Africa, where a combination of formal collection activities and an increasing informal sector can be observed, the collection rates were somewhat higher, but not more than 25%.

26.3 Impacts of current WEEE recycling practices

26.3.1 Current recycling practices

The development status of the recycling infrastructure varies considerably among African countries. Differences are graphically depicted in Fig. 26.1 in order to show the dimension of the recycling sectors. The graph is divided into four quadrants representing different shares of the recycling market between the informal and the formal sector. Normally, a sustainable recycling system should grow towards the upper right corner of the graph, where most of the established recycling schemes in Europe are now located. In Europe the informal sector exists only in collection activities, and in recycling as an exceptional case, if at all. This should not prejudice informal recycling activities being unwanted per se. Depending on the socio-economic and cultural context of a country, a sustainable recycling system could include an organized informal system doing collection and possibly the first steps of pre-processing. In addition to the selected African countries, India and China were included in Fig. 26.1 as a reference. They represent another class



26.1 Comparative analysis and grouping of the selected African countries regarding the dimension of the formal and informal e-waste recycling sector (adapted from Schluep *et al.* 2009).

of countries of emerging and large economies, where both the informal and formal sectors depend on each other (Schluep *et al*. 2009).

The first group as arranged in Fig. 26.1 (A; e.g. Tanzania and Uganda) includes countries featuring the formal and informal sector on a small scale, if at all. E-waste volumes were too small for the formation of specialized informal or formal recycling activities. As e-waste volumes also increase over time, those countries typically could move towards more informal activities if appropriate measures are not taken. The second group (B; e.g. Ghana and Nigeria) includes countries featuring an established informal sector and some small-scale formal initiatives. Countries in this group are subject to large import volumes of used EEE from developed countries, which is the predominant driver for high WEEE volumes. This is due to the direct (illegal) importation of WEEE as a side effect of these imports, and a comparatively high WEEE generation due to higher consumption of low cost EEE with a lifespan, which is often shorter than for new EEE. As a result a well-organized informal sector was formed, while the formal sector is in its infancy with some tendency of growth. The third group (C; e.g. Morocco and South Africa) includes countries featuring a currently developing or already established formal recycling sector, while informal activities remain on a small or medium scale.

The first section in Table 26.2 characterizes the selected countries by the presence of informal activities in the e-waste recycling chain. Collection, manual dismantling and open burning to recover metals and open dumping of residual fractions are present in all countries. While in some countries these activities are performed by individuals (Tanzania and Uganda) with a low material throughput, Ghana, Nigeria, and to some extent Morocco and South Africa reveal an organized informal sector with medium to high volumes of processed materials. Informal recycling locations are often found adjacent to markets for used EEE. Well-known examples are Alaba International Market and Ikeja Computer Village in Lagos, Nigeria (Manhart *et al*. 2011). In Ghana, rather high collection rates of up to 95% are achieved by the informal collectors because of the economic benefit from both the reuse and material value from WEEE. Most WEEE is traded to informal recyclers, who prioritize the reclamation of the valuable components and substances from the recycling process.

The informal recycling processes apply manual dismantling as the primary treatment to separate the heterogeneous materials and components physically with simple tools – hammers, screwdrivers, chisels etc. After the dismantling pre-processing, the components with reuse value are usually sold to repair shops to be sold on in the second-hand market. The remaining valuable components, such as the parts containing copper, aluminium, steel, plastics, printer toner and circuit boards, are classified for further treatment. Open burning is widely used in all selected African countries to recover metals such as copper, steel and aluminium from wires and other components. Apart from a few rumours, no indications were found for further 'refining' techniques, such as de-soldering of printed wiring boards (PWB) and subsequent leaching of gold. However, open dumping of residual non-valuable fractions is known from all countries.

The second section of Table 26.2 characterizes the selected countries by the availability of formalized processes in the e-waste recycling chain. South Africa sees the most advanced infrastructure for the collection from businesses and partly from private consumers and quite well-developed manual and semi-mechanical recycling processes (Finlay & Liechti 2008). In Morocco a few private initiatives for manual dismantling processes have appeared over the last few years. In the other countries, first pilot projects have been initiated (Ghana and Nigeria) or are planned (Tanzania and Uganda) through either private initiatives or development cooperation projects. All of them at least partially are relying on financial start-up funding. Manual dismantling pilots are also appearing in other African countries not analysed in this chapter, such as Burkina Faso (PACE 2011), Egypt (Khaled 2010), Kenya and Senegal. More costly treatment processes, such as degassing chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) from recycling of cooling and freezing appliances and cathode ray tubes (CRT) are not available on the continent.

Table 26.2 Informal and formal processes in the WEEE recycling chain in selected African countries (as of 2010)

	Ghana	Nigeria	Morocco	South Africa	Tanzania	Uganda
Informal						
Collection	✓✓	✓✓	✓✓	✓✓	✓	✓
Manual dismantling	✓✓	✓✓	✓	✓	✓	✓
Open burning to recover/ concentrate metals	✓✓	✓✓	✓	✓	✓	✓
De-soldering of PWBs	×	×	×	×	×	×
Leaching of gold from PWBs	×	×	×	×	×	×
Open dumping	✓✓	✓✓	✓	✓	✓	✓
Formal						
Collection B2B	✓	✓	✓✓	✓✓	×	×
Collection C2B	×	✓	×	✓	×	×
Manual dismantling	✓	✓	✓✓	✓✓	×	×
Shredding of white goods (without de-gassing CFC, HCFC)	×	✓	✓	✓	×	×
Pyrometallurgical processing in local smelters	×	×	P	✓	×	×
Hydrometallurgical processing in local facilities	×	×	P	×	×	×
Export of PWBs	✓	✓	✓	✓✓	×	×
Export of CRTs	×	×	×	×	×	×
Disposal in general landfills	✓	✓	✓	✓	✓	✓
Disposal in hazardous landfills	×	×	×	✓	×	×
Disposal in incinerators	×	×	×	✓	×	×

✓✓ = established and organized process in the WEEE recycling chain
✓ = process is (sometimes) part of the WEEE recycling chain
× = process is non-existent in the country
P = process in pilot stage

In some countries formal refining processes exist for metallic fractions such as steel and aluminium. This ranges from rather simple remelting operations to large metal smelters and refineries. Metallic scraps from WEEE usually are treated in these facilities together with mixed metal scraps from other sources or sometimes with mining concentrates. While formal refining operations for copper has only been observed in South Africa and Morocco, other countries export the reclaimed copper often to Asia. Activities and trials of gold recovery from PWB in plants owned by mining companies are known from South Africa (Finlay & Liechti 2008) and Morocco (GIZ 2010). While these pyrometallurgical plants can be effective and environmentally sound for predominantly metallic fractions, they should not be used for PWBs or other fractions that contain halogenated flame retardants, unless the necessary off-gas treatment installations have been installed.

26.3.2 Environmental impacts

Emissions from informal recycling activities have already been assessed in many studies (Sepúlveda *et al*. 2010) and their impacts on the environment and health are evident. Major impacts from current recycling practices in Africa result mainly from the processes of dismantling, material recovery and final disposal. During collection as well as refurbishment or repair of EEE, negative impacts can occur, but are generally at a significantly lower level. Recycling activities often take place directly on unfortified ground. Harmful substances released during dismantling therefore lead directly to discharges to soil. Burning copper cables and wires as well as monitor and TV casings create an accumulation of ash and partially burned materials at the burning sites. Insulating foam from dismantled refrigerators, primarily polyurethane, or old car tyres are often used as the main fuels for the fires (Amoyaw-Osei *et al.* 2011), contributing in itself to acute chemical hazards and longer-term contamination at the burning sites. A sampling campaign carried out by the Greenpeace Research Laboratories in Accra Ghana at the main informal recycling sites (Agbogbloshie and Korforidua) revealed copper, lead, tin and zinc concentrations in soil and ash samples over one hundred times higher than typical background levels (Brigden *et al*. 2008). Increased levels of polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) found in breast milk samples in Accra Ghana were also linked to informal e-waste recycling activities (Asante *et al*. 2011).

As burning of cables is seen to have one of the most direct severe impacts on human health and the environment, a small survey was conducted in the Greater Accra Region, in order to estimate the resulting dioxin emissions (Amoyaw-Osei *et al*. 2011). Based on site inspections at the four main informal burning sites it was estimated that approximately 625 tonnes of cables were burnt per year. About 10–20% of these cables were associated with WEEE, while the rest originated mainly from old vehicles. The estimation of dioxin emissions to air from open burning of cables was based on the 'Standardized Toolkit for Identification and Quantification of Dioxin and Furan Release' (UNEP 2005) and resulted in a source strength of ~3 g/year. Compared with the European dioxin air emission inventory for 2005 (Quass *et al.* 2004) this equals to 0.15–0.3% of total dioxin emissions, 1.5–3% of dioxin emissions from municipal waste incineration or 7.5–15% of dioxin emissions from industrial waste incineration. Bearing in mind that cable burning most probably occurs in all African countries, this is a major source of dioxin emissions.

26.3.3 Socio-economic impacts

Insights about socio-economic impacts of e-waste recycling in the informal sector are drawn from two studies in Ghana (Prakash *et al*. 2010) and Nigeria (Manhart *et al.* 2011), currently being the only detailed studies available for Africa. As mentioned before, the informal sectors in Ghana and Nigeria are much more active in WEEE recycling than in other African countries. However, the socio-economic impacts can be compared to these two cases, wherever informal activities take place.

Employment in the refurbishing and WEEE recycling sector involves exposure to rigorous and insecure working conditions and severe health hazards. Even children, sometimes as young as 5 years old, were observed to be involved in the recovery of materials from WEEE. Most of the people employed in the WEEE recycling, aged between 14 and 40 years, worked for 10–12 hours a day. Despite the long working hours, most of the people continue to live in extreme poverty. Monthly incomes of collectors in Ghana were between US$70 and 140, refurbishers between US$190 and 250, and recyclers US$175 to 285. Expert opinion suggested that these incomes could go lower, if the regular supply or collection of WEEE was hindered. Hence, considering the partial or full dependency of family members – in urban areas of up to six people – on such incomes, it can be concluded that most of these workers live below nationally and internationally defined poverty lines. Nevertheless, employment in the informal EEE refurbishment and WEEE collection and recycling sector is remarkable. Although these jobs are not all exclusively related to WEEE, as collectors and recyclers also concentrate on other waste streams, the contribution of informal WEEE recycling to national gross domestic product can be relevant.

26.4 WEEE policy and legislation

As of 2010, Africa did not have any dedicated national legislation dealing with WEEE. However, a few countries presented drafts for specific WEEE-related policies and legislations. Also some references to WEEE have been introduced to existing environmental and general waste management legislation in the past 2–3 years. In addition, the absence of specific WEEE legislation does not imply that countries do not have legislation covering hazardous substances or waste, or the management and disposal thereof. Answers are certainly found in laws governing topics such as the environment, water, air, waste, hazardous substances as well as health and safety. As a general pattern seen in all countries, each of these, however, examines the issue from a different perspective, thereby confusing the problem. A further difficulty is the fact that these laws are enforced by different government departments or alternative levels of government, so that there is no uniform approach in dealing with WEEE or, for that matter, hazardous waste in general. The general status and development to overcome these challenges are discussed in the following for each of the selected countries.

26.4.1 Ghana

There are a number of laws and regulations that have some relevance to the control and management of hazardous wastes (including e-waste) in Ghana, but they do not address the dangers posed to humans and the environment. The existing law in Ghana that could best form the basis for e-waste management is the Environmental Protection Agency Act, 1994 (Act 490). Section 2 of the Act requires, among others, (i) to prescribe standards and guidelines relating to the pollution and the discharge of toxic wastes and control of toxic substances; (ii) to coordinate activities and control the generation, treatment, storage, transportation and disposal of industrial wastes; and (iii) to control the volumes, types, constituents and effects of waste discharges, emissions, deposits or other sources of pollutants and/or substances which are hazardous or potentially dangerous to the quality of life, human health and the environment. Section 10 of the Act establishes the Hazardous Chemicals Committee tasked to monitor the use of hazardous chemicals by collecting information on the importation, exportation, manufacture, distribution, sale, use and disposal of such chemicals. Although this Act does not make specific reference to e-waste, it provides a framework for the management of hazardous substances.

Ghana has also ratified a number of chemical and waste-related multilateral environmental agreements (MEAs) and adopted a number of codes and international declarations including, for example, the Basel Convention (UNEP 1989), the Rotterdam Convention (UNEP 1998) and the Stockholm Convention (UNEP 2001), though these conventions have not yet been incorporated into local law and therefore have not come into force. New specific regulations with relevance to EEE and e-waste are the LI 1932 Energy Efficiency Regulations, 2008 (Prohibition of Manufacture, Sale or Importation of Incandescent Filament Lamp, Used Refrigerator, Used Refrigerator-Freezer, Used Freezer and Used Air-Conditioner). They prohibit the importation as well as the sale and distribution of used refrigerators, freezers and air conditioners. The enforcement of these regulations at this moment remains challenging.

26.4.2 Nigeria

Among the existing legislative framework related to e-waste in Nigeria, the Hazardous Waste (Criminal Provisions) Decree. No. 42 of 1988 has the most influence in the current development of regulating e-waste management. The law prohibits the carrying, depositing and dumping of harmful waste on any land, territorial waters and related matters. It prohibits activities relating to harmful wastes, and lists such activities. The decree is linked to two other key regulations. The National Environmental Protection (Waste Management) Regulations S.I.15 of 1991 regulates the collection, treatment and disposal of solid and hazardous waste from municipal and industrial source. The National Environmental (Sanitation and Wastes Control) Regulation S.I.28 of 2009 applies to issues in environmental sanitation and all categories of wastes including e-waste. It regulates the adoption of sustainable and environmentally friendly practices in environmental sanitation and waste management to minimize pollution. Furthermore it stipulates the obligation of all manufacturers and importers of various brands of products to comply with a product stewardship programme and extended producer responsibility programmes. In particular it is planned that e-waste becomes amenable to extended producer responsibility (EPR) programmes from 2011.

Based on that, the National Environmental Standards and Regulations Enforcement Agency (NESREA) drafted regulations, which may be cited as the National Environmental (Electrical/Electronic, sector) Regulations, were approved in July 2011. The principal objective of the regulations is to prevent and minimize pollution from all operations and ancillary activities of the EEE sector to the Nigerian environment. The regulations are based on life-cycle approach and cover all the aspects of the EEE sector from cradle to grave, hence also including e-waste.

26.4.3 Morocco

Again, in Morocco there is no specific WEEE legislation. However, some legislation can be read as favourable to the introduction of a framework for the regulation of WEEE management. Though the question of sustainable WEEE management has not been raised explicitly, both the government and the private sector are active with environmental protection initiatives: the former with the Environmentally Sustainable Industrial Development scheme; and the latter with the Social Responsibility Charter of the General Confederation of Moroccan Enterprises. In order to translate these commitments into action, existing conventions and strategies need to be amended to take WEEE management into account.

26.4.4 South Africa

Until 2009 there was no specific legislation to deal with WEEE in South Africa. A range of laws however, ranging from national, provincial to local, can be read as having an impact on WEEE management. A fundamental problem though is that WEEE is not mentioned in any legislation, nor is it identified anywhere as being hazardous. Furthermore, seeing that waste removal and disposal is largely regulated on a local level there are differences in terms of strictness and enforcement (Dittke 2009).

As a response to this, the new National Environmental Management, Waste Act (No. 59, 2008), came into effect in 2009. It provides several definitions impacting the management of WEEE, such as: what constitutes ‘acceptable exposure’ (i.e. the maximum permissible concentration of a substance, which is relevant when collecting or recycling e-waste in volume); ‘best practicable environmental option’ (relevant to a context when the latest technology for recycling e-waste may not be available); ‘hazardous waste’ and ‘inert waste’ (which includes waste that does not undergo significant transformation after disposal, and which may have relevance to some WEEE fractions); and ‘extended producer responsibility measures’ (which are likely to impact on the responsibility of vendors and others after the sale of a product).

To help implement the objectives of the Waste Act the Department of Environmental Affairs (DEA) has amended the framework for developing the National Waste Management Strategy. The final strategy is expected to be published in 2011. Industry is now required to provide an Industry Waste Management Plan which has to detail how the stakeholders propose to ensure effective take-back and recycling is achieved. It is the first time that legislation has been used to drive a waste minimization approach. It is limited to waste streams that are not dealt with by other pieces of legislation in order to avoid duplication and to complement existing legislation.

The Second-Hand Goods Act (No. 6 of 2009) holds further restrictive implications for the WEEE sector. Objectives are to ‘regulate the business of dealers in second-hand goods and pawnbrokers, in order to combat trade in stolen goods; to promote ethical standards in the second-hand goods trade; and to provide for matters connected therewith’. It includes the aim to introduce greater control over certain second-hand goods sectors, and to implement a degree of self-regulation and policing. This implies that refurbishers of EEE and WEEE recyclers will most likely be required to form a dealers’ association.

26.4.5 Tanzania

In Tanzania WEEE is managed through the solid waste and hazardous regulations prescribed under the Environmental Management Act (2004). Part VIII of the Environmental Management (Hazardous Waste Control) regulations, 2009 addresses the issue of WEEE. Regulation 35 (1) requires every person who possesses or has control of electrical or electronic tools, accessories or equipment to segregate WEEE from other types of waste and deposit separately into receptacles as prescribed by the national or local authorities. The obligation to segregate WEEE applies to collection, transportation and final disposal of WEEE from equipment and devices listed in the 8th schedule of the regulations. Regulation 37 (1) allows manufacturers of EEE to set-up and operate individually or collectively voluntary take-back systems for WEEE from customers (households or institutions) provided that no fee is chargeable for that service while regulation 39 elaborates the role of the local government authorities in ensuring safe handling of WEEE so as to minimize risks to human health and the environment.

Based on this, the Vice President's Office, Division of Environment, has developed a draft National Waste Management Strategy and Action Plan (2009–2013) which includes, among others, WEEE management. The goal of the WEEE management action plan is to minimize environmental and health risks associated with improper WEEE management. The specific objectives are to review related policies and legislation, promote environmentally sound disposal practices, promote investments for material recovery and recycling infrastructure and promote awareness. The draft strategy and action plan includes key targets for WEEE management in the country which are to ensure that: (i) by 2013, 80% of imported EEE conform to product standards; (ii) by 2010, the quality of end-use of electrical and electronic equipment imported into the country is controlled; and (iii) two to four e-waste collection and recycling centres are established and operationalized by 2013. The strategy is yet to be implemented.

26.4.6 Uganda

In the absence of a specific WEEE legislation, Uganda drafted a WEEE management policy in 2010. The policy aims at enforcing several strategies, including the establishment of e-waste management infrastructure, fostering awareness and education, supporting the development of a legislative framework, skills development and technology transfer, as well as resource mobilization. An 'e-Waste Fund' fed by 'sellers and buyers of EEE' through an advanced recycling fee is under discussion. The draft policy also presents a strategy for the enforcement process and lists parastatal stakeholders along with a description of their responsibilities. This includes the Ministry of

Information and Communication Technology as the leading arm and others such as Ministry of Trade Tourism and Industry, Ministry of Health, National Environment Management Authority, National Information Technology Authority, as well the private sector and others.

26.5 Conclusions

This chapter points out several challenges for African countries in managing e-waste. Challenges are especially related to the control of used EEE imports, collection strategies and sound technological recycling solutions, and support through policy and legislation.

26.5.1 Imports

The analysis suggests that import hubs for used EEE, such as West Africa, receive a considerable share of non-functioning and non-repairable EEE, which correctly have to be defined as import of e-waste. It is unclear how much of the remaining imported used EEE functions for a reasonable time after it is sold. This so-called near-end-of-life equipment can be another major source of equipment imported into African countries and becoming waste in a relatively short time-frame. In addressing this, one major challenge for African countries is to avoid the import of e-waste and near-end-of-life equipment without hampering the meaningful and socio-economically valuable side of the used EEE trade. Refurbishing of EEE and the sales of used EEE is an important economic sector in, for example, Ghana and Nigeria. It is a well-organized and a dynamic industry that has potential for further industrial development. Indirectly, the sector has another important economic role, as it supplies low and middle income households with affordable ICT equipment and other EEE. In the view of the sector's positive socio-economic performance, all policy measures aiming to and improve e-waste management in Africa should refrain from undifferentiated banning of second-hand imports and refurbishing activities and strive for a cooperative approach by including the market and sector associations.

26.5.2 Collection and recycling

Even if the trade of used EEE is controlled, African countries will still face major challenges related to properly managing domestically generated e-waste. It can be assumed that in 2010 between 50% and 85% of e-waste was domestically generated out of the consumption of new or used EEE of good quality with a reasonable lifespan. There is thus strong demand for a functioning take-back and recycling system.

Challenges include appropriate collection strategies, ensuring that high volumes of valuable and non-valuable waste fractions are collected equally and that those fractions reach appropriate treating facilities. In addition, connecting the informal collectors to a formal recycling structure is pivotal in countries with large informal WEEE management activities, demanding for appropriate capacity building and training. Any strategy addressing e-waste management should carefully consider the possible roles of informal collection before establishing a parallel system in competition to these structures. In particular, it is recommended that those people who are currently engaged in informal e-waste collection and pre-processing become an officially acknowledged part of the recycling chain. This needs to include health and safety measures, as well as opportunities for the informal sector to gradually transform themselves into formal structures.

Recycling activities with adverse impacts on human and the environment, such as open burning of cables, need immediate attention. As specialized recycling companies exist in only a few African countries, another challenge is to attract investments for sound and locally adapted recycling technologies. Taking socio-economic conditions into account, locally adapted recycling technologies for many African countries should make use of the abundant labour force instead of deploying expensive shredding and sorting machinery. In addition treatment possibilities for hazardous fractions need to be identified. Further refining processes – especially those for precious metals – need to be carried out in state-of-the-art facilities that are only available in very few countries globally. Hence African recyclers should interlink with international recycling companies and networks to develop market outlets for their pre-processed e-waste fractions for a maximal return of value for secondary raw materials. This also requires that government bodies guarantee a smooth, reliable and timely handling of export licences and other administrative procedures to facilitate exports of certain e-waste fractions.

