Master thesis

Reduction of hazardous flows of electrical and electronic equipment through induced technological change

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28.05.2013

Abstract

Electrical and electronic products enrich the cultural and social life and deliver essential intermediary goods in modern economies. With regard to an effective transformation of the economy towards a more sustainable one, electrical and electronic products play a crucial role. However, waste electrical and electronic equipment (WEEE) is the fastest growing waste flow within the European Union and raises serious problems due to the high amount of illegally treated WEEE and its hazardous components.

The objective of this study is to depict regulatory instruments that induce technological progress to reduce hazardous and avoidable waste flows generated by electrical and electronic products. An interdisciplinary approach aims to integrate the knowledge and analytical tools of other sciences to assess economically but also environmentally meaningful solution paths.

First, a material analysis gives an overview of the important components of electrical and electronic equipment (EEE) and their environmental weight. A life cycle perspective permits to discuss different recovery options and possible trends to reduce the environmental burden of EEE. Moreover, the analysis assesses regulatory instruments that trigger technological progress and allow the reduction of harmful flows into the environment. In addition, a model of the electrical and electronic industry gives an insight into the dynamics of the technological progress and the waste development of a profit maximizing industry.

The results of the profit maximization and the external sustainability criterion indicate a necessary level of an environmental tax on harmful waste. Interestingly, positive growth is only possible in the case of increasing returns to scale or a decreasing price of inputs.Accordingly, the qualitative analysis establishes the need for further regulatory intervention. Combined regulatory instruments such as environmental labelling and an environmental management system would induce technological progress and improve environmental performance.

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I Introduction

The economic activities of the last centuries burdened the eco-system of the planet and weakened its absorptive capacity leading to a reinforced greenhouse gas effect. The growth of emissions to the air and the pollution of water and land areas harmed seriously the biosphere so that the effects such as biodiversity loss and anthropogenic climate change get actually uncovered.

The flows of the environmental sphere to the economic sphere and vice versa have been increased to an unsustainable level that endangers processes in the nature, human society and also the economic activity. Therefore the necessity emerges to transform economic activities in such a way that environmentally intelligent products allow sustainable consumption and a more conscious use of goods and services of the environment. The sectors of the economy have different potential to reduce their harmful impact on the environment. Certainly the energy sector has still a huge potential to increase efficiency and to substitute fossil fuels against renewable energy sources. Also other sectors are essential for the transformation of the economy to a more sustainable one. The Brundtland Commission defined sustainable development as the 'ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987, I.3.§27, p.16). Moreover, sustainability is understood as a multidimensional concept that includes social, environmental and economic needs.

This analysis will focus on the material throughput generated by electrical and electronic equipment (EEE)[1] and particularly on the flows from the economic sphere to the environment - on the waste streams. According to an impact assessment of the European Commission, the waste electrical and electronic equipment (WEEE)[2] is the fastest growing waste stream within the European Union (European Commission, 2008, p.5). EEE contains hazardous substances so that the treatment of WEEE requires sophisticated technologies and installations to fulfill environmental and safety standards. Different approaches are considered to direct the reduction of waste flows. The increase of resource efficiency allows using less material per output unit. Prevention of waste flows and substitution promote a change in processing, manufacturing or in material and design concepts. Recovery activities aim to employ most of the material of waste streams and reintegrate components in a new product life cycle [3].

[1] "EEE' means 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 and designed for the use with a voltage rating not exceeding 1000 volts for alternating current and 1500 volts for direct current' (European Parliament and the Council, 2012, p.43). Furthermore, EEE are distinguished from electrical and electronic products that are integrated in large-scale stationary industrial tools and large-scale fixed installation.

[2] ´´Waste electrical and electronic equipment' or ´WEEE' means electric and electronic equipment which is waste within the meaning of Article 3 (1) of Directive EC 2008/98/EC, including all components, subassemblies and consumables which are part of the product at the time of discarding' (European Parliament and the Council, 2012, p.43).