26.5.3 Policy and legislation

It is an encouraging sign that some countries have already adopted specific regulations for the management of e-waste, and that a similar development is underway elsewhere. However, many African countries are lagging behind and similar processes at governmental level are yet to be initiated. With the implementation and enforcement of those regulations still ahead, the main challenges are yet to be faced in all countries. It will be key to ensure that all actors will play under the same rules, in order to avoid cherry picking. In addition existing policies and legal frameworks especially related to environment, general waste management, as well as health and safety need to be enforced, likewise posing challenges to the coordination between different regulatory bodies.

A sustainable e-waste management system will demand financing mechanisms. There are costs involved in the collection, transportation, sorting, dismantling and environmentally safe recycling of the waste. In case the intrinsic recoverable value is not enough to meet these processing costs, additional income streams are required. Moreover, recent studies, reflecting the all-time high raw material prices in 2011 and the economic conditions of developing countries (e.g. low labour costs) suggest that if recycling businesses can be run by relying on the intrinsic value of the treated material only, changing conditions can pose relevant risks to the business (Blaser & Schluep 2011). Hence some kind of financing safety net, which can be activated once unfavourable conditions prevail, needs to be in place in any e-waste management system.

Policy makers need to be cautious in predefining financing mechanism directly in their legislative framework. Complementary control mechanisms need to be in place to ensure the transparent collection and utilization of collected funds. If not, there is the danger that unscrupulous agents could abuse the system by charging recycling fees from the consumer for proper disposal, but instead selling the e-waste to recyclers who pay the highest price and not necessarily follow sound disposal practices. Therefore it is thought that according to the development in OECD countries systems should be developed under the principle of EPR. Producers and importers should be given an appropriate role to manage the waste generated out of their products. While the regulatory framework needs to be clear and precise in defining the obligations for the main actors, it should give producers and importers some flexibility in choosing their preferred way and mechanisms of implementing a sustainable system.

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27
Hewlett-Packard's WEEE management strategy

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Abstract: This chapter describes Hewlett-Packard's approach to environmental business management and electronic waste (e-waste) in particular. Section 27.1 describes environmental business management at HP, including a description of its strategy and approach, and the business benefits and challenges that have resulted. Section 27.2 provides a case study of HP's e-waste management system. It focuses on HP's end-of-life product return and recycling, and includes insights from an industry perspective. Section 27.3 discusses trends that HP expects to have an impact on WEEE and WEEE management in the future.

Key words: HP, Hewlett-Packard, WEEE, environmental business management, e-waste, IT.

27.1 Environmental business management at Hewlett-Packard (HP)

27.1.1 HP's environmental strategy

More than a billion PCs are in use worldwide, and the number is expected to reach nearly two billion by 2014.[1] As the quantity of electronic products increases, so does the challenge of managing their impacts responsibly – not only at the end of their life, but at every stage of their life cycle from raw materials to design, manufacture, usage and disposal. Information and communication technology (ITC) accounts for 12% of WEEE by weight.[2] Taking a whole life approach to IT is vital in managing WEEE. This is because the decisions made at every stage in the product's life, such as design and material choice, have an enormous impact on its end-of-life.

Hewlett-Packard (HP) is the world's largest information technology (IT) company, shipping approximately 3.5 products every second.[3] HP takes this responsibility seriously, recognizing that no matter how durable or well made, these products will eventually reach the end of their life. HP recognizes that social and environmental responsibility are essential to its business strategy and to the value proposition the company represents to its customers. In order to effectively manage the impacts created by HPs business operations, HP's environmental strategy focuses on three core areas. These can be summarized as 'our house', 'your house' and 'our world'.

- *Our house*: the environmental impact of HP operations and supply chain. This encompasses all stages of HP's business from the sourcing of raw materials from suppliers to product design, manufacture and office space.
- *Your house*: the environmental impact created by customers when using HP products and services – for example, energy and paper consumption when using computers or printers.
- *Our world*: how HP products can help to minimize the environmental impacts HP customers have in other areas to facilitate the move towards a low carbon economy – for example through smart grids or fuel-efficient navigation systems.

This life-cycle approach to the theme of environmental responsibility is also reinforced by HP's Design for Environment practice. This carries some of the 'our house', 'your house', 'our world' themes into every day business practice. The Design for Environment program has the following areas of focus:

- energy and climate;
- supply chain responsibility;
- material resources;
- product reuse and recycling.

Energy and climate

This sets out a commitment to producing devices and architectures that use less electricity, and enable customers to use IT to reduce their carbon footprint. The design stage offers the best opportunity to increase a product's energy efficiency. By adding energy-saving features to HP products and services, it helps customers reduce their greenhouse gas emissions and save money.

Material resources

The choices of materials used in designing products represent opportunities to improve HP's environmental performance. HP has a long history of working to improve the use of materials in HP products and to enhance their environmental and safety performance during production, manufacturing, distribution and, ultimately, disposal. HP is focused on:

- being transparent about product material content and working to eliminate materials shown to, or likely to, pose an environmental, health or safety risk;
- developing products that are smaller and lighter, and require less material;

- innovating to use new materials;
- using recycled materials;
- using materials that will be easier to recycle.

Supply chain responsibility

HP is the world's largest IT company, and has one of the industry's most extensive supply chains. HP works with more than 1000 production suppliers in more than 1200 locations worldwide, and works with nearly 50 000 non-production suppliers. Priorities remain to:

- protect workers' rights and dignity;
- ensure strong health and safety standards;
- reduce environmental impacts;
- uphold high standards of business ethics.

Product reuse and recycling

HP started recycling in 1987 and by 2011 had recovered a total of 1.07 million tonnes of electronic products (for reuse and recycling) and supplies (for recycling).[4] However, good environmental management demands that impacts are considered at every stage, not just when the item becomes waste. As the environmental impact of a product is largely determined at design stage, HP takes a cradle to grave approach. This includes designing products in a way that makes recycling easier.

Innovations include:

- minimizing the number of different products, for example using two kinds of plastic instead of 15;
- designing products to snap together instead of using glues and adhesives;
- minimizing the use of hazardous substances, for example, by ensuring all HP notebook products made after the end of 2010 are brominated flame retardant (BFR) and polyvinylchloride (PVC)-free;
- creating the world's first closed loop ink cartridge recycling process which uses plastic from returned cartridges to make new ones.

HP has also invested heavily in its Planet Partners recycling program. This includes:

- free recycling of unwanted computer hardware and printing supplies for HP customers;
- a trade in program which allows customers to get cash back from aging technology to put towards new HP technology;
- a donate to good causes program (US only);

- a return for cash program where eligible equipment will be refurbished and resold.

27.1.2 Putting strategy into action: designing an integrated approach

Setting out a clear environmental strategy is crucial, but for strategy to become practice, implementation is key. Environmental strategies tend to be implemented in two different ways. One approach is to have a central environmental or CSR department that is responsible for designing green products and driving green initiatives across the business. The other is to integrate environmental strategies into the goals of each business unit. Each unit then decides how to implement the strategy and achieve its goals.

HP has found that different challenges affect different areas of the business. Thus, the most effective way to ensure responsible environmental management across the business is for it to be integrated. At HP, integration has been promoted by creating environmentally focused job roles and internal goals throughout the business units. However, although the implementation of the environmental strategies is in the hands of all business units, compliance assurance processes are managed across the company. This is necessary to ensure the requirements of international environmental legislation are met. Integration is a challenging process that is yet to be completed, but HP is working to ensure environmental elements are a standard part of HP business strategy at all levels.

27.1.3 The benefits of a strong environmental strategy

Environmental sustainability is a key element of HP's long-standing commitment to global citizenship and has been, and continues to be, a basis for its long-term business success. This is because good environmental management is good business. For example, large commercial customers are attracted by HP's high environmental standards and product criteria; while high energy and raw material costs have created a strong economic case to reduce these inputs and to use recycled or alternative materials.

The strong inter-relationship between the business and environmental case aids the company-wide integration of environmental principles. This is because initiatives do not need to be driven out of the environment department, but can be driven out of the business units who can easily appreciate their value. Some examples of the business benefits of HP's environmental management approach across different areas of the business are outlined below.

Brand benefits

HP's market-leading approach to environmental management has had wide-ranging business advantages that include brand benefits and market positioning. It contributed to HP being named no. 1 on *Corporate Responsibility Magazine's* 100 Best Corporate Citizens list for 2010 as a result of its scores in seven criteria categories: environment, climate change, human rights, philanthropy, employee relations, financial and corporate governance.[5]

HP's recycling program and achievements were also recognized in the inaugural 'Magic Quadrant for North America Information Technology Asset Disposition', published by Gartner 30 September 2010.[6] The report names HP as a leader in the responsible disposal of old or unwanted IT assets. HP's product take-back program is also commercially important because businesses and consumers increasingly choose manufacturers that offer responsible take-back options for used equipment.

Operating advantages

HP's commitment to applying IT to reduce waste and increase the efficiency of products, processes and systems, has also had operational advantages when applied to HP's own business practices. For example:

- Using innovative design and HP equipment, HP's data center in Wynyard, UK, is 40% more energy efficient than the industry average, saving up to US$4 million a year.[7]
- Consolidating 85 data centers to six energy-efficient facilities has helped to reduce costs by 60%.
- HP Visual Collaboration has avoided 20 000 business trips annually, reducing CO_2 emissions by 35 000 tonnes and saving millions of dollars.
- The company's internal recycling programs have helped to reduce running costs, for example by reducing landfill costs. In 2010, HP recycled, reused, or incinerated for energy 67 300 tonnes of waste, achieving a non-hazardous landfill diversion rate of 84.3%. In the United States alone, this saved over $8 million in 2010 by avoiding landfill fees, and selling recyclable commodities such as paper, beverage containers, scrap metal, excess foam packaging, and cardboard.[8]

Recycled plastic R&D pays dividends

HP has invested considerable time and capital in researching recycled plastics to establish how and when they can be used in the manufacturing process successfully. This is a key component of the waste hierarchy and is a vital component of WEEE as it important to provide a market for recycled materials. This investment has paid off as HP has found that certain recycled plastics are now more cost effective than virgin materials.

Creating an industry first – the closed loop recycling of printer cartridges

HP reached a milestone in 2010 by producing 1 billion HP ink cartridges containing post-consumer-recycled plastic. Some 800 000 000 of those cartridges were manufactured with recycled plastic from the HP ‘closed loop’ ink cartridge recycling process, which uses plastic from returned cartridges to make new ones.

HP was the first company to recycle old cartridge plastic in this way – an industry first that has conferred brand benefits. The new cartridges are made from plastic recovered from used ink cartridges and plastic bottles. As a result, HP estimates this has kept 1.46 billion items out of landfill, including 1.3 billion plastic bottles and 160 million ink cartridges. Using recycled plastic instead of new plastic in Original HP cartridges is currently reducing fossil fuel use associated with HP cartridge manufacture, transport and recycling by up to 62%.[9]

Legislatory advantages

HP’s well-developed environmental strategy meant that the company had considerable WEEE knowledge and expertise long before legislation appeared. When the EU was developing the EU’s WEEE Directive, this knowledge allowed the company to participate in the Directive’s consultation process. Closely following the discussions of EU bodies, and the dialog within member states, allowed HP to estimate the direction the legislation would take early on. This gave the organization time to develop practical and cost-effective strategies for implementation across the business. These ranged from technological issues, such as implementing a system to monitor product weights (a Directive requirement), to choosing the most effective business model for dealing with take-back partners.

HP was also able to use its excellent knowledge of the recycler market to help develop take-back infrastructure that promoted a competitive marketplace. This was done through the joint founding of the European Recycling Platform (ERP)[10] with Sony, Procter & Gamble and Electrolux. The ERP is a compliance scheme for recycling electrical and electronic waste at a pan-European level. Battery and packaging take-back has since been added to its service portfolio. The ERP created a competitive recycling industry in many countries which had faced a monopoly with only one compliance scheme offering recycling services. With more than one supplier on the market, cost was driven down for the benefit of member companies, and ultimately, their customers. A pan-European system also ensures that the same, high recycling standards are applied in all countries, even where regulations are not as stringent (for more on HP and the ERP, see Section 27.2.3).

27.1.4 Challenges for the environment team

Despite the many benefits and successes that have resulted from HP's environmental strategy, challenges still remain. Some of these are fundamental to the environmental arena because determining the environmental impact of a product or an environmental program is more difficult than measuring other technical attributes. This is because it is hard to ascertain if a product or system is better or 'greener' than another, even if a tool such as life-cycle analysis (LCA) is used. This could be because one option might have a lower carbon footprint, but a higher water footprint, making it complicated, and potentially subjective, to decide which option is better for the environment overall. Or, it can be difficult to incorporate accurate measurements for all components of an LCA. For example, data regarding the impacts of the mining operations used to source components of a product's raw materials may not be available. This can lead to LCA boundaries being chosen where the impacts can be measured and quantified. This can mean some impacts – such as those from the mining of raw materials – are excluded, even though these impacts could change the result of an LCA comparison.

Electronic goods and WEEE also present their own particular challenges. These include:

- the lack of ownership of WEEE creates conflict with extended producer responsibility (EPR);
- a challenging legal landscape;
- the difficulty in capturing consumer interest;
- environmental fashions can be faddy.

The lack of ownership of WEEE creates conflict with EPR

WEEE is legally the property of the customer, not the producer. This lack of ownership is one of the most significant challenges for IT companies. It makes it hard for producers to ensure WEEE is recycled as the customer is in control of the product at the end of its life. This is particularly challenging because a significant portion of WEEE legislation – such as the EU's WEEE Directive – is based on EPR. This is an approach that puts the responsibility for the product at the end of its life with the producer. In addition, many WEEE structures and legislation are based on systems where the IT owner brings unwanted items to a municipal collection point. Producers then pay for it to be collected and treated.

In practice, only a small proportion of e-waste enters official channels. Customers may decide to put old IT in their general waste, or it may enter the informal sector if the customer decides to sell it to a scrap merchant or broker. This can be an effective way for items to be treated, but there is also a significant risk that the item can then be disposed of in an environmentally or socially irresponsible way.

Even within the jurisdiction of the EU WEEE Directive – legislation designed to increase WEEE recycling in Europe – Dutch research from 2008 showed that while 80% of WEEE was being recycled, only 31% was recycled by producer-funded WEEE systems and is therefore logged by the official system. Instead, the majority of WEEE (around 50%) is recycled by commercial collectors.[11]

IT owners often use the informal sector rather than official channels because brokers who purchase items for reuse or recycling can pay more than producer's asset recovery systems. Conversely, municipal services typically charge consumers for their waste disposal services rather than paying them for discarded WEEE. While producers support IT being sold on the second-hand market as reuse is higher up the waste hierarchy than recycling, when a product is handed over to a second-hand buyer, it is even harder for a producer such as HP to ensure the safe disposal of that product.

To help end-of-life IT be dealt with responsibly, HP provides information and a free recycling service which aims to make it easy and convenient for customers to safely dispose of electronic waste. However, despite these efforts, as a manufacturer, HP has a very limited scope to change customer behaviour. One of the few tools producers can use is communication but information-based advertising campaigns usually carry high costs and have only a limited impact on public behavior. For example, the UK-wide 'Are you doing your bit?' campaign ran from March 1998 to October 2000, at a total cost of £28.4 million. It included TV, radio and press ads, along with incentives.[12] Yet, an internal Defra review concluded that while it had created a strong brand and raised awareness, 'there had only been small changes in consumer attitude or behaviour'.[13] The challenge is to find a way to harness the commercial and informal sector for WEEE collection, while ensuring that WEEE is channelled into the proper recycling and processing facilities.

A challenging legal landscape

Producers also have a challenging time managing environmental impacts because legislation and implementation systems are completely unsynchronized – both within the EU and globally. This applies across the environmental spectrum from eco labels to WEEE. WEEE legislation is particularly varied. Legislation appeared first in European countries and there is now a proliferation of legislation in regions and countries which include the European Union, the US, Canada, Japan, Mexico, Brazil and China. Yet, there is a lack of harmonization both within countries and between them.

The complex implementation of the WEEE Directive in different regions and the differing or absence of e-waste infrastructure in other regions also make it costly and resource intensive for producers to manage WEEE internationally. In addition, environmental legislation has been developed in countries that have inexperienced governments in this area, leading to ineffective implementation.

The difficulty in capturing consumer interest

HP's research shows consumers use a variety of criteria when making purchasing decisions, making it hard to isolate the impact that environmental features have on product choice. Thus, finding ways to support the move towards more sustainable lifestyles and to promote environmental features in a way that capture consumer interest and supports sales is a complex proposition.

Consumer acceptance of use of recycled materials in products poses another challenge. This is because customers often equate products made from recycled material with poorer quality. When recycled materials have been rigorously tested and implemented appropriately, as HP has done through its research and design process, quality is not an issue. However, it will take time for consumer perceptions around recycled content to change.

Environmental fashions can be faddy

Fashions in consumer and media focus are often different from where major impacts lie or they are related to issues that producers have limited control over – such as how consumers dispose of their products. Alternatively, customer, media and market focus can follow trends which can help support environmental programs. However, when the focus moves on, the lack of public interest can change marketing priorities. This can, in turn, halt or slow investment funding in that issue during the R&D stages of new products, allowing gains to be lost.

27.1.5 A necessary work in progress

HP has found that having a clearly articulated and integrated environmental strategy has allowed the company to formulate clear and productive action plans to tackle issues such as energy efficiency and electronic waste. It has also led to many tangible business rewards, from brand benefits to competitive advantages. Attempts to integrate environmental thinking into everyday business practice have been successful on many levels, but full integration remains an important, ongoing process. The complex and ever-evolving nature of the environmental sphere also demands a pro-active and energetic approach in order to successfully deal with and conquer challenges. The next section takes one element of HP's environmental strategy – end-of-life product return and recycling – to demonstrate how the principles work in practice.

27.2 HP e-waste management in practice: HP end-of-life product return and recycling

This section describes various components of HP's electronic-waste (e-waste) management system to demonstrate how HP tackles e-waste in practice. The aim is to demonstrate a selection of successful innovations and strategies in order to share best practice and inform the debate to help workable solutions for industry-wide issues be developed. Topics covered include:

- HP's e-waste management system;
- the European Recycling Platform – a tool for the EU WEEE directive;
- E-waste in Africa;
- Putting theory into practice.

27.2.1 HP's e-waste management system

HP has been recycling since 1987. By 2010, HP had recovered a total of 1.07 million tonnes of electronic products (for reuse and recycling) and supplies (for recycling). In 2010, HP also achieved its target to use over 45 000 tonnes of recycled plastic in HP printing products.[14]

The HP approach

These successes are partly the result of HP's integrated approach to putting its environmental principles into practice. HP treats its obligation in the area of end-of-life product return and recycling in the same way that it manages other processes such as supply chain manufacturing. This means using the same principles of protecting workers' rights and dignity, ensuring strong health and safety standards, reducing environmental impacts, and upholding high standards of business ethics. Despite having one of the IT industry's most extensive supply chains (with approximately 50 000 suppliers in more than 120 locations worldwide), this is done through a variety of mechanisms which include:

- setting clear expectations and integrating social and environmental requirements into HP's sourcing operations;

- evaluating performance through self-assessments, audits, and key performance indicators;
- improving performance by approving corrective action plans developed by suppliers, and engaging workers and management in capability-building initiatives;
- engaging with local and global stakeholders to better understand and address issues in HP's supply chain;
- reporting fully and transparently the results of HP's efforts to improve supplier SER performance.

The Planet Partners recycling and reuse program

HP runs a variety of programs to recover unwanted IT. Since the launch of its internal recycling program in 1987, the scope and breadth of the recycling and reuse program has continued to grow, becoming known as the Planet Partners program in 1991. From 2008, consumers have been able to receive cash-back for many types of unwanted IT (see Table 27.1 for these achievements in more detail).[14]

HP's Planet Partners recycling and reuse program includes:

- free recycling of unwanted computer hardware and printing supplies for HP customers;
- a trade-in program which gives customers cash-back for aging technology (of any brand) to put towards new HP technology;
- donation for reuse programs that makes IT available to individuals who might otherwise not have access to computer technology;
- a return for cash program where eligible equipment goes on to be refurbished and resold.

To run these programs, HP works with a global network of vendors to process, resell and recycle returned IT products. In many cases, this means customers can bring their old IT to a municipal collection point where it is treated free of charge, or business customers can return IT to a designed point for free recycling. HP audits vendors annually to ensure they conform with HP standards, policies and supplier code of conduct.

HP's e-waste strategy also has several other components. These include working with legislators and governments to inform policy and infrastructure decisions to ensure regulation and systems are workable and effective.

To tackle e-waste in developing countries, HP collaborates with governments and non-governmental organizations (NGOs) to boost local capabilities to properly repair, reuse and recycle unwanted electronic equipment (see Section 27.2.3 for more details). To avoid illegal dumping of electronic waste, which poses a risk to the environment and human health, HP does not

Table 27.1 HP return and recycling timeline[a]

Year	Event
1987	HP establishes its own hardware recycling program.
1991	The Planet Partners program is launched for HP LaserJet print cartridge return and recycling and quickly expands to other product lines.
1997	HP becomes the first computer manufacturer to operate its own recycling centre.
2008	The new HP Consumer Buyback and Planet Partners Recycling program means consumers receive cash back for their unwanted PCs, monitors, printers, digital cameras, PDAs and smartphones of any brand. If there is no value, consumers can responsibly recycle their HP and Compaq-branded products free of charge.
	The HP Planet Partners print cartridge return and recycling program is expanded to include HP authorized retail recycling locations for HP ink cartridge and LaserJet toner cartridge collection, in addition to other recycling options.
	HP announce an industry-first engineering breakthrough. It uses recycled content – from cartridges returned through the HP Planet Partners return and recycling program as well as materials such as plastic water bottles – in the manufacture of new Original HP inkjet cartridges. This is the first closed loop ink cartridge process globally.
2011	HP continues to expand its global reach with hardware reuse program in 53 countries or territories; a hardware recycling program in 49; and a print cartridge recycling program in 54 countries or territories.[b]

[a]HP (2009), HP Environmental History. Available from: http://www.hp.com/canada/corporate/hp_info/environment/commitment/hp_environmental_history.pdf [accessed 16 August 2011].
[b]HP (2011), HP Product reuse and recycling. Available from: http://www.hp.com/hpinfo/globalcitizenship/environment/product_reuse_and_recycling.html [accessed 16 August 2011].

allow the export of electronic waste from developed to developing countries for recycling.

Taking an approach that tackles the issue of e-waste in an integrated way across the company and in wider society has been a major factor in the success of HP's e-waste strategy. HP is committed to working with competitors, suppliers, government, NGOs, customers and other partners as collaboration is the most effective way to tackle the issue of e-waste.

27.2.2 The ERP: a tool for the WEEE directive

The ERP and the WEEE Directive are excellent showcases of the benefits of collaboration and partnerships. The WEEE Directive is arguably the most significant piece of environmental legislation to come out of the EU in recent years. It aims to reduce the amount of electrical and electronic equipment being produced and to encourage people and organizations to reuse, recycle and recover it. The electronic waste it targets consists of washing machines, TVs, microwaves, mobile phones, printers, and computers. ITC typically accounts for 12% of WEEE by weight.[2] In general, WEEE is collected when consumers give their unwanted WEEE to the municipality. The e-waste is then handed over to waste management companies who transport and treat it on behalf of the manufacturers.

HP participated in all stages of the legislative process to help ensure that the Directive worked in practice as well as on paper. HP also joined together with Electrolux, Procter & Gamble and Sony to found the ERP – a compliance scheme for recycling electrical and electronic waste at a pan-European level.

Creating a competitive advantage

By pooling volumes and procuring recycling services on a European level, the ERP opened up opportunities for pan-European recycling services and cross-border competition. This ensures the lowest costs for member companies and their customers. This is because waste management companies compete to meet WEEE collection and treatment targets and to win contracts.

The ERP is also designed to ensure that the same, high recycling standards are applied in all countries, even when regulations are not as stringent. The ERP is also designed to encourage innovative waste management strategies and the national implementation of the directive according to a set of core principles which are fundamental to the protection of consumers and business, as well as the environment.

To design the platform, a team of recycling experts from the four companies contacted some of Europe's leading recycling firms. Numerous market surveys were also undertaken, alongside extensive benchmarking of existing recycling schemes.

Thus, the platform has provided the opportunity to reduce each company's annual recycling costs by millions of euros. This element of competition has been particularly beneficial because it has helped to ensure cost-effective implementation of the WEEE Directive. This also helps the environment as cost savings can be reinvested in improved product design for recycling. It has been more difficult to shield customers from the costs of WEEE in regions where monopolies exist as they have been able to set higher charges.

Building on its success

The ERP continues to expand and grow. Other multinational producers have joined ERP, attracted by the pan-European solutions it offers. It now operates in 12 EU countries and has extended its scope to batteries and packaging to become a full service waste provider for producers. By July 2011, ERP had collected and recycled over 124 0000 tonnes of WEEE on behalf of its 1765 members[10] whether at country or pan-European level, testament to the power of partnerships in finding effective e-waste solutions.

27.2.3 E-waste in Africa: making the informal, formal

HP is committed to tackling the illegal dumping and mistreatment of electronic waste in Africa. HP works with partners to find, develop and test sustainable solutions to ensure the proper treatment of old IT. The success of these projects in harnessing the informal sector can be an especially useful learning tool for Europe and the rest of the world.

E-waste in Africa: background

Africa is a growing market for new products, with some regions becoming as important to producers as Western markets. For example, South Africa has become as significant for HP as smaller European markets such as the Netherlands and Switzerland. As the volume of electrical goods, such as fridges, TVs and computers, in use in Africa grows, so does the importance of sustainable e-waste management systems. It is this growing domestic e-waste that presents the most pressing problem – because although the media has highlighted the issue of illegally imported e-waste, transporting e-waste to Africa usually costs more than recycling it in Europe. For example, the cost quoted to HP in Germany for the recycling of cathode ray tube (CRT) monitors and TVs – the most costly product in the IT e-waste hierarchy – was less than €100 per tonne. This is far less than shipment costs to Africa. This creates financial reality that naturally restricts volumes of imported e-waste.

Second-hand products – some of which may originate in Europe or America – play a vital role in Africa as they make technology, and the benefits that technology offers, accessible to those unable to afford new products. However, manufacturers cannot control the second-hand market as it is in the hands of the both the seller and the second-hand purchaser. In addition, shipments of second hand products may illegally contain products which are too outdated for the African market, or that cannot be repaired.[15]

E-waste in Africa and other developing countries is handled by the informal sector. Research has shown that while the logistics of the informal sector is effective, their recycling is substandard and can damage ecosystems and human health. The sector provides valuable jobs for people who have difficulty accessing formal employment, yet many working in e-waste end up putting their health at risk through improper treatment practices, such as burning items to access precious metals. The collection and proper recycling of e-waste could provide many with a decent livelihood.[16] The challenge is to use the informal sector's strength in collection, while avoiding it being involved in improper recycling.

HP's 'E-waste Management in Africa' program

HP's 'E-waste Management in Africa' program[17] supports the development of practical, socially just and sustainable local e-waste solutions. The challenge is to use the informal sector for collection and channel the e-waste into proper recycling facilities.

Research and pilots undertaken by HP[17,18,19] to date demonstrate that sustainable e-waste management practices can complement existing infrastructure while creating jobs and protecting health and the environment. Reuse projects also help to bridge the digital divide by making IT more affordable. Projects undertaken in Kenya[17] and South Africa[16] have shown that it is possible to harness the informal sector by setting up sustainable waste treatment facilities. These provide a safe deposit point and working environment for workers and can become self-sustaining.

Other partnerships tackle other elements of the e-waste challenge – such as developing country-wide infrastructure or fit-for-purpose legislation. For example, in Morocco, a public private partnership with German Cooperation Department to develop a country-wide e-waste take-back and recycling system is showing promise. In Nigeria, HP has been involved in a training workshop for the informal sector on best practice for recycling and is in consultation with Nigerian Environment Agency (NESREA) on e-waste regulation in compiling an E-Waste white paper/solution.

Case study: South African recycling facility[16]

Designed to test the feasibility of an integrated local e-waste management system, this material recovery facility incorporated current informal e-waste processing activities and transformed them into sustainable and environmentally sound operations by ensuring unwanted IT was recycled or refurbished in a safe and efficient manner. The unit focused on refurbishment, repair, reuse, dismantling and recycling of equipment, with environmentally responsible disposal a last resort.

Project outcomes included:

- the creation of a sustainable waste management blueprint;
- job creation and skills transfer;
- promoting digital inclusion by making e-goods more affordable.

Case study: investing in a South African partner

When HP wanted to establish a hardware recycling program in South Africa, the challenge was finding a recycling company which could comply with HP recycling standards. Discovering that none existed, the South African Environmental Manager and his team worked with a South African recycler over many months to bring them up to HP's environmental, legislative, employment, and heath and safety standards. Their efforts paid off and in 2009, the recycler became the first recycler on the African continent to be approved by an HP third party auditor as a recycler supplier. HP invested a huge amount of expertise to create a South African recycling solution but this now means that HP customers have been able to use the service to responsibly dispose of unwanted IT.

Case study: East African Computer Recycling (EACR)

In 2010, HP supported the establishment of East African Computer Recycling (EACR) by Camara Education.[17] Based in Mombasa, EACR is the only IT e-waste recycling facility in Kenya operating to high international recycling standards. The long-term aim of the facility is to capture 20% of IT e-waste in Kenya. Its goal is to improve health and safety and recycling standards and to establish a local, sustainable IT e-waste recycling industry.

Following the establishment of the facility, HP offers its Planet Partners program to HP business and public sector customers for the free recycling of their end-of-life IT hardware.[20] The EACR also receives end of life IT from Camara Education's schools, and the informal sector. The IT e-waste is assessed for reuse, refurbishment or recycling. End-of-life products are dismantled and separated into the different components, such as plastics and metals. Complex parts will be sent to advanced treatment facilities. HP's audit process includes second and third tier companies to ensure that when the dismantled IT parts leave the EACR for further processing they are treated appropriately.

An important outcome of this process is working with the informal sector to encourage them to understand both the personal safety and economic benefits of this approach to e-waste recycling. For example, workers will learn that delivering whole products to EACR is more profitable because formal break-up processes will allow more value to be extracted whilst also minimizing negative health and environmental impacts.

27.2.4 Putting theory into practice: insights from industry

HP's focus on designing for the environment whilst also recovering, recycling and reusing end-of-life IT and dealing with the reality of meeting WEEE targets has allowed it to gain many valuable insights into how principles, legislation and practices can work in reality. Some key findings are described below.

The independent producer responsibility (IPR) principle: admirable but unworkable

The WEEE Directive aimed to utilize the principle of independent producer responsibility (IPR). IPR aims to internalize the environmental burden of products by asking producers to cover the costs of managing the end-of-life for any of their own products. This approach was expected to encourage producers to use sustainable designs and materials as this would allow them to minimize the cost of end-of-life processing. In practice, this has not been common. This is partly because the treatment of waste put onto the market before August 2005 was financed by producers according to the market share of that product, and not the actual end of life processing of that product. Many countries continue to apply the market share model to products made after the 2005 deadline. This means that a product containing a hazardous material or that is hard to recycle costs the producer exactly the same as a non-hazardous or easily recycled one, providing no incentive for producers to design for the environment.

Another barrier has been the logistics of identifying e-waste by manufacturer, both for record keeping and to allow any design for the environment recycling features to be identified and treated appropriately. However, with 9800 WEEE producers registered in 2009 in Germany alone,[21] and many thousands more across the whole of the EU, the additional sorting, transport and storage that would be required to do this make the whole process unviable by inflating the costs and the environmental impact.

Costs per category more desirable than a flat tax or visible fee

The IPR approach is preferable to a flat tax, visible fee or charge for e-waste. This is because these mechanisms do not recognize the varying recycling costs for different products.

The Visible Fee is a method of organizing the WEEE Directive where a visible tax on IT pays for recycling. The tax can either be on the consumer, i.e. an additional sales tax, or on the producer. In practice, a visible fee tends to be on the producer whatever way it is manifested, as producers are more likely to absorb the cost internally than put their prices up. The Visible Fee mechanism can also be very inefficient as the internal administration costs (e.g. changes to and maintenance of the companies invoicing system) can be much higher than actual recycling costs, which can be cost neutral if managed effectively as part of a competitive recycling system.

An alternative more sympathetic with the IPR principle is a system where costs are separately captured within a product category for recycling. This would allow like products, such as monitors and TVs, to be charged appropriately, and could even allow refinement to products within the categories to allocate the recycling/waste management costs to the manufactures of that category. This would be relatively easy to implement and therefore would be unlikely to carry prohibitive costs.

Producer sampling has potential

Product categories could also be refined to include sampling the amounts of a specific producer in each waste stream. This would reward responsible producers who design for reliability and durability, as HP's research has shown that the amount of HP products that appear in the WEEE stream is much lower than HP's market share. This is because customers use HP products longer, and HP products are more likely to be reused, which also keeps them out of the waste stream for longer. This means HP products typically appear in the waste stream after ten years.

Recognition of manufacturers' own programs

Another important next step would be to allow manufacturers to reconcile what they collect internally with their legislative target. This would reward producers for their achievements in recovering WEEE directly from their customers, and allow a greater budget for implementing effective take-back and cash-back programs.

WEEE systems do not recognize value or the role of the informal sector

WEEE structures and legislation is typically based on systems where the IT owner (that is, the customer) brings their old equipment to a municipal collection point where the manufacturers pay for it to be taken and treated. This system works well if the WEEE recycling value is lower than collection and treatment costs. But it does not acknowledge that a large proportion of unwanted WEEE has a recycling value higher than the collection and treatment costs.

WEEE systems need to be designed in a way that reflects the intrinsic value of a large proportion of WEEE to encourage proper treatment. It also raises questions about the role of the manufacturer in a system where waste is a valuable commodity because the waste management system in 2020 will be considerably different from the system in 2011. This, and other future trends, will be discussed in Section 27.3.

27.3 Future trends

The global population in 2010 was 6.7 billion, of whom 1.2 billion had the financial wealth to buy electronic products. By 2050, the OECD estimates that the population will be more than nine billion. The UN estimates that 6–7.5 billion of these will have the financial wealth to buy electronic products.[22] This growth in the electronic goods market is expected to have a significant impact on WEEE. This section outlines the major trends that HP feels may influence WEEE in the future. These include:

- the influence raw materials pricing and scarcity will have on recycling;
- exploration of new business models;
- EPR and its impact on recycling;
- lessons from other WEEE management systems.

27.3.1 Raw materials pricing and scarcity on recycling

The IT industry utilizes a variety of raw materials in its products. The security and affordability of these materials are of central significance. Increased population and demand for IT, plus wider range of products incorporating IT, will lead to an amplified demand for raw materials. This is anticipated to have an impact on WEEE in two main ways. First, end-of-life WEEE will become more valuable as a source of raw materials. Second, the composition of WEEE will change as rare or expensive materials are substituted. This issue is discussed in more detail below.

Pressures on supply

Acute supply problems (caused by conflict, unstable regions, increased demand and scarcity, for example) and dramatic price increases in raw materials have caused many industry experts and commentators to question future availability. Rising energy costs will also have an impact on the price of raw materials as many are either made out of oil – such as plastics; or energy is a significant element of the production cost – for example, the high electricity cost for aluminium. These issues are especially relevant for the high-tech metals and rare earths used in electronic products.

Manufacturers have several choices to enable them to minimize the impact of physical scarcity or dramatic price increases. These include:

- increased efficiency;
- long-term contracts;
- substitution of raw materials;
- increased use of recycled materials.

Increased efficiency

As materials become more scarce and/or expensive, they will be used much more efficiently. Product designs will become more intelligent, focusing on how to get more from less. For example, incorporating thinner walls in struts or honeycombs which provide strength can achieve the same product quality with reduced materials. Manufacturing processes will also be honed to reduce waste or to capture it for reuse.

Long-term contracts

Consortiums of governments, companies and manufacturers will attempt to guarantee their supplies by negotiating exclusive contracts and agreements with suppliers and sub-suppliers for vulnerable metals. This has already started. The BBC reports that the Japanese government has already started to negotiate such contracts with mines in Vietnam,[23] while the *Financial Times* reported that SOJTZ, one of the biggest importers of rare earths in Japan, has brokered a deal with the rare-earth rich, Australian-based Lynas Group, to reduce their dependency on Chinese rare earths.[24]

Substitution of raw materials

Substituting metals with another material that occurs in large quantities, or with renewable resources like bio-plastics, would be a sustainable strategy for securing raw materials. This has already happened in the automotive sectors where parts traditionally made out of metal are now made from plastics. HP Labs is currently working on a project to replace copper lines with optical fibers – a solution already used in telecoms. If successful, substituting copper in PC-boards and chips could avoid the mining and processing of thousands of tonnes of copper. Innovations such as these will also change the properties and optimal treatment options of WEEE.

Increased use of recycled materials

One of the most sustainable solutions is the substitution of raw materials with recovered or recycled materials. A portion of this is likely to come from WEEE as WEEE management systems become more commonplace and effective. However, there are huge differences in the availability, price and processing characteristics of secondary raw materials. Many mass metals, such as copper and iron, have established recycling structures and properties that remain constant throughout reprocessing. In contrast, the recycling of high tech materials is more complicated.

This is because many are often used in one electronic item – for example, a mobile phone has 15 or more high tech metals. This makes separation challenging, and volumes are not high enough to make reuse practical from a technical or economic point of view. However, this could change if efficient recycling processes are developed.

One possible measure to increase the concentration of precious metals is the manual separation of specific product components – such as the connector strips from circuit boards – which have higher concentrations. Measures such as these can mean recycling and precious metal recovery rates of above 90% can be achieved.[25] In addition, 'urban mining' could become more commonplace in order to locate materials for recycling. This is when materials are extracted from waste streams, landfills and previously constructed products, infrastructure and buildings.

Rising prices for scrap – both metal and other components such as plastic – will dramatically change the structure of the waste business as more and more players seek to enter the market. This will transform the waste industry from being handled municipally to being a mainly privately owned and managed sector. This will in turn raise the return rate for e-waste as private companies will be able to offer more convenient recycling options to the owners of WEEE, such as household collection services. If supported by changes in legislation, today's disposal companies could be transformed into raw material producers who recover valuable materials to try to create a closed resource cycle.

27.3.2 Exploration of new business models

The effectiveness of extended producer responsibility is limited by the lack of ownership producers have over IT at the end of its life (see Section 27.1.4 for more on ownership). Attempts to address the ownership issue are expected to lead to a growth in the development of new business models. In the commercial market, business models will evolve from selling hardware to the provision of services.

This reflects a shift towards increased dematerialization – that is a reduction in the consumption of materials and energy used to achieve an end goal. The replacement of business travel to meetings with Internet-based video conferences is one example. It is estimated that the market for these types of services reached US$36 billion in 2011[26] and is expected to grow by a further 20% in the next few years. This trend will lower the use of raw materials in the long run. This could reduce the pressure on high tech metals, and also on WEEE management systems as less hardware should result in less WEEE.

Companies such as HP have recognized the trend towards dematerialization and have started selling services – such as video conferencing, printing or data management – in place of hardware. In the data management example, this means that instead of clients buying and running their own data center, HP provides computing resources in its own data centers for the customer. This means the customer does not have to worry about capacity and performance constraints, upgrading and replacing hardware, software or even service. And, as HP can manage the capacity in a virtual way amongst its clients, less hardware is required, reducing the demand for raw materials and physical products, which in turn has a long-term reductive impact on WEEE volumes.

The new business models are very successful in the commercial customer segment and have unfortunately not yet found their way into the consumer market. These models, where the producer retains control of the hardware, will also have a significant impact on WEEE as they enable the producer to retain ownership of the item at the end of its life. This means that producers will be able to benefit more easily from investments in design for recycling, reuse or upgrades.

27.3.3 An evolving e-waste market

Involving the informal sector

As described in Section 27.3.1, scrap prices are linked to raw material prices. This will have a knock-on effect across the whole e-waste market. The higher raw material prices are, the higher the value of recycled materials and the value of e-waste. The higher the value of e-waste, the more WEEE owners will expect to be paid for their unwanted electrical goods at their end-of-life. And the higher the value of e-waste, the larger the e-waste market as more individuals, small companies and mid-sized companies collect e-waste outside of municipal or manufacturer schemes. This is already an issue – with a Dutch study suggesting that 80% of products and devices on the market are recycled, but approximately 50% of this is done by individuals or organizations operating outside of official WEEE systems.[11] The challenge is to guide those in the informal e-waste market (from scavengers and refurbishers to e-waste processing plants) towards a structure where all e-waste is handled safely and efficiently.

The most likely structure is one which uses the informal sector in areas where they excel, such as collection, sorting and basic dismantling in local environments. However, the more complex processes such as recovering and recycling of precious metals require greater technical effort and specialized facilities. These facilities require high levels of investment to be established, and need high volumes in order to be economic. This means they will need to be supplied by several countries.

This is vital as the recovery of precious metals can harm the environment and health if not properly performed, which is common when WEEE is subjected to ‘backyard recycling’. This is when items are roughly broken down and often burned by untrained individuals to retrieve precious metals in a way that is dangerous and which harms the environment and human health.

As WEEE evolves into a commodity instead of waste, e-waste legislation needs to be completely reviewed to reflect this changing dynamic. It also raises an interesting question over the role of producers in a world where retired products are not waste but valuable objects.

27.3.4 Lessons from other WEEE management systems

The successes of other regions in tackling components of WEEE management are likely to have an impact on Western systems. For example, many African countries such as Nigeria, Kenya and South Africa have a very active informal e-waste management system. This system is very effective in collecting and capturing e-waste. Treatment is often poor – with WEEE often being treated in a way that has negative health or environmental impacts. However, the success of projects which harness the informal sector to collect and carry out basic dismantling and sorting is a model which could be usefully employed in Europe. This could be used both in the treatment of WEEE and in terms of job creation. Research and pilots undertaken to date as part of HP's E-waste management in Africa program (see Section 27.2.3 above) demonstrate that sustainable e-waste management practices can complement existing infrastructure while creating jobs and protecting health and the environment. Reuse projects also help to bridge the digital divide by making IT more affordable.

Projects undertaken in Kenya and South Africa have shown that it is possible to harness the informal sector by setting up sustainable waste treatment facilities. These provide a safe deposit point and working environment for workers and can become self sustaining. These projects have the ability to become learning tools for others in developing countries, as well as Europe and North America.

27.4 Sources of further information and advice

For further information on HP's environmental strategy please visit HP's Global Citizenship website at www.hp.com/hpinfo/globalcitizenship. For more information on HP's Planet Partners product return and recycling program, please visit http://www.hp.com/hpinfo/globalcitizenship/environment/recycling/product-recycling.html.

27.5 Conclusions

WEEE and other environmental legislation pose challenges for producers in the IT industry. However, the development of a strong environmental management strategy that is integrated into the business enables companies such as HP to tackle these challenges effectively. This means that concrete environmental benefits can be achieved in a cost-effective way.

In a finite world where material scarcity is likely to become more pressing, and landfill becomes less accessible, design for recycling is ever more pressing. As the e-waste market evolves towards end-of-life IT as valuable commodities instead of waste, e-waste management systems and legislation must evolve with it.

Most importantly, the systems and legislation must ensure that WEEE is handled appropriately – safely and in a way that safeguards the environment and human health. Good recycling systems should reduce pressure on demand for raw materials. The systems of the future are also likely to include a focus on competitive marketplaces that allow producers to meet WEEE treatment targets cost effectively. It will also include new business models that support EPR by giving producers ownership of hardware (such as the move towards selling of services instead of hardware). The informal sector will also be harnessed in the collection, sorting and basic treatment of WEEE, while overall, the distinction between the formal and informal sector will become less important.

The WEEE landscape will look very different in 2020, and in 2050, than it does today. The challenge is to work together to work towards solutions that promote closed loop systems so that in the future, WEEE as waste will be a thing of the past.

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28
Siemens' WEEE management strategy

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Abstract: This chapter explains how a corporate WEEE management strategy represents more than a focus on collection rates or recycling quotes. It is rather a company-wide resource-conserving philosophy that considers the complete life cycle of a product. The overall WEEE management strategy can contain particular strategies for refurbishment of electronic devices and systems, reuse of components, extraction of spare parts and recycling. To increase the company's WEEE management efficiency, some existing procedures will have to change and new ones will have to be created. This chapter discusses the use of a database to check the conformity of materials to regulations, the design of electronic products for reuse and recycling, the reduction of WEEE by optimising material use in a product, and the need for close cooperation with component suppliers as means to improve the efficiency of WEEE management.