[3] According to the Joint Research Centre a life cycle is defined as 'consecutive and interlinked stages of a product system, from raw material extraction, through production of materials and intermediates,

How do economies with magnetic levitation trains, systematic individual interconnectedness and immense information assessment capacities still consist of non-sustainable processes and products? The level of technological development delivers knowledge and possibilities so that products and economic processes could be pursued in a different, more environmental friendly way.
In this regard, considerations and reflections directing to the following research questions: Which are achievable goals regarding the reduction of WEEE from an ecological and technical perspective? **How should the state intervene to foster green technological progress? How can the state provide incentives so that enterprises of the electrical and electronic industry take measures to reduce hazardous and avoidable waste flows in the ecosystem?**
A possible approach to these complex issues provides a life cycle analysis. A life cycle analysis allows the evaluation of possible solution paths to reduce hazardous flows to the environment. In this analysis, hazardous flows are understood as flows that have a damaging effect on the nature or on humans. They are not correctly treated in the sense of reasonably available technology and include also flows resulting from not correctly stored products.
At first the EEE material and the related environmental weight are highlighted with the main emphasis on the product design, the manufacturing and the recovery phases. Within these stages current methods and techniques to reduce hazardous flows into the environment are elaborated as well as trends and prospective developments. Actors involved in the different stages pursue different interests that may confront each other. The huge amount of WEEE illegally treated builds up serious obstacles for an effective regulation and for the fostering of technological progress. Selected regulatory instruments provide an insight how the framework set by the state establishes interesting incentives to promote technological progress to reduce hazardous flows of EEE. Moreover, a model of the EEI gives an insight into the dynamics of the technological progress and the waste development of a profit maximization industry. An interdisciplinary perspective aims to integrate knowledge and analytical tools of other sciences to assess economically but also environmentally meaningful solution paths.

parts to products, through product use or service operation to recycling and/or final disposal'European Commission and the Joint Research Centre-Institute for Environment and Sustainability (2013).

II Directed technological change

In this analysis, technological progress encompasses enlargement and deepening of knowledge as well as the development of technical applications. Technological change includes the notion of invention, innovation and diffusion of technology and processes. Technological change and technological progress are used as synonyms where the last implies a positive subjective appraisal. Technological change is also considered to have desirable impacts for the society in general.
For Josef Schumpeter the rent-seeking entrepreneur has the innovative power to create new products leading equally to the destruction of others (IIAE Internationales Institut Österreichische Schule der Nationalökonomie, 1996, p.188).

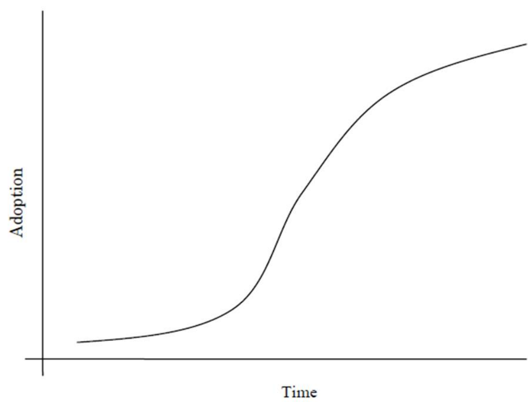
From a modelling perspective technological change leads to productivity improvements and the development of new products and processes. In economic growth theory, technological change provides explanatory power for the economic growth perceived in the economies which cannot be simply explained by the capital-labour ratio Arrow (1962). Besides the technological progress, political and social factors as the education system or the rule of law play a key role for economic development and environmental changes for example the climate change allowing countries in the north to pursue new agriculture activities. Returning to the modelling perspective, technological progress can be exogenous i.e. related to a fix parameter or endogenous i.e. related to a variable (for example to an input factor of a production). The technological change is then driven by innovation that changes the relative profitability of factors so that the direction is determined endogenously Di Maria and Valente (2006). Technological change can be captured by an input factor of the production function. In the Lucas model the production factor human capital embodies the learning and innovative capacities of workers that drive the technological progress Lucas (1988).
A bottom-up modelling framework perceives different technologies to produce the outputs so that the substitution and the emergence of new technologies become transparent. Learning curves provide possible tools to integrate new technologies. In a top-down modelling technological shifts are not perceived as shifts of different technologies to produce a certain output but focus more on demand and supply shifts between sectors. The shifts between the sectors of an economy are induced for example through changes of substitution elasticities of the production functions.
Technological change can be understood as a process of building knowledge on past results and acquiring new concepts through researching. Technological change is partly based on already existing technology and knowledge. Accumulated knowledge and techniques procure the basis for learning processes as learning-by-doing. Arrow describes learning as a product of experience and underlines its importance in the explanation for economic growth (Arrow 1962). In the case of learning-by-doing through experience the production process becomes more productive, thus leading to cost reductions.

Endogenous dynamics of learning are presented in a functional relation,for example through learning curves. A single factor learning curve can have the following shape $C = C_0X^{-\alpha}$ with C as unit cost of technology, C_0 as cost of the initial unit of the technology, X as measure of cumulative experience and α as learning index (Kettner et al., 2008, p.7). Learning curves of this type are very sensitive to the chosen parameter. Learning by doing can be integrated in a model in different ways. One option is shown in the model in section VI.