Key words: Siemens standard SN 36350, substance and material management, WEEE reduction by material optimising, supplier dialogue on web-based database, design for reuse and recycling.

28.1 Introduction: WEEE as an important element of the overall environmental protection strategy

This chapter is concerned in particular with the waste electrical and electronic equipment (WEEE) management strategy of Siemens AG, which is more precisely described using the example of the Siemens Healthcare Sector. Although special focus is put on the topic WEEE here, the handling of WEEE (Directive 2002/96/EC), Restriction on Hazardous Substances (RoHS) (Directive 2002/95/EC) and other standards should not be considered as an isolated matter. For example, the use of hazardous substances in an electronic product has a strong impact on the ease or difficulty in recycling that product. A broad 'cradle to cradle' view for the products becomes more and more important – even for the 'end' in the life cycle, which is by now a precursor of the 'beginning'. This means that products, components or materials may have more than one life cycle to take into account with reuse, refurbishment or recycling.

When looking at the product life cycle the cumulated energy consumption associated with the product should be taken into account as well as the material choices. Therefore, today WEEE management is much more than collection and exploitation of electric and electronic waste. It is furthermore a sensible recirculation of appropriate electronic devices up to the refurbishment of complete equipment. The consequent result must flow in added value both for the customer, e.g. by savings within the purchasing, and for the manufacturer, e.g. by savings within the use of resources and to complete the product portfolio as well as to win new customers. In this comprehensive survey, not just a consideration of the pure WEEE but rather a consideration of all waste generated within the life cycle of a product is imperative. This includes waste generated during manufacturing, distribution, use, service/maintenance and also disposal of electric and electronics products. Consequently WEEE management includes both product-related and operational environmental protection.

28.2 Siemens' environmental business management

28.2.1 The early Siemens' access to environmental protection

For Siemens AG, environmental protection is a business task, a social responsibility and a success factor, particularly as customers more and more assign value to environmentally sound products. The challenges existing worldwide, such as management of material resources, energy management and reduction of global warming, can be mastered only with innovative production procedures and with an ambitious environmental management. Siemens looks back to a long tradition of environmental protection.

The foundation of the Siemens business department 'environmental protection' goes back to the year 1971, a time when environmental protection hardly played a role in the public awareness. But all efforts in this direction started to raise more and more public interest and also it was to perceive that increasingly the legislature intended to develop more activities for environmental protection. Siemens recognized this tendency early, took the initiative and invested to create this special department. Siemens was one of the first major corporations promoting environmental awareness.

This was a historic time for the laying of the foundation stone of a Siemens management system, for product-related and operational environmental protection. At that time essential focal points of the newly founded business department were:

- Support of Siemens divisions with the design of environment-friendly products. The Siemens business department for environmental protection affairs coordinated the company representation to ministries, federal institutions, trade associations as well as the corporate representation of interests.

- Coordination and support of observation, measurement, evaluation and improvement of the environmental characteristics of products. Here the Siemens business department for environmental protection affairs was involved in the coordination tasks, obtained expert advice regarding company-wide information and also informed different institutions within the company. Thus a broad knowledge base was developed concerning environmental protection topics in the whole company.
- Assistance with the build-up and expansion of an environmentally compliant system of manufacturing products.

The supportive role of the business department for environmental protection affairs included the clarifying of principles of environmentally compliant manufacturing. Furthermore the department was already involved in internal and external working groups and committees. In this way the first company-wide management organisation for operational and product-related environmental protection was established. Since then the environmental management strategy has been consistently developed and adapted to the new requirements.

28.2.2 Siemens standard SN 36350

As early as 1995 Siemens introduced an internal environmental design standard: the internal Siemens standard 'SN 36350 – environmental-friendly products and plant engineering'. The company-wide validated standard is adopted in all Siemens divisions. It regulates the environmentally sound organisation of products and plants with consideration of its entire life cycle. It also qualifies Siemens to develop environmentally friendly technologies. Hereby it is to be considered that 90% of the environmental impact of a product – during the entire lifespan – is already specified in the phase of development by functional requirements, design and other criteria. Therefore it has to be considered that most of the EEE products generate their main influence on the environment mainly within the phase of use. However, the end-of-life phase should not be discounted, because materials and material recovery plays an increasing role. Moreover a global company like Siemens has to comply with the particular legislation in the different countries – not alone within Europe but also for Americas, Asia and others. This demands a strategy that reaches the maximum possible of international coverage.

As a consequence Siemens standard 36350 is concerned especially with the management of materials (e.g. RoHS) and goes up to the exploitation of used equipment (WEEE). Siemens also goes beyond legal requirements. As an example, in the context of the internal Siemens program Fit4 2010, on a voluntary basis Siemens began to change over manufacturing to lead-free soldering procedures as well as RoHS conformity for such products which are not subject to the RoHS Directive for the restriction of the use of certain dangerous materials in electrical and electronics devices.

The Siemens standard SN 36350 describes the integration of the environmentally compatible product and equipment layout into the management systems. It corresponds without exception to the specifications of the International Electrotechnical Commission standard 'Environmentally conscious design for electrical and electronic products' (IEC 62430, 2009).

A manual with examples supports development engineers with the application of the standard in the context of the product and equipment layout. This manual includes the following aspects that must be considered within project engineering:

- rules for all life-cycle phases of a product;
- rules related to plant engineering and construction;
- integration of environmental aspects into the product life cycle;
- aspects of management.

Additionally the Siemens standard SN 36350 and the associated manual contain among other things strategies for:

- reduction of resources consumption (materials, electric power, water; improvement of the energy efficiency);
- environmentally compatible technologies;
- restriction of hazardous substances (e.g. RoHS);
- materials that require declaration and material restrictions;
- ecological requirements in packing;
- customer information and product environmental declaration;
- requirements for recycling (e.g. WEEE).

An analysis tool supports the developers during the measurement and evaluation of the improvements, which are obtained by a new layout of products and equipment. This toolbox is a semi-quantitative evaluation tool, which contains several checklists, out of the Siemens Standard SN 36350. It represents a self-assessment tool for all developers during the product engineering process. Furthermore life-cycle assessments (LCA) are applied increasingly. LCAs are utilised to evaluate thinkable environmental impacts of a product or of processes in the context of all the stages of a product life cycle.

The application manual contains information and recommendations regarding the employment of materials, such as plastics or metals, that are suitable for recycling. The toolbox is improved constantly. Examples of ecologically outstanding products are compiled in the Siemens Environmental Portfolio (www.siemens.com/sustainability).

28.2.3 The global Siemens environmental, health and safety (EHS) Principles

A corporate philosophy is absolute essential, with the mission that a worldwide acting company with more than 400 000 employees is able to operate in a globally common way. This philosophy is based on the EHS (Environmental protection, Health management and Safety) Principles of Siemens. The 'Siemens Business Conduct Guidelines' provide the basis of the worldwide environmental management policy. From this the EHS Principles are derived – with the structure of responsibilities, reporting lines and the control system in the company.

The EHS Principles are made concrete and supplemented in topic-specific guidelines; for example in the guidelines for operational environmental protection, or in the guideline for product-related environmental protection. In turn, the guideline for product-related environmental protection refers to the independent Siemens Standard SN 36350. The organisation of the WEEE is covered in these guidelines. All in all, a set of rules arises, which is obligatory for all subsidiaries and enterprises with more than 50% share in an estate.

The principles regulate the EHS cooperation of the different enterprise units and they define the organisation, the obligations of the management and the employees in all EHS functions. EHS Principles are developed on structure of the ISO Standard for environmental management systems ISO 14001 (ISO, 2009) and they also contain important structures and communication paths of the EHS organisation. This organisation intervenes European-wide in the WEEE management.

The EHS Principles specify requirements for a comprehensive EHS management system (EHS MS), which has to be carried out by each Siemens organisational unit. The EHS MS is compulsory worldwide for all employees and for all processes used by Siemens. By this means a company-wide basis is given for the application of a worldwide applicable WEEE management system.

28.2.4 Principles and guidelines for environmental protection

From the Principles – which define the cooperation of the enterprise units and the organisation as well as the obligations of the management and the employees – different EHS guidelines are derived. Global guidelines were developed to meet Siemens' requirement of a consistent approach to environmental protection. Among other things the manual 'Product-related Environmental Protection' deals with the substantial stations of the products in their entire life cycle.

As well as the avoidance of dangerous substances in products, the separate collection and exploitation of electrical waste increasingly plays an important role. In the WEEE management strategy the fact that different countries have pertinent regulations is also taken into consideration; for example, the countries of the European Union, China, Switzerland, Norway, Japan, Canada, South Korea and the different states of the USA. In future, countries such as Argentina and Brazil will follow in this approach. This means that the basic requirements for the products – independent of the countries – are determined in Siemens Standard SN 36350. The regional Siemens organisations, which are responsible for the different countries, are responsible for identifying and implementing country-specific requirements to product specifications. This happens for each country designated for delivery and is oriented towards the highest demands. In this context it is important to recognise that in Europe the EU WEEE Directive is used in some non-European Union countries as a basis for similar regulations. This knowledge is the basis for the worldwide WEEE management strategy of Siemens.

In particular consumer- and/or household- and IT products play a basic role. The Siemens manual for product-related environmental protection aims, just like the EU WEEE Directive, to prioritise the avoidance of waste of electrical and electronics devices. Beyond that, Siemens seeks to encourage the reuse, recycling and other forms of the exploitation of such wastes in order to reduce the quantity of waste that is landfilled and in order to preserve valuable secondary raw materials. These requirements must be considered during the design phase of product development. Products should be designed in such a way as to reduce energy consumption, material use and generated waste as much as possible in with their production and during their use. Siemens had long adhered to product responsibility on a voluntary basis before the WEEE Directive was put into force by the European Union.

28.2.5 Management mechanism within Siemens as global acting company

An organised management mechanism enables Siemens to handle the specific WEEE requirements within the different European countries as well as within the different business units in the world. The WEEE management strategy of Siemens must consider that Siemens produces both pure industrial goods – which do not fall under the EU WEEE directive – and consumer products, which must be treated in accordance with the needs of the EU WEEE directive. This does not simplify the situation for the total enterprise, because, within the combination of industrial and consumer goods, the fact that different material and manufacturing methods as well as different collecting and recycling procedures are often linked must be taken into account.

One of the first measures which Siemens took was the company-wide demand to design step by step all industrial goods in conformity with the RoHS Directive for the restriction of the use of certain dangerous materials in electrical and electronics devices, even if they do not fall under the EU RoHS and WEEE Directives. The product's end-of-life was also taken into account when making the decision to remove hazardous substances because this means that recovered materials can be reused in the future in a universal way as basic materials for new products – both within the industrial range and within the range of consumer products. This becomes feasible even if collecting and recycling paths are distinctly different for industrial and consumer products, i.e. public collecting points are used for consumer products and professional disposers or recyclers are used for industrial goods.

In the context of the WEEE management strategy Siemens also had to consider the organisation of the take-back paths as well as the take-back organisations involved (worldwide and in particular for Europe). It is important for the implementation of the Siemens guideline – and therefore for the implementation of the WEEE management strategy – to consider that worldwide registration obligations exist in some countries for manufacturers and/or initial distributors.

Siemens fulfils the requirements of the WEEE Directive and takes part in common collecting systems in most EU member states, which were developed in coordination with branch associations. Alternatively Siemens signs individual contracts with specialised recycling enterprises.

Contract conditions regulate the Siemens standards so that with the collection and recovery, material cycles are closed and valuable resources are preserved. Particularly in Europe compliance with the registration obligation must be considered in each member state. At Siemens the performance is organised in such a way, that in each European country the particular national regional companies are obligated to it. They have to register the quantities of Siemens products which are imported into 'their' countries and which fall under the WEEE Directive. Within this framework the return flow of WEEE to the regional organised collecting points is also regulated. In the context of industrial goods, bilateral contracts regarding the returning of WEEE are made with certified business partners. For this Siemens mandates preferred contractors, who can act and who are allowed to act Europe-wide. In this way the material stream can be affected purposefully by Siemens. In this context, our many years of experience shows that with our own initiatives for taking back, refurbishment and reselling of used products and plants, a successful business model can be achieved in some product categories. Moreover, refurbishment and reselling is in consequence of the lifetime extension of equipment a real contribution to environmental protection. In this chapter a typical example is represented by the description of the products of Siemens Healthcare.

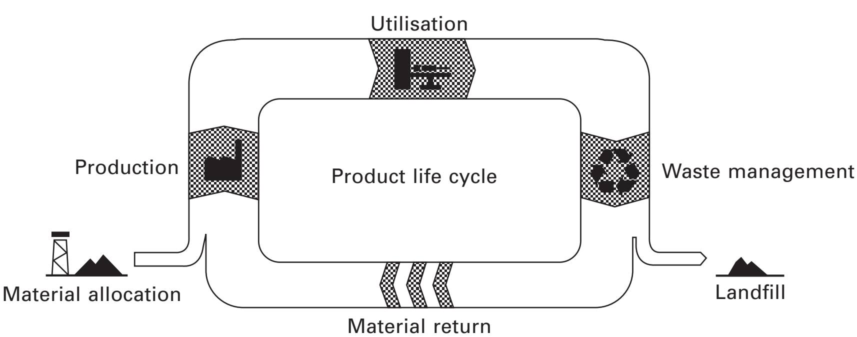
28.3 Significance of WEEE aspects within the product life-cycle management (PLM) process

The integration of all environmental protection aspects in the entire product life-cycle management (PLM) process – also with view to WEEE – is an important target. This is essential for a 'cradle to cradle' (McDonough and Braungart, 2002) philosophy at each step of product life cycle. The core statement of this philosophy is 'waste equals food'. This means, for products, that a purposeful selection of materials, in which the next use is kept in mind, would be therefore trend-setting. It would be an ideal to reach nearly zero landfill.

Figure 28.1 shows a material stream cycle. In this example the term 'material' can signify base material or the extraction of spare parts or the reuse of components or the refurbishment of systems. Within the framework of this philosophy an intensive analysis of the boundary conditions is essential. In our case a reasonable differentiation between consumer products and industrial goods and their specific needs in the beginning of the life cycle is a basic requirement – not least for WEEE requirements in the end stage.

Consumer products

Because of the fast innovation speed of some consumer products, their life cycle becomes shorter and shorter. Since consumer products have a relatively short life span, there has been in industry a general move away from using expensive materials towards more cost-effective substances (e.g. using plastic mountings instead of metal parts). This trend is worth recognising because nearly no reuse of components or refurbishment of many consumer products is to be obtained. The majority of manufacturers have standardised the materials used for consumer products.



28.1 Material stream cycle. © Siemens.

Industrial goods

Manufacturers of industrial goods often get their old devices or plants back again. These products usually have a lifetime of more than 10 up to 20 or even 30 years. For this reason it makes sense to use technically long-lived materials. Because the quantities and value of materials used in industrial goods are higher than in consumer goods the refurbishment and recycling of used devices are more profitable. To find the right way for the enterprise and for the product range, it is necessary to consider the business strategy, the product strategy and design strategy in accordance with ISO/TR 14062 (2003).

In the context of appropriate strategy tracking, the clarifying and monitoring of the following recycling-referred objectives are considered as necessary for the WEEE strategy development:

- environmentally related up-to-date requirements of the market and customer;
- inquiry of the present and future legal requirements (e.g. WEEE Recast);
- analysis of predecessor and competitor products;
- investigation of relevant environmental aspects and associated impact on the environment during the entire product lifetime;
- determination of the necessity of a concept for the treatment of the old products;
- inclusion and consideration of the current recovery situation (categories, collecting rates etc.);
- inclusion of the derived environmental related development targets;
- consideration of the development goals in the product specification and monitoring of the achieved objectives;
- development of new WEEE objectives on the basis of the improvement strategies.

According to the experience of the product developer, the implementation of the WEEE strategy can be quite complicated. For this reason consideration of all product life phases take place via process-integrated environmental protection systematics.

28.3.1 Specification/product design

Within the framework of the product-related environmental protection, Siemens optimises products over their entire life cycle, as far as the enterprise can have an effect on it. This is particularly important because the manufacturing of a product only causes a comparatively small part of the impact on the environment within the product lifetime. The majority of environmental effects caused by the product are generated in the utilisation phase. However it is possible to influence this within the planning and development phase of the product.

The manual of the Siemens standard SN 36350 'Environmental-compatible products – Solutions and examples for the Siemens standard SN 36350' shows essential points for the setting up of a WEEE management strategy:

- Aspects for design and development, e.g.
  - legal requirements
  - concept for the treatment of the old products (reuse, recovery, removal)
  - determination of relevant environmental aspects
  - evaluation of potential competition advantages
  - environmental-referred development objectives.
- Aspects of the procurement and production, e.g.
  - product weight, material diversity, number and variety of product parts
  - employment of usable materials when possible
  - avoidance of hazardous materials (aspects of dangerous property goods)
  - minimisation of the production wastes
  - optimisation of the manufacturing processes and the energy consumption
  - usability of alternative materials.
- Selling and service aspects, e.g.
  - environmental compatibility of the packing
  - advice and standards for the disposal of packing, operating supplies and of the old product
  - consideration of the property of dangerous goods
  - environmentally relevant customer information
  - information on resource-efficient modes of operation (energy, water, etc.)
  - service procedures that protect resources.
- Aspects of use, e.g.
  - design the product to be long-lived, easily repairable and upgradeable
  - avoid health and environmental impacts from materials, noise and radiation.
- Aspects of the disassembly and disposal, e.g.
  - disassembly and disposal instructions
  - information concerning declarable materials
  - information concerning product parts for selective handling (WEEE Directive)

- easy dismantling of products (connections, find ability, disassembling steps, standard tools, changes of position during the disassembling, etc.).

The aspects stated above are outlined in the design specification of the product. The guidelines regarding the aspects of disassembly and disposal describe conditions for recovery procedures with maximum pre-separation and sorting of the materials.

When other recovery procedures are expected (e.g. shredding followed by separation processes), then suitable guidelines according to the technical requirements must be selected or modified. When required, additional LCAs will be carried out in order to quantify the impact of the product on the environment during its entire life cycle.

28.3.2 Manufacturing

The production of the product plays rather a subordinate role in the WEEE management strategy.
However this is a very important supply chain management (SCM) phase as well–not only regarding industrial environmental protection but also regarding product-related environmental protection by using RoHS/WEEE-convenient auxiliary materials for production, such as cathartics, oils, grease or adhesives. For completeness two aspects regarding the manufacturing are mentioned here: the aspects of operational environmental protection and the use of RoHS and WEEE-compatible production equipment.

Operational environmental protection

The product and service spectrum of Siemens is vast and the conditions at the respective locations vary greatly. A broad product spectrum causes complex challenges. With the integration of new branches of the business, the operational environmental issues have changed significantly and they are likely to change further in the future. The most important environmental aspects on a company level are energy and water consumption, emission of greenhouse gases and the waste which arises.

RoHS and WEEE-compatible production aids

Customers increasingly value products that are produced in an environmentally sustainable way, which corresponds to the specifications of the RoHS and WEEE Directives. For example professional contract manufacturers for SMD (surface-mounted device) are asked by their customers whether their products are contaminated, e.g. by mixing lead and lead-free procedures. Here too the avoidance of dangerous materials and the search for suitable alternative materials applies. For this reason, special attention is necessary – not only for the development of products but also during the production planning. It means that at a very early stage of the development, both developers and production planners have to agree on a common strategy in the context of the PLM. Thus the avoidance of production waste also applies to manufacturing, and should be regarded under the WEEE criteria.

28.3.3 Use phase

The use phase in a product's life cycle is also characterised by WEEE-relevant aspects, e.g. the use of spare parts, which is also relevant in the area of refurbishing, recovering or recycling. A particularly important aspect in the utilisation phase is that often spare parts of electrical equipment or plants fall under the WEEE Directive. Therefore which kind of spare parts are to be used must be differentiated exactly. Here it can be spare parts, which either do not fall or directly fall under the WEEE Directive. In the latter case, in turn, whether the part is supplied directly to the recovery (in the context of the WEEE) or whether it will be prepared for later use must be differentiated.

In the interest of increased user friendliness and for useful preservation of resources for the manufacturer, the products and plants should be so designed that few repairs are required. As a rule this leads to less WEEE arising from broken-down equipment.

Beyond this, design of products and plants which allows a direct repair by the service technician on site also leads to a substantial saving of resources. In this case the exchange of complete modules or components can be avoided. In particular with the use of modules and spare parts for industrial goods, special attention should be paid to the early observance of legislation, even if these are not yet applicable for industrial goods. An example for this could be the RoHS Directive, because if modules or components are affected by such a directive at a later point of time, then the use within a refurbishment system can lead to substantial problems.

In particular the use of so-called 'Quagan' spare parts, which are qualified as new, is to be given special consideration. Quagan means 'qualified as good as new' (Belli *et al*., 2010): This term was introduced for the first time in International Electrotechnical Commission 62309 (IEC, 2004), in order to make clear that it concerns not new parts, but those which equate to a new one after being tested. Therefore Quagan designates the condition of a part that has already been used once or several times. However it differs from a conventional used part, because it is subjected to a defined and documented quality inspection – which must be passed – possibly after a revision. The necessary degree of the quality inspection and/or documentation depends on the application and/or the market requirements.

28.3.4 Final stage as beginning of a new cycle used EEE or WEEE

Recovery objectives determined in the WEEE Directive must be achieved at the end of the product life cycle. Naturally this requirement is more pronounced for consumer products, which are collected on communal collecting yards, as for products which do not fall under the WEEE Directive. In this phase all relevant settings of specification, product design, manufacturing and use become apparent in the management of used EEE or WEEE. In the early stage of development, an optimisation of the combination 'Design for recycling' and 'Design for refurbishing' is of greatest importance, especially in the context of a balanced WEEE management strategy.

Refurbishing is a particular process of renewing to produce a product in a condition which is very close to that of a new one. Refurbished systems, spare parts or components can be considered refurbished if they reach at least original equipment manufacturer (OEM) quality from the customer's point of view, with a warranty equivalent to that of a new product.

The refurbishing process consists of several steps. A basic sequence is given, but depending on the product refurbished, the particular steps may change from product to product. Typical steps are:

- sampling of the complete product;
- inspection and identification of defects;
- disassembly of the product;
- cleaning of all parts;
- reconditioning of parts (and replacement with new parts where required);
- reassembly of product;
- testing to verify the product functions as a new product.

Often the costs and benefits of 'recycling' are compared with those of 'reuse of parts and components' as well as 'refurbishment' and often the needs of these processes are at odds. On one hand, the current the WEEE Directive sets out recommendations primarily on recycling, while on the other hand purposeful reuse and refurbishment are considered more beneficial by the manufacturer because of the preservation of resources and by the customer because of the savings they can make.

Another field of tension is between the rising demands of increased functionality of products from the market, and the requirements of the ROHS and WEEE Directives, which expect an unproblematic recycling of as simple as possible electronic devices and components. Apart from the fact reuse and refurbishment seem to contradict the life-cycle energy consumption, the topics of material optimisation and recycling can also conflict with each other.

For this reason a smoothly operating WEEE management strategy which achieves the optimum compromise between these fields of tensions is necessary. A substantial indicator for this is the achievement of the greatest possible customer satisfaction with a good added value for the manufacturer and an optimum of environmental protection. Often these properties are not at odds with a purposeful strategy conversion. A typical example is technically sophisticated electrical devices with a high functionality of materials, which are particularly long-lived, designed as basis for a reasonable reuse and refurbishment (in contrast to typical low-budget consumer products which are often discarded shortly after the end of the guarantee period). Another example could be the flexible design of product components, enabling the energy consumption to be improved by an upgrade within a refurbishment process. Irrespective of product type and WEEE processing method (whether recycling, reuse or refurbishment) is the search for resource-efficient technologies and materials is fundamental. Furthermore this plays a substantial role within the supplier dialogue, whether the supplier provides only materials or semi-finished products or whether he is a system supplier.

The following sections give an overview of the activities of the Healthcare Sector within the range of refurbishment, reuse and recycling.

28.4 Healthcare products as an example of WEEE management

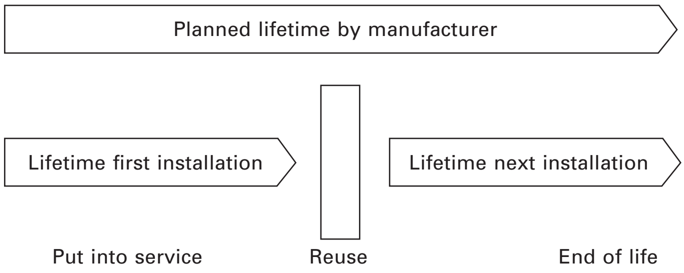
Innovation cycles for healthcare products are much shorter than the economic life cycle of these investment goods. Rapid innovation cycles in medical technology often make it necessary to replace the medical equipment a long time before it reaches its economic end-of-life.

Early replacement of the newest technology in medical equipment worldwide makes sense if the value of the replaced equipment is saved for reuse. Medical equipment is designed for a planned lifetime by Siemens Healthcare. When putting the medical equipment into service for the first time, Siemens Healthcare provides safety and effectiveness for a certain period under the assumption of scheduled maintenance procedures.

The effective lifetime of medical equipment can differ from the planned lifetime by Siemens Healthcare. There are functional and economic reasons:

- the medical equipment is no longer safe and effective;
- the medical equipment no longer meets the applicable safety or performance standards;
- the replacement of medical equipment is due to new technology becoming available.

Figure 28.2 for planned lifetime gives an overview about the correlation



28.2 Context of planned and effective lifetime and reuse. © Siemens.

between planned lifetime, effective lifetime and reuse (Plumeyer and Braun, 2011). Reuse enlarges the functional and economic life of medical equipment. At the end of its life cycle medical equipment needs to be processed for recycling as electrical and electronic waste. As a result of the replacement of medical equipment and in the context of a recycling economy, a sustainable resource management is required. At the end of the day, replacement and proper reuse of medical equipment provide value to a new user.

28.4.1 Optimising and continuous improvement, also in respect of WEEE

The implementation of integrated product policy (IPP) at Siemens Healthcare ensures that the environmental protection aspects of the total product life cycle are taken into consideration, from early in the product development through to the end-of-life. This progressive, comprehensive system not only allows for outstanding progress in environmental protection but also secures financial advantages due to lower energy and material consumption. With each new product, attention is paid to the reduction of negative impact on the environment.

The more the different phases of the product life cycle interlink, the more environmentally friendly and the more resource-efficient the products are. At Siemens Healthcare the life cycle of a product is divided into four major phases, which are subject to constant optimisation and continuous improvement.

Phase 1: Specification/product design

In the product design phase Siemens Healthcare regards the environmental influences of a new product during its entire life cycle. With the given environmental protection objectives for each new product, the product impacts can be influenced quite well; for example through early consideration and determination of the material inventory and energy consumption.

Phase 2: Production

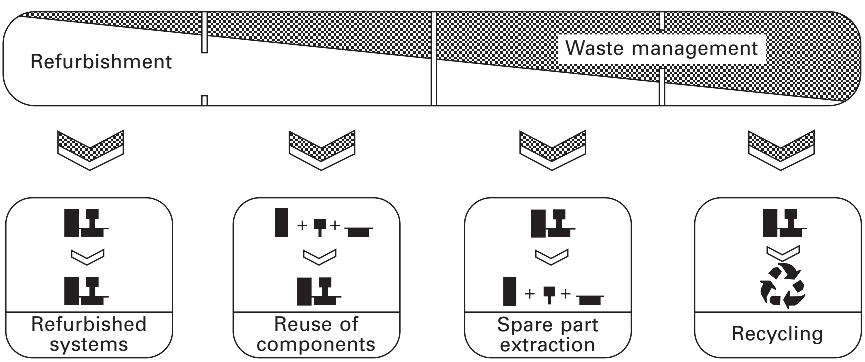
Transport of the product is also included as well as production. It ends with delivery to the buyer. Effects on the environment result mainly from the delivery chain and the production process: for example in material, energy and water consumption, waste as well as different emissions play a significant role. A primary task of environmental management is to avoid harmful environmental impacts or at least to minimise possible impacts.

Phase 3: Use

In this phase medical instruments have a great influence on the environment, for example by their energy consumption. The consumption of operating materials and spare parts is important in this phase, which in turn affects the WEEE management strategy for operating materials and spare parts. Within the product design phase possible negative environmental impacts are minimised as much as possible. In addition customers receive appropriate information in order to be able to use their devices in as environmentally friendly way as possible and how to handle operating materials and used spare parts.

Phase 4: Disposal/recycling

Siemens Healthcare developed a four-level return concept: refurbishment, component reuse, spare part extraction, and recycling (see Figure 28.3). Owing to the exact knowledge of the materials used for the products, the healthcare sector can supply the details of materials intended for reuse and therefore minimise negative impacts on the environment. In addition the information Siemens Healthcare provides explains how products should be dealt with after their expiry date.



28.3 Siemens Healthcare product take-back strategy. © Siemens.

28.4.2 Selected management examples for Siemens Healthcare products

Material usage and environmental product declaration (EPD)

Not only does Siemens keep to the existing legal requirements concerning the products, in some cases it goes far beyond that. Thus new developments have already been accomplished in the Healthcare Sector under the criteria of the RoHS Directive.

A detailed overview of environmentally relevant aspects of a product is made available to the customers in the environmental product declaration (EPD), which Siemens Healthcare provides for many products. At a glance the customers receive environmentally relevant information about their product or a technical solution.

It is very important for the customer to know a product's properties (e.g. material contents, energy consumption, radiation intensity or maintenance costs) and this plays a significant role in the purchase decision (Freie und Hansestadt Hamburg Behörde für Standtentwicklung und Umwelt, 2008). Therefore Siemens Healthcare equips each product with product information in order to make its ecological advantages visible. The integrated standardised data sheet permits a fast and manufacturer comprehensive comparison of the devices, regarding impact on the environment and saving potentials. Valuable data and references regarding the handling of used EEE and WEEE are given in the product environmental explanations. Furthermore all materials – not only hazardous substances – are basically registered. These facts are demonstrated in for example the life cycle of material and energy balances, explicit weight reductions and in very high recycling quotas. Siemens Healthcare is continuing to expand the EPDs by providing even more details. The EPD also includes a selective listing of parts, which have to be dealt with whilst taking the annex of the WEEE directive into consideration.

Refurbishment of complete system

Used medical equipment is a valuable asset that has to be preserved. By saving resources due to refurbishing products, Siemens Healthcare helps their customers to cut their CO_2 emissions and improve their environmental performance. If used medical equipment is reused it needs to be processed in a dedicated way to avoid risks for users, patients and healthcare providers to make sure that the medical equipment is as safe and effective as when it was new. Not all sold used medical equipment fulfils these ethical and social criteria. Refurbished medical equipment placed on the market and put into service shall meet the requirements for safe and effective use as specified by Siemens Healthcare. There shall be no difference whether the medical equipment is new or refurbished.

Not all used medical equipment is suitable for refurbishment. There are different key factors which determine whether medical equipment is suitable for refurbishment:

- The intended use defined by Siemens Healthcare which means that, e.g., single-use devices should not be refurbished.
- The medical equipment fulfils all applicable safety and performance standards.
- The planned lifetime defined by Siemens Healthcare, i.e. medical equipment that reaches its useful end of life defined by Siemens Healthcare should not be refurbished.
- Existing service/maintenance history for the medical equipment.
- Existing service/maintenance procedures for the medical equipment.

It is important to understand that refurbishment is different from maintenance, fully refurbishing or manufacturing. Refurbishment means actions taken, such as repair, rework, update of software/hardware, and/or replacement of worn parts against original parts, to restore used medical equipment into a condition of safety and effectiveness comparable to when it was new (COCIR, 2009a).

All actions during refurbishment are performed consistently with product specifications and service procedures defined by Siemens Healthcare for the particular type of medical equipment, without significantly changing the finished medical equipment's performance, safety specifications and its intended use as specified in its original registration.

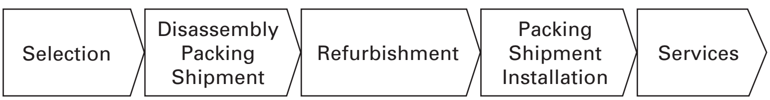
The Siemens Healthcare approach of refurbishment of complex systems is not seen under waste hierarchy (Directive 2008/98/EC) because the medical equipment used for refurbishment will not extend the planned lifetime defined by the original manufacturer (see Fig. 28.2; Plumeyer and Braun, 2011). Medical equipment for refurbishment is directly purchased as products from customers. In recent years manufacturers in the healthcare industry have established refurbishment processes and delivered their equipment across the world (COCIR, 2009a). The list of users of refurbished systems is not limited to small hospitals or countries with limited healthcare budgets but includes well-known leading medical institutes. The worldwide market for used medical equipment has been growing rapidly - the largest market for Siemens Healthcare is the USA followed by the EU (Braun and Arglebe, 2007).

In most countries around the world the market for used medical equipment is not regulated by governments. Some countries established bans or restrictions on the import of used medical equipment to protect public health and safety (US Department of Commerce, 2008). Usually the ban on import does not distinguish between high-quality refurbished medical equipment and second-hand equipment of undefined quality, with the effect that healthcare providers of more limited means are denied access to the safe and economical medical equipment they need.

It is not only the improper refurbishment of used medical equipment that poses a risk. Compared with new medical equipment, used medical equipment may bear additional health risks for patients, users and the environment, for example from contamination or missing required maintenance. Beyond these equipment and market-related issues, the choice to reuse medical equipment could be due to increased environmental awareness of manufacturers and users. Reuse of used medical equipment may be a way for organisations to contribute to a closed loop recycling management and to a sustainable society.

Good refurbishment practice (GRP): the process

Based on several approaches different manufacturers in the healthcare industry followed a common position on the refurbishment of medical imaging equipment defined and published by COCIR named good refurbishment practice (GRP; COCIR, 2009b). GRP makes sure that medical equipment processed in this way will meet all quality, performance and safety standards applicable when the medical equipment was put into service for the first time. Siemens Healthcare is applying this refurbishment approach with its 'proven excellence' process. Figure 28.4 describes Siemens Healthcare's five step refurbishment proven excellence process (Plumeyer and Braun, 2011).



28.4 Five step: the proven excellence five step refurbishment process. © Siemens.

1. Selection of medical equipment for refurbishment, based on
   - intended use of the medical equipment;
   - planned lifetime by Siemens Healthcare;
   - applicable standards;
   - service/maintenance history and existing procedures.
2. Disassembly, packing and shipment of used medical equipment for refurbishment:
   - The used medical equipment needs to be checked before disassembly regarding unit identification.
   - The used medical equipment needs to be disassembled in a way that it will not be damaged. It should be in the same condition as it was before disassembling (i.e. avoid additional risks due to disassembling).
   - If the medical equipment was used in a special environment (e.g.

emergency room, laboratory) it might be necessary to decontaminate it before disassembly.
- The medical equipment is packed and shipped so that it will not be damaged.
- Appropriate actions are taken to avoid violation of privacy rules concerning patient data stored on the relevant medical equipment.

3. Refurbishment:
   - A refurbishment plan has to be described and followed to define the equipment configuration (e.g. according to customer order) within the scope of the original product registration from Siemens Healthcare when the equipment was put into service for the first time.
   - The used medical equipment is systematically cleaned and disinfected before refurbishment, because of its use in a medical environment.
   - Cosmetic refurbishment is done in conformance to the refurbishment plan.
   - Mechanical and electrical refurbishment and system configuration in accordance with the refurbishment plan.
   - Inspection, identification and replacement of worn parts or components.
   - Worn parts or components are to be repaired or replaced with original parts or original spare parts or original components.
   - Additional parts or components necessary to meet customer's requirements are original parts or original spare parts or original components or original accessories.
   - Provide original manufacturer's user documentation in the required language or in a verified translation.
   - With the installation of safety updates (hardware/software) all applicable safety updates which are released for this type of medical equipment are performed.
   - With the installation of performance updates all applicable performance updates which are released for this type of medical equipment are performed.
   - For any medical equipment refurbished, performance and safety tests are to be verified so that it meets the defined performance and safety specifications for its type.
   - After successful completion of all necessary refurbishment actions, Siemens Healthcare labels the medical equipment with the 'proven excellence' label.
4. Packing, shipment and installation of refurbished medical equipment:
   - The packing and shipment of the refurbished medical equipment are the same as for new medical equipment and meet the applicable performance and safety standards.

- Refurbished medical equipment is installed following the same installation procedures as new medical equipment.

5. Post-market services:
   - After the installation of refurbished medical equipment, Siemens Healthcare provides services and support similar to the relevant type of new medical equipment.

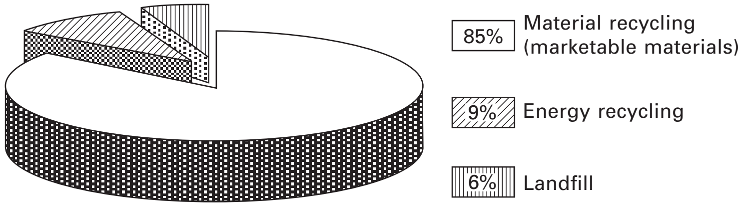
The refurbishment of used medical equipment using this process produces safe and effective medical equipment. Refurbishment contributes to a sustainable society. But only if the refurbished medical equipment is as safe and effective as when it was new it is applicable for users, patients and healthcare providers and can contribute to a sustainable society. With regards to a recycling economy, refurbishment saves resources and energy. On average, refurbished X-ray medical imaging equipment requires 73% less energy to be processed compared with new medical equipment, based on the life-cycle phases, materials supply and parts of production phase. The life-cycle assessment – using the cumulated energy demand method (VDI 4600, 1997) – of an typical X-ray system with a mass of approximately 2 tonnes covers the life-cycle phases material supply, production, use and end-of-life (Plumeyer *et al*., 2005).

Reuse of components and extraction of spare parts

The reuse of components and the extraction of spare parts must be separated according to product take-back strategy. The reuse of components describes the technical process of repairing, refurbishment or reconditioning of products or components which have not become waste (e.g. reuse of X-ray tubes). The extraction of spare parts describes the technical process of repair, refurbishment or refabrication (e.g. rework) of products or components, which have become waste i.e. preparation for reuse according to the directive on waste (Directive 2008/98/EC).

At Siemens Healthcare X-ray tubes as components are successfully reused. The components reused are mostly gained within the customer services activities of Siemens Healthcare. They are processed in a dedicated quality process. Highly used X-ray tubes have an average lifetime up to several years. Some components especially non-wearing parts of the X-ray tube can be reused.

After disassembly at the customer's site and transport to Siemens Healthcare the X-ray tubes are thoroughly quality checked in a defined process. After checking the reusable non-wearing parts, they may be reused or have to be refurbished. The reconditioned components can be used for the manufacturing process of X-ray tubes if they are qualified as good-as-new according to IEC 62309 (IEC 62309, 2004). Around 50% of the weight of an X-ray tube will be reused (Illini, 2007).



28.5 Recycling quota of a Siemens Healthcare X-ray system. © Siemens.

Siemens Healthcare recovers components or spare parts for preparation for reuse out of end-of-life products as part of WEEE management. The components are recovered and handled according to the applicable requirements, e.g. electrostatic discharge (ESD). The recovered components will be sent back to the original manufacturer of the component or spare part for repair or refurbishing because only the original manufacturer has the knowledge, tools and processes to do this work. Following this process the recovered components are put back into the spare part loop of Siemens Healthcare. At the end the components become available for the Customer Services once again as qualified as good as new according to IEC 62309 (2004).

High-quality recycling

After planned lifetime according to Fig. 28.2 a Siemens Healthcare system can no longer be used in a safe and effective way and has to be treated under the local waste regulations to prevent any harm coming to the user and to the environment. At the end-of-life 85% of the materials of a typical X-ray system (e.g. fluoroscopy system – AXIOM Iconos R200) are recovered as marketable secondary materials, a further 9% by weight goes in to energy recovery and 6% to landfill (Plumeyer *et al*., 2005; Sterbak, 2007).

Figure 28.5 shows the recycling quota. For example in Germany, Siemens Healthcare offers its customers a certified waste management process (executed by service providers under Siemens Healthcare control) to take back their medical equipment if they become end-of-life products and need to be treated and processed in a dedicated way in compliance with local waste management regulations.

28.5 Future trends

For producers of high-end technologies the shortage of rare raw materials plays a more and more significant role. Future technologies will change the requirements for raw materials drastically. Many EEE technologies depend on conventional metals such as copper and silver but now there is a growing demand for special metals such as lithium, gallium, indium and rare earths. Therefore long-term strategies to preserve valuable raw materials or to find new designs and materials are essential. This means, that the possible conflicts – described in section 28.3.4 – are no longer inevitable conflicts, but much more useful mutual complements controlled by an intelligent WEEE management strategy. To simplify the efforts within these attempts, the following short description outlines future trends, which will help the manufacturer and the supplier in their work.

28.5.1 Corporate substance and material management

Numerous legal demands limit the use of hazardous substances in electrical and electronic products. For a globally acting company, a corporate database for substances and materials is a constant challenge, especially against the background of an increasing number of RoHS and WEEE-related directives and regulations worldwide.

In order to conform to these regulations Siemens Healthcare has developed a material data information system. This information system permits an overview of the substances and materials used in the products. This facilitates not only the preparation of EPDs but also supports the further development of a comprehensive substance and material management. The exact knowledge of all used substances and materials helps in the continuous improvement of reuse and recycling processes. The corporate substance and material management works in harmony with the extended supplier dialogue and information exchange tool described in Section 28.5.4.

28.5.2 Design for reuse and recycling

Resource efficiency is going to be immensely important in the future. Design for reuse and recycling during product development will become essential for a proper and efficient handling of used EEE or WEEE. To reach the best compromise between reuse and recycling, the trend that seems likely to continue is that industry activities will focus less on individual products and more on product families, based on similar technologies and used raw materials. The advantages of this concept are that it is both efficient and versatile, so the collection for reuse is no longer aligned to different product lines. Parts or components from various different products can be used for several other products in turn. The strategy of product families based on similar technologies also entails further development strategies for a more sophisticated module-oriented design of components, which allows an ingenious combination of different modules in different products. This will enable more straightforward separation and collection of materials within the recycling process.

28.5.3 WEEE reduction by material optimisation

Both the scarcity of required rare raw materials and the quantity of WEEE materials present immense problems for the future. In this context new technologies – like nanotechnology – may help overcome these problems by providing substitutes for rare materials and significantly reducing the quantity of material used in products. Already, research is being carried out in this area, for example to substitute gold and silver as contact materials, to substitute nickel as a conductor and to substitute magnets of rare earth materials with innovative nanomaterials. It will also become a future trend to search for nano-compositions of plentiful substances to replace materials or technologies, which are based on rare materials. The future trend will be less waste of EEE by specific material substitution, reduction and increased circular flow through reuse and recycling.

28.5.4 Extended supplier dialogue

An extended supplier dialogue will become increasingly significant to determine the optimal materials and technologies to make RoHS and WEEE compliance more convenient. Certain components of Siemens products are not produced by Siemens directly, they are supplied. Therefore close cooperation with suppliers is indispensable. For example Siemens Healthcare and the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry (COCIR) initiated a web-based database, called BOMcheck (www.BOMcheck.net). BOMcheck stands for Bill of Materials and is a constantly updated list of materials contained in the products.

BOMcheck supports the manufacturers to fulfil their legal responsibilities concerning the restrictions of materials. Both suppliers and manufacturers profit from substantial cost savings from this web-based solution. This declaration tool supports suppliers with the material declarations, by explaining legal requirements. BOMcheck contains many mechanisms, which allow the information to flow automatically through the delivery chain. Suppliers at different stages in the delivery chain can enter their data accordingly. Thus time expenditure is reduced substantially. The obligation to use BOMCheck will extended to Siemens supplier contracts.

28.6 Sources of further information and advice

Environmental sound product design

Dr Ferdinand Quella was the head of the Siemens corporate department of Product-related Environmental Protection in Munich. He is the initiator of the Siemens Standard SN 36350 and was significantly engaged with the further development of this standard. The following book considers that the

discussion of environmental sustainability of products will often be led from the point of view of e-waste utilisation. To design an environmentally sound product, it is necessary to consider the complete life-cycle of the product. This means treatment from the marketing up to utilisation:
Quella F. (1998), *Umweltgerechte Produktgestaltung*, Erlangen-München, Verlag Publicis MCD.

Usage of pre-owned components in new electrical engineering products

The main objectives of this book are the provision of technical decision criteria for the reuse of components, to specify rules for product improvements and to set ecological decision criteria for reuse. An additional aim is the explanation of the legal and normative background:
Belli F., Quella F., Bohnstedt J. (2010), *Einsatz gebrauchter Komponenten in neuen Produkten der Elektrotechnik*, Berlin-Offenbach, VDE Verlag.

Ecodesign – the competitive advantage

Dealing with environmental issues should no longer be considered simply as a cost of doing business. Effective environmental improvements to a company's products and services can be turned into business opportunities. This book was written with the express purpose of helping managers of companies, in particular of small to medium sized enterprises, to better deal with environmental challenges and address customer requirements, all in order to turn their environmental investments into competitive advantages. Several examples are provided throughout the book, but also warning signs:
Wimmer W., Lee K.-M., Quella F., Polak J. (2010), *Ecodesign – The competitive Advantage*, Dordrecht-Heidelberg-London-New York, Springer Verlag.

Web links for additional information referring environmental protection by Siemens and Siemens Healthcare

www.siemens.com
www.siemens.com/sustainability
www.siemens.com/healthcare
www.bomcheck.net
www.cocir.org

28.7 References

Belli F., Quella F. and Bohnstedt J. (2010), *Einsatz gebrauchter Komponenten in neuen Produkten der Elektrotechnik*, Berlin-Offenbach, VDE Verlag.

Braun M. and Arglebe C. (2007), Gebraucht und doch wie neu – Aufarbeitung von bildgebenden medizinischen Systemen, *Medizinprodukte Journal* **14**. Jahrgang Heft 4.

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29
The history of take-back and treatment of WEEE at the Philips Consumer Lifestyle division

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Abstract: This chapter describes how the Consumer Lifestyle division of Royal Philips Electronics has dealt with take-back and treatment issues. There has been a strong emphasis on developing systems on the basis of facts obtained through research and development (R&D). Through this approach an eco-efficient implementation was developed in the Netherlands where legislation came into effect before the Waste of Electrical and Electronic Equipment (WEEE) Directive was introduced. At a European level, however, the situation turned out to be much more complex due to the big diversity of opinions in the industry federations, in the EU and the EU member states and the other stakeholders. This resulted in several forms of implementations, some of which are less satisfactory from the Philips perspective. It is hoped that the present WEEE recast will result in more harmonization and will enable substantial improvements in the environmental and economic performance of the take-back and treatment systems.

Key words: material recycling, recycling systems, toxics control in e-waste, legislation on WEEE, eco-efficiency of take-back and recycling.

29.1 Introduction

Philips Consumer Lifestyle, a division of Royal Philips Electronics, has engaged itself from the very beginning in the 1990s in take-back and treatment issues of discarded consumer electronic products. It has been a long journey, which is described in this chapter to a large extent in historical order. This is relevant because the process has been dynamic with several unexpected turning points. Many experiences and lessons from the past are still relevant today, so describing this history is by no means dealing with a period of time which is definitely over.

The author of this chapter was involved in these matters as of 1 January 1993 to his retirement from Philips on 1 September 2004. However in the capacity as part-time professor in Applied EcoDesign at Delft University his engagement continued. It ended officially on 1 December 2008 but in practice continues today.

Much of the content of this chapter has been described in the book *Adventures in EcoDesign of Electronic Products 1993–2007* by Stevels (2007): chapters 7 ('Recycling of Electronic Products', 128 pp), 8 ('Organizing Take-Back and Recycling', 34 pp), and 9 ('Legislation', 58 pp). This book is available on request from the author.

29.2 The period 1990–1998

29.2.1 Dealing with environmental concerns about products

The publication of the Brundtland report (United Nations World Commission on Environment and Development, 1987) evoked a lot of attention for environmental issues about products. Whereas production processes came into the limelight as early as in the 1960s, it took several decades before the resulting products became the subject of scrutiny.

In this initial phase materials, and in particular the presence of potentially toxic materials and waste of discarded products, were addressed. The debate among stakeholders started in the early 1990s and soon a large variety of proposals for legislation/regulation and/or voluntary action were discussed. Electronic and electrical products were at the core of these discussions. This category of products was perceived to be 'hazardous' both in the use and the disposal phase. Moreover, the installed base and the volume of discarded products were growing faster than GDP.

In this initial phase, emphasis was on 'toxics'. Remarkably 'resources', let alone 'energy', played a lesser role. Ecodesign/design for environment was seen as the pre-eminent way to solve the problems associated with electrical and electronic equipment (EEE) and waste of electrical and electronic equipment (WEEE). The current view on ecodesign as to be the minimization of environmental impact over the life cycle (with all the compromises included as a result) was not yet in place.

Parallel to the optimistic view on what ecodesign could achieve, a concept had also been developed which was seen by many as a simple solution for WEEE problems: the concept of extended and individual producer responsibility (EPR/IPR). This was the idea that if producers are made responsible for the costs of end-of-life, they will redesign their products (design for recycling) so that these costs will be reduced to zero or even turn into a profit. In this concept logistics costs were to be almost zero because discarded products were thought to be returned to shops ('old for new'). Subsequently these could be transported back to producers when goods for sale were delivered ('the empty return truck').

Although ideas like the ones presented above are seen as utterly simplistic today, they have had a profound influence on the discussions which took place later on. Even the WEEE Directive shows a clear echo of it. As things stand now, this echo is even to stay after the WEEE recast.

As a result of the developments in the early 1990s, Royal Philips Electronics decided to engage itself strongly in environmental matters. Each division had to set up an environmental department. This also happened at the Consumer Lifestyle (at that time called the Consumer Electronics) division. The author of this chapter started in the Environmental Competence Centre with three chief assignments:

- Setting up a chemical content information system for all materials and components purchased by Division.
- Developing the principles of ecodesign to make them applicable to future consumer electronics products.
- Gaining knowledge about take-back and treatment of discarded consumer electronics products.

In a later stage, the development of management methods for 'Eco' were added to this.

In the present chapter the focus is on take-back and treatment of discarded Consumer Electronics. Experiences of the author in the 'Eco' field have been described in a more general way in Stevels (2007).

29.2.2 Getting facts about take-back and treatment

From the very beginning it was clear to Philips Consumer Electronics (PCE) the take-back and treatment systems should be built on facts rather than on principles. Moreover for the discussions about future legislation (these had already started in 1993 in Germany and the Netherlands) it would be advantageous to know as much environmental and financial detail as possible. Furthermore, since the EPR was supposed to apply to individual companies, the opportunities to get a competitive advantage through take-back were ranking high on the agenda. Last but not least opportunities to lower cost in related domains (for instance production costs) were to be explored as well.

Philips Consumer Electronics was excellently positioned to get facts to optimize take-back and treatment systems:

- The Mirec company (today SIMS-Mirec) belonged to the Philips group. It started in World War II as an operation to alleviate resource problems and it had developed in the 1990s into a fully fledged internal recycling operation. Its main scope was to deal with industrial waste and production rejects but basically all the expertise was in place to treat post-consumer waste as well. The Mirec operation provided rapid insights into disassembly and mechanical processing/operations both as regards technicalities and cost. Moreover Delft students (see below) had access to Mirec to test their ideas in practice. In 1994 Mirec produced an internal document which contained experience-based recommendations for recycling-friendly design of TVs and other electrical appliances. This has been a strong support for the ecodesign activities at PCE.

- Glass for picture tubes of TVs was produced in-house as well. The Glass division developed methods that allowed post-consumer glass to be recycled in its melting tanks. Mixtures of screen and funnel glass, as well as separated screen or funnel glass were considered. This kind of capability was seen as a special asset, particularly if producers would be seen to be individually responsible for secondary material streams.
- At Royal Philips Electronics there used to be a Plastics and Metal ware production group. The expertise about potential use of recycled plastics was derived from this group. Soon the quality of recycled material required and the maximum amounts of such material which could be applied in the externally visible and in the inner parts of new products could be mapped.
- Flame retardants in plastics are a special issue. On one hand these are needed for safety reasons on the other hand there are problems associated with them in the environmental domain – both as regards potential toxicity and as regards (hampering) recycling. Flame retardant-free housings (of, for instance, TVs) complying with safety regulations would be therefore a bonus from any perspective. The Philips Centre for Manufacturing Technology had great expertise in this field. A solution was found in 'thermal management' of designs through which hot spots in the products were eliminated. This allowed PCE to comply with safety requirements, to lower initial costs more than the competition could, and to achieve better recycling/lower end-of-life cost as well. Unfortunately safety requirements became stricter by the turn of the century (on the basis of investigations which still can be contested) and flame retardants had to be reintroduced.

As can be seen above, PCE was operating on a practical basis to get insights and to lower its end-of-life costs. The connection with Delft University of Technology had the ambition to dig deeper. This will be discussed in the next section.

29.2.3 The cooperation between PCE and Delft University of Technology (DUT)

Delft University of Technology (DUT) was and is deeply interested in environmental and sustainability matters and is looking actively for cooperation with industry. After a period in which some Delft students did their graduation projects at PCE, a formal cooperation agreement was made in 1995. This included free exchange of information, sponsoring of PhD students by PCE and the establishment of a (part-time) chair in Applied EcoDesign at DUT.

Under this umbrella numerous activities were carried out; an overview is given in Stevels (2007). In the field of take-back and treatment there have been some 60 joint publications and 15 graduation reports, whereas four PhD students got their doctorate in this field (two of these have been sponsored by third parties). In the early stage of this cooperation several studies were performed which were of direct relevance for the discussions with the Dutch authorities on the forthcoming recycling law:

- The issue of which products to disassemble manually and which to separate mechanically. By considering products as a 'hierarchy', product–subassembly–sub-subassembly–part, the appropriate borderlines could be traced. Environmental and economic considerations yielded almost identical answers as regards this issue. An important conclusion was that products with a weight of less than 5 kg can be best treated mechanically.
- For TVs and monitors the estimate was that recycling cost could be cost-neutral, provided that for the secondary glass a price could be obtained representing the 'replacement cost' of the raw materials (which is not the case on a division basis but is a benefit which could be reaped by Philips as a whole because it had its own glass factories). For other products there would be a clear cost in take-back and treatment. Therefore it was hypothesised that if (extreme) ecodesign would be applied these costs could be reduced to zero. In tests, this turned out not to be true, even if some functionality was sacrificed. Most easy-to-disassemble audio sound boxes fell short by a factor of 3, for smaller portable products this was a factor of 7–10.
- In the study above, a table of standard disassembly times was used, which was also developed under the Philips–Delft programme (see Table 29.1). The data in this table turned out to apply to all CE products with

Table 29.1 Standard disassembly times (s)

Screws	6.5	Nuts/bolts	11.5
Glue joints	12.0	Display from PWB	25.0
Screws not directly accessible	10.5	Click, simple	3.5
Clamps	15.5	Cooling plates	26.0
Screws to be broken	18.5	Click, complicated	7.5
Wire connections	2.0	Axis etc.	9.0
Change screw driver	4.0	Nails	13.0
Electrolytic condensator (elco) from printed wire board (PWB)	4.5	Bending joints	6.0

an average bandwidth of 10–15 %. Moreover the data was supported by a theoretical model (Boks *et al*., 1996). The important effect of the availability of such data was that disassembly analyses of products could be done up-front, no prototypes were needed anymore. Even more important, however, was that the disassembly times could be correlated with assembly times of products. This triggered a wave of 'design for product architecture simplification'; this activity contributed directly to cost reduction. The important indirect effect was that this success contributed enormously to the credibility of the Environmental Competence Centre.

- The availability of the standard times also allowed an end-of-life chapter to be added to the environmental product benchmarking activities. This benchmarking yielded all kinds of data which enabled a comparison of end-of-life costs of Philips and competitors. Table 29.2 shows 'learning' for 'Design for Product Architecture Simplification'. This table shows that for five TVs of different brands the total disassembly time is approximately equal (400 s) but that for individual activities there can be huge differences even for simple things such as unscrewing the back cover.

The above disassembly items have been discussed extensively by Stevels and Boks (2002).

29.2.4 Cost considerations

Since the concept of individual producer responsibility (IPR) is that the producer will have to pay these costs, it is of utmost importance to know what these costs are in an absolute way but also in comparison with competition. On the basis of in-house data (for instance about material composition), the cooperation with Mirec (Section 29.2.2) and the studies of Delft students (see

Table 29.2 Disassembly benchmark TVs

Gross time (s)	TV1	TV2	TV3	TV4	TV5
1. Getting ready	18	24	38	32	34
2. Mains cord/plug	18	20	12	16	12
3. Unscrew back cover	56	66	16	32	28
4. Clean and sort back cover	34	42	22	44	14
5. Take out and sort PWB	24	18	22	18	16
6. Take out and sort speaker	20	16	56	54	22
7. Deflection unit	34	26	30	32	28
8. Get cathode ray tube (CRT) out	72	50	74	70	90
9. Clean and sort CRT	74	62	68	46	46
10. Clean and sort front cover	74	58	74	44	82
Total	424	380	414	386	372

Section 29.2.3), PCE has been able from the very beginning to calculate these costs for their (key) products as a function of time. The chief conclusions were as follows:

- Take-back and treatment will be a cost in the foreseeable future for plastic and glass-dominated products even when the best EcoDesign was applied. This is due to the insufficient value of the materials and the fact that take-back logistics and overheads constitute together approximately half of the total cost.
- For TV sets there is a substantial difference between Philips TVs and the cost of the competing TVs. For companies like Sony and Panasonic there was a factor 1.3; for some other less well-known brands the difference was even bigger.
- Economy of scale has a substantial influence on take-back and treatment cost/piece. Empirically it was found in 1998 that

$$\text{Recycling cost (€)} = = 3E + 3 * (100\,000/X)^{0.5} + 1.5F \qquad [29.1]$$

  In this formula E is an ecodesign factor ranging between 0.85 (best ecodesign) and 1.15 (worst), X = the number of pieces processed by one recycler and F = is a factor dependent on the presence of flame-retardants: $0 < F < 1$. For the Philips TVs and monitors (representing more than 70% of the market) E and F were lower than the competition, whereas, because of its market share, which was high in the Netherlands, X was high as well. Combined with a good position for the reapplication of secondary materials, everything indicated that it would be better for PCE to go it alone and not to cooperate with the competition. There was only one strong argument against this – in the past the Philips market share had been even higher – although the cost/piece would be lowered, no competitive advantage would be achieved unless companies had to pay on the basis of WEEE 'put on the market' rather than paying for what comes back. Therefore 'generation financing' (new pays for old) was strongly supported. The outcome of the negotiations with the Dutch government about producer responsibility ended, however, in an unexpected surprise; see below.

29.2.5 Negotiating with the Dutch government about producer responsibility

The negotiations between the Environmental Ministry of the Dutch government and the industry associations were dominated by Philips. This was logical since Philips was the largest player in the Dutch market (40% share on a weight basis for consumer electronics and the company had by far the most expertise in the e-waste field). These discussions took a long time. In 1999 a system started operating – seven years after the start. There were several reasons for this long delay:

- Voluntary agreements had dominated previously; for electronic waste it was the first time that the principle of producer responsibility was introduced.
- The environmental and financial ins and outs of the take-back and recycling systems were not shared: each party had its own view on this. The question of how much environmental gain for how much money could not be answered and thus the goals of take-back systems to be set up were not shared. Results of studies such as the ones mentioned in Sections 29.2.3 and 29.2.4 were seen as biased. Conversely, reports written by consultants hired by the government were seen by industry as partial as well.
- In the period of the negotiations (and the period before), there had been several scandals as regards toxics (heavy metal, dioxin emissions on incineration). Emotion about this pushed politicians to act. When industry reacted saying that the volume of electronic waste was low and that full recycling was costly, this had the result that they were only pushed harder.
- The government used the legitimacy argument in the debate. This killed the preparedness to come up with sensible alternatives. Some people even thought (or said): let the government push through their ideas, implementation will become a mess and as a result they will come to their senses.

All these circumstances meant that the discussions were dragging on for many years; in fact it was a quasi-stalemate position. The government did not dare to really push its ideas through. The huge problem with the German take-back system for packaging (D&D) in which the extended producer responsibility had been applied in a very strict way definitely played a role in the restraint as well. On the industry side, a differentiation of opinions was starting to appear. Some companies – like Philips – became interested in a compromise (see also Section 29.2.4), others were not – it became more and more difficult to keep the industry ranks closed.

29.3 Implementation of a take-back and treatment system in The Netherlands (1997–2000)

29.3.1 The pilot project Apparetour (1997)

The breakthrough in the situation depicted above came through the opportunity to do a pilot project for take-back and recycling. Funding came chiefly from the EU – Eindhoven was considered to be a weak region in 1997 due to the industrial restructuring at Philips and at the truck industry DAF. The stakeholders contributed as well: the common hope was that the pilot would bring a practical way out of the stalemate. For this reason Philips strongly supported the project and made a lot of resources available for it.

The project called Apparetour brought a wealth of findings which were often on the positive side of expectations but sometimes surprises occurred as well:

- Most discarded goods came back through the municipal waste yards, not through shops or a take-back service.
- Almost all goods returned had no reuse value.
- The recycling percentages which could be realized on treatment were very high (partly due to the almost complete absence of small plastic dominated items).
- Mechanical processing followed by separation was much more effective than anticipated – as a result the amount of manual disassembly to be done was limited.
- Detoxification turned out to be relatively simple. Halogenated flame-retardant plastics were kept in the copper stream. In the subsequent smelting processes control is through the flue gas purification.
- Costs were higher than the projections of the government but much lower than the ones by the industry (and approximately in line with the Philips projections).

The results of Apparetour brought events in a flux; in a burst lasting only a few months decisions were taken about the Dutch take-back and recycling scheme for WEEE. All stakeholders supported these to a large extent.

29.3.2 The Dutch Take-Back and Recycling Law and its implementation (1998)

The Dutch Take-Back and Recycling Law was passed in a time path parallel to the Apparetour project. The law formulated in a strict way extended and individual producer responsibility and gave to the environmental ministry strong powers to control the implementation of individual companies. Under the law these had to notify the ministry about technical and financial details of their take-back and recycling schemes and get approval for it. Soon it became clear that the ‘soup did not have to be swallowed as hot as it had been served’. It was made clear that individual responsibility could also be fulfilled in a collective way. There are many good reasons for this dual approach. These range from environmental ones (lower environmental load of collection), technical ones (economy of scale) and financial ones (investment, economy of scale) and last but not least administrative ones (in case of strict individual responsibility, the ministry had to process and approve 600 notifications of companies putting products on the Dutch market). On the other hand keeping the principle of individual responsibility gave a strong empowerment to intervene in case something went wrong.

The biggest surprise came, however, at the financial side. Recycling fees were allowed to be levied from consumer at the purchase of new products, provided that 75% of the companies in a sector (like consumer electronics) supported the idea. This rule solved a lot of problems such as changing market share over time, free riders from inside or outside the sector. It prevented companies from applying strategies to minimize collection to limit costs, and last but not least the issue of structural deficits in recycling cost. Philips had, for instance, calculated that for plastic and glass-dominated products such as TV and audio, recycling (excluding logistics) according to the legal requirements would remain as a cost even if the best ecodesign was applied (see Section 29.2.3).

The Dutch government assigned the logistics cost (at least up to the level of municipal collection centres) to the municipalities. The chief reason for doing so was the 'duty of care for waste' which is a legal obligation for local governments. Separately financing collection of e-waste out of this would, strictly speaking, lead to a lowering of the municipal waste tariffs – municipalities had argued against this. Also experiences in Germany where EPR for packaging waste had been abused by municipalities to collect unreasonable amounts of money from industry, could have contributed to the decision of the Dutch Environmental Ministry.

These developments led to a change of mind at Philips Consumer Electronics. Whereas there had been an inclination to go alone (economy of scale, know-how, in-house channels for secondary materials), the availability of the fee for consumers changed the landscape. Instead of paying less than competitors, there was now the opportunity of not having to pay at all. The change of mind-set was very quick; Philips became a strong supporter of the collective take-back and recycling system NVMP (Dutch Association for Recycling of Metal/Electronic Products).

Take-back and treatment of WEEE started in the Netherlands as of 1 January 1999 (for the bigger equipment) or 1 January 2000 (for smaller equipment). Two organizations took care of the organization of take-back: NVMP for household appliances, consumer electronics information and communication technology (ICT) for IT and telecom equipment. In both cases these organizations operate through contracting recyclers and transportation companies (for transport from municipalities to recyclers) through a competitive bidding process. Also government reporting is taken care of as well as providing information to the general public. Consumers can deliver their discarded goods for free to the systems. However for NVMP products there is a recycling fee at purchase whereas for ICT products there is none. Since these products (with the exception of computer monitors) have low weight and contain more metal and precious metal than the NVMP ones, costs for most ICT products are close to zero.

Philips has supported NVMP throughout and has seen it as the reference model for WEEE implementation in the EU member states as of the year 2005. In the year 2000 Delft studies showed that it was technically possible to introduce *bonus-malus* systems in collective processing. In this way, good ecodesign could be rewarded. Introduction of such systems would have brought PCE substantial amounts of money. In the start-up phase of NVMP this issue had a low priority, however. In a later stage it was abandoned because the amounts involved were expected to diminish but most of all because management wanted to keep industry ranks closed.

Ideas about introducing 'opt-out' clauses for collective systems had a similar fate. Such a clause means that if a company can do the treatment cheaper than in the collective scheme, it is entitled to get its stuff out of the system and have it processed elsewhere. The cost difference is in such a situation to be paid by the collective system to the individual producer. Currently, ideas like the ones above are dead throughout Europe. Maybe these will get new life after 2011/2012 when visible fees (for recycling) at purchase will most likely no longer be allowed.

Philips has been less satisfied with the ICT system. On one hand that had to do with credibility: the issue of how to explain that there were fees for consumer electrics and not for IT and phones. Although there are good reasons for this (see Section 29.3.1) this is difficult to explain to people not knowledgeable in the field. On the other hand, there was a managerial problem. Philips had sold its computer and its peripherals businesses. Philips-branded monitors formed a big part of the products sold to the market before this operation was sold. However, when it came to take-back the national Dutch sales organization had to come up with the cost. Insights like the ones at the Consumer Electronics division did not exist in this organization. The classification of monitors as IT rather than CE (or in fact glass-dominated products) have cost Philips millions; there was no 75% majority of the producers involved in favour of a visible fee for this specific product. Moreover it was initially agreed that payments should be made on the basis of return share rather than on market share; also the initial lack of action against free-riders has hit Philips very hard. Later these issues have been remediated but in the meanwhile a lot of relative advantage had been reaped by smarter competitors.

The start of the take-back and treatment systems in the Netherlands around the turn of the century gave Philips very good terms of reference for the European WEEE debate which was about to start. This debate was to be much more complicated; 27 member states were to be involved. Moreover, Philips had a strong position in the Netherlands because of its roots and its high market share. Last but not least, other industry sectors such as IT and telecom, which have clearly different views on WEEE issues, were more vociferous in the industry federation.

The Philips-supported research at Delft University, however, brought a lot of insights. These could be the basis for further development of the take-back system. Basically this work pointed to differentiation in the requirements per product group and was calling for tailor-made solutions. This is to be described in the section below.

29.3.3 Research of the Applied EcoDesign group at Delft University of Technology

Introduction

Although partly Philips sponsored (Dutch government agencies contributed a larger amount), the goal of this work has been primarily to understand the fundamentals of take-back and treatment systems. Through this work more effective legislation was thought to be supported, although it was realized that the political component in all these matters would stay big. From the Philips perspective the work was seen as bringing potential enhancements to the Dutch system (see Section 29.2.2).

The basics of the Delft work have been laid down in three dissertations. These will be summarized below.

The relative importance of uncertainty factors in product end-of-life scenarios

This research by Boks (2002) analyses the effect of economic, technological (material qualification, treatment) and juridical (legislation) developments for a variety of scenarios which can be envisaged (with the year 2001 as a baseline). Four product categories in consumer electronics have been considered: metal-dominated, plastic-dominated, glass-dominated and precious metal-dominated products.

The calculation models show that the biggest cost impacts are caused by fluctuations in precious metal (Au, Pd) prices. This particularly holds true for miniaturized products. Achieving economy of scale is highly relevant for plastic and glass-dominated products.

Legal requirements (high recycling percentages to be achieved, removal of potential toxics) have relatively little impact. There is one exception to this: requirements of high collection rates will imply return premiums to be paid to consumers. This will push up costs. A similar conclusion would also hold for a legal obligation to apply metal housings for products in order to avoid flame-retardants or to push up recycling percentages. Also the effect of other items like fluctuations in copper prices, changes in mechanical processing cost and logistic cost is less drastic – although these are substantial in absolute terms.

Lifetime extension and product discarding

At the instigation of Philips a lot of research attention has been paid to issues such as lifetime extension of consumer electronics products and 'post-first-user' or 'second-hand' (products which have been discarded by their first user) business (Rose *et al*., 2002; Stevels, 2007).

For TV and audio products there turned out to be little environmental potential product lifetime extension and/or reuse at least compared with the usual discarding and material recycling scenarios. Also ecodesign with the aim of improving the current products in these respects could contribute in only a limited way. The chief reason for all this that in the product category – in contrast to IT and telecom – wear and tear dominate replacement behaviour. Replacement of durables has been studied extensively by Nicole van Nes (2003). The discarding behaviour of consumers could be quantitatively described for the various product categories. Combined with the work of Rose it showed that for reuse scenarios at levels higher than material reuse, the chief benefit is rather economic than environmental. Moreover it has been demonstrated that such benefits can only be reached if the structure of the value chain allows this.

The QWERTY/EE concept

A PhD project which had a profound impact on the attitude of Philips towards WEEE is the work on the QWERTY (Quotes for environmentally WeEighted RecyclabiliTY) and eco-efficiency (EE) concepts (Huisman, 2003). In this work, models were developed allowing the complete environmental and economic mapping of material recycling chains. In order to do so, a large amount of data had to be collected but once this had been achieved a large amount of hot issues could be analysed properly – per product category and for individual products as well.

The analysis showed that the eco-efficiency (environmental gain/cost) of take-back and recycling varied greatly among EE products. It was the highest for precious metal-dominated products (like cell phones and DVD players). Metal-dominated products like computers were second, glass-dominated products (TVs, monitors) had a relatively low eco-efficiency, whereas plastic-dominated products ranked even lower.

Some products had a very high eco-efficiency. This is not due to recycling but to control of toxicity (for instance of chlorofluorocarbons (CFCs) in fridges/freezers). Others had a moderate eco-efficiency at least if toxicity was properly controlled (liquid crystal display (LCD) TVs).

Moreover, the QWERTY/EE tool enabled analysis of the merits of existing ecodesign concepts of products, logistics and treatment of WEEE and last but not least of the WEEE Directive itself (first its drafts, then the implementation of the Directive and now its Recast). In comparative studies also improvement proposals for design, investment in technology, modification of legislation could be studied and prioritized. Through this approach, for instance, roadmaps for the WEEE Directive could be published (Huisman, 2003).

29.4 The WEEE Directive (2000–2008)

29.4.1 The Philips vision on the WEEE Directive

The work at Philips and the connection with the Delft research (see Sections 29.2.3 and 29.3.3) and the practical experiences with take-back in the Netherlands (see Sections 29.3.1 and 29.3.2) excellently positioned the company for the WEEE discussions.

In the Philips position there were three underlying ideas in the debate:

- The intent of the WEEE Directive is clear ('maximum environmental gain at minimum cost'); however owing to the complexity of take-back systems the best approach can be formulating the general principles accompanied by guidelines for implementation for the member states.
- Solutions which work for one product category or business sector are not necessarily the best for other ones (there is no 'one size fits all'). This is in fact a call for allowing a differentiation in approaches.
- Times have changed. The ideas of 1995 on which the Directive has been based need to be updated with insights and knowledge acquired later on.

On basis of these Philips had a clear strategy (see also Stevels & Huisman, 2003):

- Maximum environmental gain at minimum costs implies the quest for economy of scale, including trans-border movement of waste – it had been calculated that countries (or systems) in which less than 100 000 tonnes/year had to be processed would have a too weak a basis to allow for high-tech investment in treatment and upgrading. Competition among recyclers would be in such a situation insufficient as well.
- Sector solutions would imply that fees paid by consumers had to be allowed for products where there was a structural recycling deficit (a cost which could not be reduced to near zero through design). Such a deficit was calculated to be in place for more than 95% (on a weight

basis) of the PCE. Absence of the fees would cost PCE approximately €50 million in the 27 member states.
- The knowledge acquired after 1995 implies that ideas about reuse, organization of collection, disassembly/mechanical treatment, Annex II (removal of hazardous substances) and about the importance of upgrading secondary streams were to be revised.

This was altogether a far more ambitious agenda than had been realized before in the Netherlands. However, the NVMP system was functioning very satisfactorily, so in practice this was a good reference position.

For a big organization like Philips there has been difficulty in consistently conveying these messages at all levels of the organization and in all member states. Take-back and treatment is a subject which is pretty outside 'business as usual'. Moreover the interpretation of what a Directive means (is the law the law or will serving the intent do?) is subject to cultural differences. Finally there were different views on the role of getting competitive advantage versus reducing cost through economy of scale and getting fees.

A second reason why Philips only had limited impact on the WEEE discussions was that communication to member states and the EU was chiefly through the industry federations. Whereas Philips in the Netherlands is relatively big and influential, it was confronted at the EU level and in other states with divergent opinions of industry, either from a different business sector (IT and telecom) or from other companies having a bigger European market share in consumer electronics. Such a situation meant that discussions in the industry federation were protracted and that agreement was mostly found in a negative reaction to EU proposals. The lack of offering alternatives meant a lot was lost; the reaction of politics to this was only 'push them harder'.

Some companies who were not satisfied with the compromises that were struck in the industry association or felt that the association was too slow to act, decided to contact the EU directly to communicate their company's views, circumventing the industry association. Philips decided not to do this and may have lost strategic advantage compared with other companies that did.

In the opinion of the author the flaws in the handling of the WEEE issue by the industry in the 2000–2008 period has contributed to the fact that the WEEE Directive was already out-dated at the moment it was introduced in 2005.

The main cause has, however, been the EU itself: it failed to translate the principles and ideas of 1995 into realistic environmental goals for collective recycling and toxicity control and was reluctant to go for differentiation in product categories. Moreover it did not realize that after the Directive came into effect, implementation in the member states would be an issue in itself. Since no guidelines had been prepared to steer these processes there were in practice 27 different regulations instead of one with a very strong common basis. This caused a lot of extra organizational and administrative effort for Philips. In many member states its ideas as regards the technical implementation could be realized only partly. In the financial domain visible fees were allowed in the Directive as a ‘not preferred option’. After long discussions, fees systems were allowed in practice in many member states but not in all of them. Combined with lower returns this reduced the European-wide cost of WEEE for PCE to some 10 million. However, according to the directive, fees will not be allowed after 2011. This is currently causing a lot of new debate.

29.4.2 What went wrong with the WEEE Directive? What are the avenues for improvement?

In the opinion of PCE two things went basically wrong with the WEEE Directive:

- *Lack of a clear goal setting*. Basically, the two goals are recycling and control of toxics. In the initial version of WEEE emphasis was on toxic control. Soon this changed to recycling in view of the preparation of a separate Restriction on Hazardous Substances (RoHS) Directive. However, particularly the exemptions in RoHS mean that there is a ‘gap’ which is not closed by the Annex II for treatment of toxics in WEEE. Depending on the product group, the two goals have different priorities: toxic control for fridges/freezers (CFCs), LCD TVs and monitors (mercury in backlights), recycling for telecom and other miniaturized products (precious metals), metal dominated products (metals), whereas other categories (for instance CRT containing products, most plastic dominated products) have a ‘mixed priority’. Whatever the precise priority is, this situation calls for differentiation in requirements as regards collection, treatment and dealing with secondary streams.
- *Attributing responsibilities*. It is a societal interest to realize the goals as formulated above at the lowest cost (for society). In the end citizens have to pay directly or indirectly for take-back and treatment and generally speaking they are prepared to do so provided that there is environmental value for money. Therefore there is a logic in attributing responsibilities in the end-of-life chain to those actors which can achieve the best environmental gain (either in terms of recycling or in toxic control over cost ratios). The best ratios will be scored by those actors which will have the most capability and power to influence the outcomes to the positive. Experience has shown that technical and financial responsibility should coincide. If this is not the case, either take-back systems do not work optimally or cost a disproportional amount of money.

The fact that these two fundamental issues have not been properly addressed meant that member states had to find their own way out during the implementation. While the Directive was still under discussion, a lot of practical experiences (see for instance Section 29.3.1) and science-based input (see for instance Section 29.3.3) could have contributed to improvement of the draft Directive 'on the fly'. Little of this has been taken into account and therefore the EU ended up with an 'old-fashioned', 1995 style Directive. It is hoped that the WEEE Recast (see Chapter 2) will improve the situation.

In the meanwhile member states are struggling with the implementation. A summary of the chief issues is given by Huisman *et al*. (2006). Improvement agendas for short term, medium term and long term within the present Directive are given by Huisman and Stevels (2004). Options for further development and simplification of WEEE are given by Magalini *et al*. (2006).

The proposals in these papers consider:

- definitions and clarification of goal setting (making more clear what is really meant, scope/boundary issues);
- stakeholder responsibility items (shared responsibility);
- administrative items (simplification at the front end, better monitoring at the back end);
- technical items (collection, treatment, upgrading of secondary streams, toxic control);
- financial items ((in) adequacy of fees, guarantee issues, opt-out conditions in collective systems);
- organizational items ('put on market'/who is a producer, no distinction between B2B and B2C, enforcement).

In view of the dynamics of take-back it is proposed to introduce a general 'environmental equivalence rule'. This means that any action for which it can be demonstrated that it is better from an environmental perspective than the current implementation practice is to be accepted. It is hoped that the Recast of WEEE (see Chapter 2) will create a strong basis for enhancing the effectiveness of the WEEE Directive.

29.5 Summary and conclusions

Royal Philips Electronics has engaged itself strongly in take-back and treatment issues. In a first phase there has been a strong emphasis on getting more facts on such systems. Key questions were what the environmental and economic effects are of such operations and whether green performance, low cost and competitive advantage can be combined. The cooperation with Delft University turned out to be very useful in answering a lot of questions in the field. These activities positioned the Lifestyle division well to negotiate with the Dutch government about a Recycling Law for electronic products.

Practical experience through a pilot project as well as solving the structural financial benefit in take-back and treatment formed the basis for the Dutch system to start as of 1 January 1999.

In the WEEE discussions, the Dutch NVMP system has been the reference of Philips. Combined with increased knowledge from further projects with Delft, the initial expectations about the WEEE Directive were optimistic. Soon, however, this turned to the opposite. Differences of opinion in the industry federations, sticking to 1995 ideas by several stakeholders including the EU itself and sheer complexity meant that the results of the WEEE Directive were disappointing from many perspectives. This has been recognized widely with the current recast of the WEEE Directive as a result.

Philips, in conjunction with its academic partners, has made numerous proposals to improve the WEEE Directive and its implementation practice. It is hoped that many will be taken on board in the years to come.

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30

Creating a corporate environmental strategy including WEEE take-back and treatment

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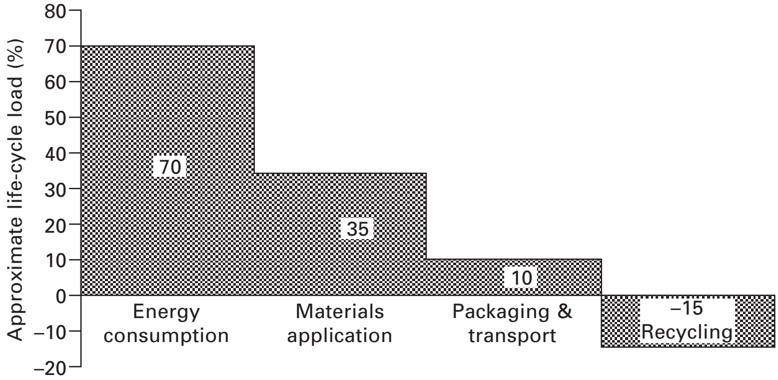
Abstract: This chapter describes the position of take-back and treatment in a comprehensive corporate environmental strategy, including how such strategies can be made and what data are needed to come to a meaningful setting of priorities. In this respect, knowing product characteristics in detail is essential for creating a strategy for reuse/remanufacturing as well as material recycling and control of potential toxics. The implementation of the WEEE Directive in its current form is in many respects at odds with environmental and business rationale. The reasons for this are briefly explored and it is also indicated how the 'spirit of WEEE' which is very positive can be best realized in practice. To make an effective take-back and treatment strategy and for WEEE implementation, a lot of data are needed and many issues must be addressed. A comprehensive list of these is given at the end of this chapter.

Key words: take-back and treatment strategy, reuse/remanufacturing, WEEE implementation

30.1 Position of take-back and treatment in an environmental strategy

Take-back and treatment of discarded products are only part of a comprehensive environmental strategy. Such a strategy considers the complete life cycle of a product: production of materials and components, assembly into a product, the use phase and the end-of-life phase. In between these phases there is a lot of packaging and transport as well. The average environmental effects for electronic products are given in Fig. 30.1.

This figure indicates that for the total life cycle, energy consumption (in the use phase) dominates. The average of 70% has a spread between 45% (cell phones) and more than 90% (fridges). Materials (and auxiliary materials) represent an average 35% of the load whereas packaging and transport represent 10% as a maximum, even if goods are produced overseas. Take-back and recycling represent a 'bonus' of 15% only. This figure is low because take-back and treatment involve energy consumption, materials cannot be recouped for 100% and end up in lower grades and also because even after treatment waste is left, which represents an environmental load.



30.1 Average environmental load of an electronic product over its life cycle.

However, there are strong societal drivers drawing attention for take-back and treatment. There is lack of landfill space in densely populated areas for instance in most countries of the European Union. Moreover conservation of resources and control of potentially toxic substances play an important role, both from an emotional and a rational perspective. This, combined with the fact that in the past little attention has been paid to waste from electronics, is a strong justification for the Waste Electrical and Electronic Equipment (WEEE) Directive.

From a business perspective, considering more intensively the end-of-life of products can lead to several enhancements of an environmental strategy going beyond legal compliance:

- New business models: ‘trade-in/trade-up’ instead of selling ‘new’ only.
- Life-cycle extension business and selling upgrades.
- Remanufacturing and component reuse: ‘post-consumer business’.
- Use of recycled materials (cheaper than virgin ones).
- Focus on ‘monomaterial’ plastic application (increase of recyclability but also volume discount on purchasing).
- Simplification of product architecture (recycling but also lower assembly cost).
- Reduction of potential toxic content.

From a strategic perspective, attention for take-back and treatment is therefore much more than following up on legal requirements, customer wishes and challenges put by non-governmental organizations. When handled properly, there is substantial business opportunity as well.

30.2 Corporate environmental strategy

30.2.1 Making an environmental strategy

The making of an environmental strategy should preferably be an explicit process. This creates awareness, unleashes creativity and provides the necessary links with other business processes. Simultaneously the collection of facts and figures creates the basis for performance measurement after implementation of the strategy.

Basically, making an environmental strategy is nothing special. The same procedures can be followed as for making business strategies such as doing a strengths, weaknesses, opportunities and threats (SWOT) analysis. The only difference is that scenarios underlying such analysis should be described in both environmental and monetary terms. For the environmental part, simplified life-cycle analysis (LCA) using eco-indicators (such as Eco-indicator 99) will do.

Generally speaking there is for products a positive correlation between money and environmental load, so reduction strategies generally work out positively in both fields, be it sometimes with quite a different effect in absolute terms. Therefore, in practice few real contradictions occur between environment and money, although this is a widespread prejudice both in internal and external value chains of companies. Nevertheless it is important to use the two 'languages'. This is because of the variety of audiences to be addressed; some of them want to know more about the environmental aspects, others are more interested in financial matters.

A specific strategy for take-back and treatment has a relation with a comprehensive environmental strategy that is similar to the one between an environmental strategy and the business one in general. This implies that for such specific strategies similar approaches can be followed. Also here there are perceived contradictions, particularly between product architecture simplification and modular structure of products, as well as between material reduction and recyclability.

30.2.2 Vision, strategy, roadmap

Vision

Making environmental strategies starts with formulating a 'vision': where are we now and where do we want to be in for instance five years from now. Visions should be sufficiently challenging to drive the improvement and sufficiently realistic to be successful. This has little to do with legislation (legal compliance is a minimum requirement for any strategy) but a lot with the expectations of customers. Such customers are not necessarily proactive in buying 'green' (environmentally friendly) products (Stevels, 2000). In

Chapter 6 of Stevels (2007) it is demonstrated that although in Western Europe 75–80% of the people say they are prepared to buy green products, their actual behaviour shows only a positive interest of 25%. Some 50% of the public is sympathetic or neutral whereas about 25% is outrightly negative.

A more recent investigation (Pascual & Stevels, 2006) showed that one-third of the general public in Western Europe consists of price buyers (low price) having a neutral or negative attitude towards green products. Slightly better is the situation for 'tech buyers' (latest technology, features) representing one-third of the public. Only for quality buyers (nice design, quality of life) do green products get a positive (or neutral) reception. In other regions of the world (America, Japan) tech buyers represent a larger percentage. In countries with a low income/head, price buyers dominate.

The environmental vision of a company should match with customer attitudes but should also apply globally simply because most electronic companies operate worldwide. Customer attitudes towards 'green' buying also vary per product sector: IT and telecom equipment is associated with utility and have therefore more tech buyers; consumer electronics are associated with fun/pleasure (relatively a lot of quality buyers). Household appliances are a combination of utility and convenience (price buyers, quality buyers).

Factors like the ones described above mean that in actual practice, the explicit or implicit environmental visions of electronic companies are quite different. As a consequence their attitude as regards take-back and treatment and as regards WEEE will be quite different as well.

Strategy

In order to realize the vision, a strategy is needed. A strategy describes in general terms the types of action required to do so. In the environmental field three types of action exist:

- *Defensive actions*. These include the achievement of compliance with legal requirements and fulfilling the (explicit) requirements of (chief) customers. Actions to prevent bad publicity belong to this category as well. In this domain the issue of 'how to realize the compliance' is the most important issue. As regards take-back and treatment, the questions to be answered are: should we go alone as a company or join collective systems, to what extent should we make coalitions with competitors and should we strive for fees paid by customers?
- *Actions to achieve cost reductions through 'green' strategy*. For end-of-life treatment (and often for upfront costs as well) such actions include ecodesign of products (simplification of product architecture, lowering chemical content, going for monomaterial and material reduction) (here a balance between reduction of the kilograms to be treated and the cost per kilogram has to be sought). Also the application of recycled material

belongs to this category. Moreover the supply chain can contribute as well (enabling ecodesign, take-back in place of processed fractions).

- *Actions to generate more business through 'green' strategy*. For take-back and treatment this includes the enhancement of current business by introducing trade-in/trade-up options and selling upgrades for products already in the market. Also remanufacturing and reuse businesses fall into this category.

In order to make an appropriate strategy to realize the vision, a detailed analysis ('getting facts') is of great importance; it is the experience of the author of this chapter that the very fact-finding process to support the environmental strategy has a lot of ramifications for business issues which are completely outside the environmental strategy, i.e. they are not 'green as such'.

The analysis of 'green' factors can have a structure of a SWOT analysis which is often used in such processes. Considering opportunities and threats forms the external part of the analysis. Opportunities and threats change over time and are profoundly influenced by trends such as increased consumer awareness, increasing legislation and legislation-related demands, such as limitations on disposal in landfills and on incineration and more 'green' taxes. Also the developments in technology and the availability of more and more environmental tools are a significant development to assess. Last but not least, increasing prices of raw materials and energy have a profound influence on the environmental strategies to be followed.

Strengths and Weaknesses assessment forms part of the internal analysis. Typical internal issues include the availability of know-how and skills, the integration of green strategy in the business process and the systematic nature and completeness of environmental reporting. Also management of green technology and ecodesign and leveraging green supply chain management and green communication to stakeholders is to be considered.

In last named part what is happening in the world outside the company is analysed; this includes looking at what the competition is doing. Also in the environmental field, being better than the competition is highly relevant for customers of a business; in practice it is even more important than scoring well in absolute terms. It is to be noted that the opposite holds true for stakeholders like non-governmental organizations (NGOs) and academia; here green is considered rather in absolute terms than in the relative ones.

For take-back and treatment, getting environmental and economic facts forms the basis of any strategy-making process. If the internal skills to do so are insufficient, cooperation can be sought with recyclers and academia – today searching on the Internet is of great help as well. In this way the end-of-life properties of products brought to the market can be established. Benchmarking with respect to products of competitors will allow strategy makers to learn how to improve and to identify sources of competitive advantage.

Combining such data with the parts of the SWOT analysis which are relevant for take-back and treatment create the end-of-life strategies which match well with the business and its outside stakeholders.

Roadmaps

A roadmap is a further specification of the environmental strategy in the form of items, a timetable of realization of targets and reasons responsible for realizing the target. For electronic companies, such roadmaps have six chapters:

- *Chapter 1* is about the implementation of policies, programmes and roadmaps (and their updates) in the organization. Regular updates and progress/performance measurement are to be addressed as well.
- *Chapter 2* is the business chapter and specifies items about 'green' products. For take-back and treatment this chapter addresses financial items as well.
- *Chapter 3* is the product design chapter. It deals with ecodesign, including 'design for recycling'.
- *Chapter 4* is the manufacturing chapter. It deals with the reduction of use of utilities and materials/auxiliaries in production. Also remanufacturing, reuse of components and use of recycled materials are located here.
- *Chapter 5* is specifically about programmes relating to ISO 14.001 implementation and the realization of internal targets. Also status/progress of take-back programmes are considered in this chapter.
- *Chapter 6* is about the organization, deployment and education and budget performance of environmental activities. Also external communication can be positioned under this heading.

Good environmental roadmaps including specific items for take-back and treatment, have proved in practice to be a very powerful tool to manage activities. Progress in performance can be measured in an easy way as well. For instance Philips Consumer Electronics (PCE; Boks & Stevels, 2002) has introduced an environmental key performance indicator (EKPI) which is defined as follows:

$$\text{EKPI (\%)} = \sum A_i \text{* score per item}$$

In this formula A_i is the weight of importance of roadmaps item i. The sum of all A's totals 100%. The score item can be:

1 = OK = 'green'

or 0.5 = more or less fulfilled = 'yellow'

or 0 = not fulfilled = 'red'

Values for A_i are to be dependent on product characteristics, maturity of environmental implementation in the business and legislation. The A_i can be changed as a function of time and are therefore flexible. In this way a maximum relevance of EKPI is ensured. Therefore EKPI can be (and is) used to score the environmental part of incentive schemes for (senior) executives.

30.3 Product characteristics, take-back and treatment

30.3.1 Environmental priorities in end-of-life treatments

In practice, for electronic products, material recycling is the dominating end-of-life treatment. From a purely environmental perspective it ranks fourth in the hierarchy of preferred end-of-life destinations. The complete priority ranking is given in Table 30.1 (see also Stevels, 2007, chapter 7). This table gives priority to each end-of-life strategy based purely on environmental concerns. It does not take into account technical and value chain feasibility considerations or cost aspects. Most likely such issues play an important role in practice. Nevertheless it was determined worthwhile to investigate under what conditions higher ranking strategies (1–3) can be implemented. A first attempt to do this qualitatively was made in 2000 by Rose. Type of

Table 30.1 Environmental hierarchy of end-of-life strategies for products discarded by their first owner

Priority rank	Strategy
1.	Prevent discarding
2.	Reuse of the product a. Reuse as complete product b. Reuse after servicing c. Reuse after remanufacturing
3.	Reuse of parts of the product a. Reuse of subassemblies b. Reuse of components
4.	Material recycling a. Back to original application b. In lower grade applications c. Back to feedstock (plastics)
5.	Energy reuse (use as fuel, plastics)
6.	Incineration a. With energy recovery b. Without energy recovery
7.	Disposal as waste a. Controlled b. Uncontrolled

ownership, product price, size, weight and average use time were identified as the main parameters to determine what is the best strategy possible. Apart from product characteristics, value chain issues such as relations with suppliers, recyclers and second-hand markets were demonstrated in the same work to have a big impact on identifying the best strategy.

The same study by Rose focused on the quantitative differences between the different end-of-life strategies. Taking disposal of the existing product as a baseline scenario, the environmental gains of applying higher ranking end-of-life strategies were calculated (Rose, 2000). In order to be able to make the calculations several assumptions had to be made, which as such can be contested to a certain extent. However, the primary goal was to get a feel for the order of magnitude of the differences in environmental load when applying the different scenarios. For 28″ TVs, this led to the outcome shown in Table 30.2. It is concluded from this table that for scenarios 2a, 2b, 2c and 4a the environmental gains with respect to disposal are substantial. On the basis of these calculations scenarios 1, 3a and 3b can also be expected to show substantial gains too. Taking scenario 4a (material recycling with disassembly where appropriate) as a baseline, the gains of the reuse scenarios, with respect to materials recycling, are limited; even the doubling of the lifetime of the products provides only a 30% gain against the recycling scenario only. There is a significant difference in the environmental effects of end-of-life strategies for TVs between scenarios 1–4a and 4b–7. This split is between materials recycling with disassembly and materials recycling with shredding/separation only.

It is important to realize that all gains in Table 30.2 are small, particularly compared with the total life-cycle impact for 28″ TVs (without any recycling or reuse bonus) which is approximately 4000 milli Points (mPt) (Rose *et al.*, 2002). This is largely due to energy consumption in the use phase, which accounts for 80% of the environmental load of this type of product. The study therefore concludes that it is a real priority to pay attention to the energy consumption of new generation TV products rather than to improve reuse characteristics. For other electronic products, calculations have been made which lead to similar conclusions as above.

Table 30.2 Environmental gains of end-of-life scenarios for 28″ TV with disposal (scenario 7) as a base line

Scenario	Environmental gain (according to the Eco-indicator 95 method)
2a. Reuse (doubling of lifetime)	396
2b. Service (extended lifetime 4 years)	357
2c. Remanufacture	344
4a. Recycle (disassembly)	291
4b. Recycle (shred/separate only)	77
7. Disposal	baseline

Table 30.3 Comparison of environmental impact of materials and of processing of components/subassemblies

Component	Material impact (%)	Processing impact (%)
Integrated circuit (IC)	80	20
Diode	19	81
Line output transformer	91	9
Deflection unit 28″ TV	99	1
FR-2 print with copper strips	74	26
Electrical condensators	69	31
Connector	56	44
Potentiometer	88	12
Copper wire	96	4
SMD components	51	49

FR-2, flame retardant, safety class 2; SMD, surface mounted device.

In a second study, efforts have been made to determine the relative merit of reuse strategies for subassemblies/components and materials. In such calculations the environmental impact of producing the materials in the component/subassembly is determined (the material impact). This result is compared with the impact associated with manufacturing those materials to achieve the appropriate form and function (the processing impact). The results are given in Table 30.3. It is concluded from this table that for most components the material impact is much higher than the processing impact. This suggests that the environmental difference between a material (only) recycling strategy and reuse strategies will be small. The deciding factors are therefore in practice often the economic aspects (for instance: there are only small environmental gains but bigger profits in reuse of subassemblies/components rather than in recycling of materials) and the value chain factors (reuse of these components is profitable but an appropriate value chain cannot be organized).

30.3.2 Product characteristics and reuse/remanufacturing strategies

Although it is concluded in Section 30.3.1 that applying end-of-life strategies ranking higher than material recycling brings relatively small environmental gains with respect to that baseline there is still a gain in absolute terms. If this absolute gain can be combined with (substantial) gains in the economic sense, there is a strong rationale to go for the high-level strategies.

Rose (2000) and Rose *et al*. (2002) have investigated this issue in great depth. Primarily product characteristics have been related to preferred end-of-life strategies. By using numerical values of the characteristics and applying a calculation program, preferred end-of-life strategies can be obtained. In this end-of-life design advisor (ELDA) programme the following parameters play a role:

- *Wear-out life*: Long wear-out life is correlated with lower level reuse strategies such as material recycling, unless wear-out is concentrated in a few parts/products of which the functionality has been degraded and therefore are difficult to sell.
- *Technology cycles*: Short cycles for technology in products are favourable for high-level reuse strategies; the resulting products can be sold to customers who are not so much interested in the latest technology or who have a low budget.
- *Level of integration*: High levels of parts integration make high-level reuse strategies problematic due to technical problems.
- *Number of parts*: For products with a high number of parts, mostly material recycling will be applied due to the high costs involved in making these products suitable again for second-hand markets.
- *Design cycle*: The potential for higher levels of reuse will be high with short design cycles; products will be sold to customers who are not interested in latest design.

It is to be realized that these strategy recommendations are on the basis of product characteristics only. Even if there is a potential for high reuse levels, there can be obstacles in practice, such as absence of markets or a company policy to sell new products only. Conversely, suitable design (lower level of integration, lower number of parts and shorter design cycles) can foster higher reuse levels.

It is concluded in this section that strategies for reuse of products can be economically successful if product characteristics as sketched above for the resulting 'post-consumer' products allow this. Apart from that, there are conditions from the market as well. Most markets for electronic products are characterized by a fast increase of functionality over time. The functionality ambition of the customers goes along with that. This also holds for the category of customers which has interest in post-use products. Therefore only high-end products which are returned by first users before the end of the technology cycle will in practice be successful candidates for reuse/remanufacturing. For computers and telecom products the increase of functionality ambition is high so there is quite some potential for this category. The opposite holds true for washing machines and fridges, TVs range somewhere in between.

30.3.3 Market characteristics and reuse/remanufacturing strategies

Applying strategies to increase remanufacturing can be highly beneficial if the hardware business is to be combined with consumables or software. Examples of this are inkjet printers requiring brand-specific ink cartridges and game consoles requiring software. In such cases most of the profit is made through the consumables and/or software. It pays therefore to maximize the 'fleet in the market'. Even if there is a financial deficit in the remanufacturing, the total business proposition can be very positive. Such a strategy can be enhanced by actively promoting trade-in/trade-up schemes for first users; in this way the number of products with an age lower than the length of the technology cycle can be substantially increased. In a proprietary study (Rose *et al*., 2002), the authors demonstrated that such a combination of strategies can be environmentally very beneficial and economically attractive. Implementation failed, however, because the company concerned decided to only sell new products.

Active engagement in remanufacturing and reuse can also be through subcontracting third parties which specialize in the field. When the flow of goods is sufficiently controlled, the risk of damage to the brand image and of price erosion of new market launches is very low. However, if there is no such control and discarded goods are exported to second or third world countries before remanufacturing and reuse, there is much more potential for negative fall outs. This happened for instance when the borders of Eastern Europe opened in 1990. This is relevant today as well: although the export of e-waste is forbidden by the Basel Convention, export for reuse is allowed in most cases. It is estimated in the Netherlands that some 15% of the total WEEE disappears out of the country through (il)legal exports. It is suspected that most of this will end up in the informal recycling sector or will be improperly reused; in practice very few of it will end up in state-of-the-art remanufacturing.

In spite of all this, there is considerable potential for reuse and remanufacturing of products in the developed world. This can be concluded by comparing the figures for the units sold, and the number in the market. For TVs this points to a period of 8 years for first use. The average life at discarding is, however, 12 years. This suggests a large amount of secondary use. Other indications are the observation that the amount of discarded products coming back through trade is relatively low. Apparently in this sector there is a business in post-consumer goods. Also trading of goods returned at municipal recycling centres occurs – in some countries in Europe, municipalities even have official contracts with dealers in secondary goods (or have export contracts). All of this takes place outside channels used by producers; in the opinion of the author there would be an environmental potential and added value if producers would engage themselves more actively in secondary markets. This potential is bigger than anticipated on numbers alone. Many users feel negatively about a brand when products have to be discarded completely because of something which is perceived by them (or really is) as a minor defect. Also high examination and repair costs raise a lot of anger. Even if a product really has to be discarded there is still the idea that it has value. Producers who are capable of dealing well with such issues generate a lot of goodwill and as a consequence, a lot of brand loyalty.

Add-ons to these secondary consumer markets could be given by including returns from business to business commercial activities and repaired production rejects. Even in such a case reuse and remanufacturing activities will stay relatively limited. The WEEE Directive therefore rightly focuses on material recycling.

30.4 WEEE implementation, materials recycling and corporate environmental strategy

30.4.1 Introduction

It has been explained in the previous sections that a comprehensive corporate environmental strategy in the field of take-back and treatment entails much more than just the implementation of the WEEE Directive. Compliance with the WEEE Directive is basically a defensive item. However it is a defensive item which is in constant flux. This is because many of the ideas behind WEEE are excellent but that in its current form the Directive has serious flaws. Member states are, as a result of that, struggling with implementation and unfortunately this has resulted in big differences in the forms in which companies have to realize compliance. Moreover, the cost of implementation of WEEE will increase dramatically in the future: as of the year 2011 recycling fees which are allowed in many states are not allowed anymore. Simultaneously the amounts of E-waste which will have to be collected and processed will have to increase substantially. This will result in a situation in which companies will not join forces anymore to maximize environmental results but as the first priority will be to minimize cost.

The increased collection target will be only one of the outcomes of the WEEE recast process currently going on in the EU. At the time of writing the outcome is unsure. Whatever happens, implementation practices in the member states will have to be changed. Moreover there will be changes in transportation costs, material composition of products and technology for treatment. Also the prices which can be obtained for secondary materials or that have to be paid for residual waste will change, resulting in additional dynamics. All these matters mean that companies should have a detailed knowledge about all these items in order to position themselves optimally in the discussions and in order to make the best choices within the latitude which the future WEEE Directive will allow.

30.4.2 Ideas and realities about WEEE

The six chief issues which in the opinion of the author cause the problems with the WEEE Directive and its implementation are as follows:

1. The individual producer responsibility (IPR) principle. Many tasks resulting from WEEE can – both from an environmental and cost perspective – be carried out better collectively. Moreover attributing responsibilities to parties who cannot 'manage' or influence sufficiently will result either in low performance or high cost (or both).
2. Appropriate treatment of WEEE will be enough to realize the envisaged environmental goals. However, in practice a combination of high collection rates, appropriate treatment and adequate upgrading of secondary material streams is needed to fully realize the environmental ambition of WEEE.
3. Design for recycling (DfR) will result in better environmental performance and will lower or bring back to zero costs for producers. However, in practice advanced technology, availability of industrial infrastructures and outlets for secondary materials, and appropriate organization of take-back systems can contribute much more to environmental performance than just DfR. Even under such optimal conditions the vast majority of discarded electronic products keep a financial deficit at the end of their usual life, particularly if transportation costs are included as well.
4. Environmental gains and costs of WEEE differ greatly depending on the material composition of the products (precious metal, metal, plastic and glass-dominated products). This calls for a differentiation of requirements according to composition rather than on application (as currently is the case).
5. For some electronic products (cooling/freezing, lamps, TVs/monitors with LCD screens), controlling potential toxicity is the dominating environmental item, for others (computers, telecom, washing machines) recycling is the top priority. A third group (TV/monitors with CRT screens, several smaller items) should have '*mixed*' treatment goals. In the current WEEE directive recycling issues dominate. The Directive on Restriction on Hazardous Substances (RoHS) is thought to cover the toxicity issues in combination with the so-called Annex II provisions). However, the RoHS exemptions are not adequately mirrored by requirements in the WEEE Directive.
6. Among member states there are big differences, both as regards administrative procedures and reporting duties but also in what is allowed in practice to reconcile the WEEE basic ideas with reality. This concerns technical issues, organization of recycling systems as well as financing (allowing or not allowing fees).

Apart from this there are several environmental shortcomings of the WEEE Directive:

- Product categories per application, not per material composition (no real 'resource focus' see above).

- Unfocused collection targets (no ‘input rules’).
- Weight-based recycling targets (only remotely serving ‘green’ needs).
- Ignoring the level of material reapplication (no ‘output’ rules, in fact a ‘not to landfill’ only directive). Also, cost/eco-efficiency items have not been considered.
- The idea in the WEEE Directive is that products come back as ‘individuals’. In practice they come in ‘streams’, consisting of a wide variety of brands, types and sizes.
- Focus on ecodesign, not on system organization (economy of scale).
- Unclear recycling definitions (what is counted as recycled – fraction basis or pure material basis).
- Unclear definition of removal in Annex II (toxic control).

In order to address the issues above the EU has set up a Technical Adaptive Committee. So far, progress in this Committee has been slow. The current recast of WEEE will modify the current WEEE Directive but will change the basic ideas behind it very little. Therefore it is most unlikely that the gap between these ideas and the realities in practice will be closed. This will mean that in practice stakeholders will keep on struggling with the implementation and differences between member states will stay in place.

There is good news in spite of all this: in the last decade a lot of common ground has developed among stakeholders about the intent of the WEEE Directive. This intent can best be described as all stakeholders wanting the Directive to achieve the maximum environmental gain at the minimum cost. Real compliance with the WEEE Directive by producers is therefore seen by the author as working actively to reach this goal (and the capability to demonstrate achievements towards this end).

30.4.3 Data needed for making a WEEE strategy

In this section, lists of items about which data can be helpful in making the take-back and treatment strategy of an organization are presented. This is not an exhaustive list; neither is completeness required to make decisions. For each item it is mentioned where the data can be helpful.

Products and treatments

Product characteristics:

• Total weight of product	Determination of recycling efficiency Comparison with competitors/products Potential of material reduction (ecodesign)
• Constituent materials	Value of secondary materials

	Determination of recycling efficiency (physical, economic, environmental)
• Presence of toxics which have been specifically removed or could increase cost of disposal of residuals	Cost, cost reduction potential
• Product architecture, number and type of fixtures	Disassembly cost Cost reduction potential of simplification of architecture
Collection of products:	
• Amounts of products discarded in relation to products sold 10 years ago	Cost of take-back and treatment Position on payment on basis of return volume or on basis of market share today
• Reason for discarding	Opportunities for reuse/remanufacturing or life extension services
• Age of products handed in	Potential for competitive advantage
Treatment of products:	
• Economy of scale of recyclers	Cost of treatment
• Availability of latest treatment technology	Environmental performance, cost
• Possibility to do company specific treatment, return/supply of secondary materials	Competitive advantage
Secondary streams resulting from treatment:	
• Leverage recyclers versus secondary streams upgrades	Cost of treatment
• How are streams combined or separated	Cost and environmental performance
• Final destination of secondary streams	Environmental performance

Data sets

• *Environmental data set* (for instance Eco-indicators):	• Determination of environmental performance • Setting priorities recycling versus toxic control • Proving environmental improvement

or equivalency of actions in ecodesign, technology or system organization
- Support of discussions with stakeholders

Prices/cost data set (per member state):

• (Secondary) materials • Transportation costs • Recycling costs	Choices of transportation companies, recyclers, PRO's (professional recycling organizations)
• Overhead cost of PROs	Identifying best practices
• Administrative costs	

Data about competition:

• Products	Identify opportunities for competitive advantage
• System operation	Identify partners for cooperation

30.4.4 Issue lists for making decisions on WEEE implementation

The issues as listed below are to be decided on the basis of the data as mentioned above in order to be effective as an organization, priorities need to be set. Although the WEEE Directive works out differently in the member states of the EU and the interpretation of the basic rules and provisions is different as well, it is the experience of the author that inside the organization as little differentiation as possible should be allowed.

Business issues: optimization of the environmental gain/cost ratio:

• Realizing economy of scale in all take-back and treatment perations	Increase gain/cost ratio
• Using best available technologies in treatment	Increase gain/cost ratio

• Apply ecodesign
  ○ Fewer materials
  ○ Less material diversity
  ○ Application of secondary material
  ○ Fewer potential toxic substances
  ○ Simplify product architecture
	Chiefly environmental gain in take-back, cost reductions mostly elsewhere in the company

• Get fees from customers for take-back and treatment	Cost reduction

• Explore reuse/remanufacturing and life-extending services	New business
• Let take-back from private consumers piggy back on take-back from business customers	Mostly cost reduction

WEEE implementation issues:

• Involve PROs (Collective systems)	Improve gain/cost ratio Reduce complexity for own organization
• Mixed system (mixture collective individual)	
• Differentiation of system choice depending on size of the member state	For optimum results in gain/cost complexity reduction
• Get cross-border solution	Environmental gains (secondary stream processing), Economy of scale

Debate issues (industry federations, other stakeholders, member states/ Commission/European Parliament):

- Harmonization of rules
- Clarifying definitions
- Attribution of (shared) responsibilities
- Simplification of WEEE by splitting between a basic directive and implementation rules which can be updated in faster procedures
- Differentiation according to environmental priorities (recycling versus toxic control)
- How to close the gap with RoHS
- Scope of the directive
- Collection amounts
- Treatment (recycling quotes, Annex II)
- Fees
- Guarantees

Future issues ('what if'):

- Fees are not allowed anymore
- Raw materials prices go up strongly
- China opens its borders for recycling

30.5 Summary and conclusions

Take-back and treatment of discarded products are only part of a comprehensive strategy. For electronic products its potential to contribute as such to reduce the environmental load of products is relatively small. However, since the ramifications of addressing reuse, remanufacturing and recycling can be substantial in environmental, business and customer satisfaction, it is worthwhile to consider take-back and treatment in considerable detail.

Owing to this interlinkage, first the making of environmental strategies is considered. Subsequently the take-back and treatment aspects are considered. It is concluded that product characteristics determine to a large extent what the best strategy is. Because of the large variety in such characteristics, optional strategies to be followed by companies will be quite diverse. This holds for reuse, remanufacturing, recycling and even for control of potential toxics.

Since the WEEE Directive is based on a 'one size fits all' approach which has been developed on the basis of principles rather than on science, there are in practice many problems linked to achieving the maximum environmental gain at the minimum cost. In order to make the best out of this complicated situation it is recommended to collect data about product characteristics, discarding and collection, potential treatments and (upgrading of) secondary streams. Combined with data about environmental effects and price/cost this will allow the business to come to the most eco-efficient solutions.

These solutions primarily apply to business issues related to take-back and treatment in general and more specifically to WEEE implementation issues. However, the data will also be helpful in finding positions in debates with other stakeholders, including industry itself. The WEEE Directive is still in full development so looking to data-based 'what if' scenarios will be helpful for the business and for society.

30.6 References

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