Market failures in relation to technological change

Drivers for market failures in relation to technological progress may be financial tightness, uncertainty about future demand, technologies depending on specific infrastructures and positive externalities as spillover effects.
Technological change has positive externalities leading to a distorted market. An enterprise that has invested in research and development incorporates this effort for example in the knowledge of its employees. Knowledge leads then to positive externalities favouring enterprises that already pursued research and development (R&D) activities in the past. On the other side, if gained knowledge and technical application are not protected, for example through patents, they will become a public good. Technological progress comprehends positive externalities due to spillovers of technology and knowledge which are negative externalities for enterprises investing in R&D. The State sets up a patent system that protects inventions for a certain time period. However the state has also to weight the social benefits of a widespread invention and profit loss of the enterprise and the resulting incentives for future RD investments of enterprises. Diffusion of a technology can be restricted by trade or foreign direct investment barriers. For instance, manipulated and genetically changed food is forbidden in some countries. Diffusion may also depend on the status of the economy within its business cycle. As the S-shaped diffusion curve of new technologies in Figure 1 indicates, after a certain threshold is reached, diffusion accelerates. The dynamics can be driven by consumer and producer's acceptance, by ex-

Figure 1: *S-shaped diffusion curve*



(Kettner et al., 2008, p.3)

perience or by the development of downstream infrastructure. For instance, after getting integrating in smart phones the touch screen technology diffused and largely spread to other products. Often the lack of finance is a crucial point for the diffusion. The adoption of new technologies and production methods requires experiments and large investments. The development of ICTs and interconnected markets and short-orientated time perspective of investors lead to the preference of short term investments, an evolution that gets transparent in the intensive growth of derivative financial markets. If the financial sector does not provide financial supply, the enterprises will be limited in their investment possibilities. Uncertainty is inherent in R&D activities where success cannot be precisely planed and future demand is ambiguous. Therefore risk-aversion may restrain enterprises from investing Karshenas and Stoneman (1995).

Some technologies are applied in such a way that they are locked-in for a certain time period. Long life cycles of technologies can lead to a lock-in situation as it is the case for fossil fuel power plants with a life time of 15 years. Lock-ins can also arise through an adaptive network where different modules are synchronized and adapted to certain technologies. Path dependency arises for instance in the energy system where transmission network is first locally connected to power plants and also to technical requirements of energy transmission relative to the power plant.

Induced technological change

In contrast to a 'neutral' technological change concept as developed by Schumpeter, where innovations are driven by rent-seeking actors, induced technological progress is a directed form of change to fulfil policy aims (Anger et al., 2005, p.22). In order to correct the market failures, policy maker may intervene and foster specific technologies which would be implemented under a desirable social level and necessitate state intervention. State supports universities and cooperation programmes between universities and industries to benefit from spillover effects. Germany subsidizes the build-up of photovoltaic panels to foster renewable energy and specifies sale prices of electricity generated by renewable energies. Furthermore, the state intervenes to forbid certain technologies to avoid environmental harm and preserve human health. For instance, France and Bulgaria have forbidden hydraulic fracturing, a technology applied to extract shale gas (Camatsos, 2012). Regulatory instruments to support technological change are the centre of gravity in section V. The notion of induced technological change comes also from the model framework in which, for example, a tax affects the choice of technologies.

The impact of regulatory intervention in growth models with endogenous technological change has been analyzed in the context of climate change and particularly relation to CO_2 emissions and energy production. Acemoglu, Ahion, Bursztyn and Hemous developed a model with one final output good that can be produced by the inputs of the environmentally friendly industry or by the environmentally harmful industry (Acemoglu et al., 2008). A tax on the input delivered by the 'dirty' industry and subsidies for research activities in the clean industry induce a transition to the more environmental friendly industry. They emphasize in addition on the cost of delayed policy intervention. Gerlagh, Kverndokk and Rosendahl also focus on the optimal timing of state intervention in an environmental problem set (Gerlagh et al., 2009). They set up a model with a pollutant stock and abatement sector and analysed the effect of different policy tools (2009). Some authors concentrate on concrete modeling of learning and analyze learning rates and experience curves and how they affect technological change (Gerlagh and Van der Zwaan, 2004). Acemoglu deals furthermore with market failures in relation to technological progress leading for instance to a preference of current gains enabling technologies which do not mirror the prospective social benefit of a technology (Acemoglu, 2011).

How can technological change lead to a reduction of hazardous waste flows of EE products and which are adequate regulatory instruments for this aim are questions that will be analysed and answered in the following sections.

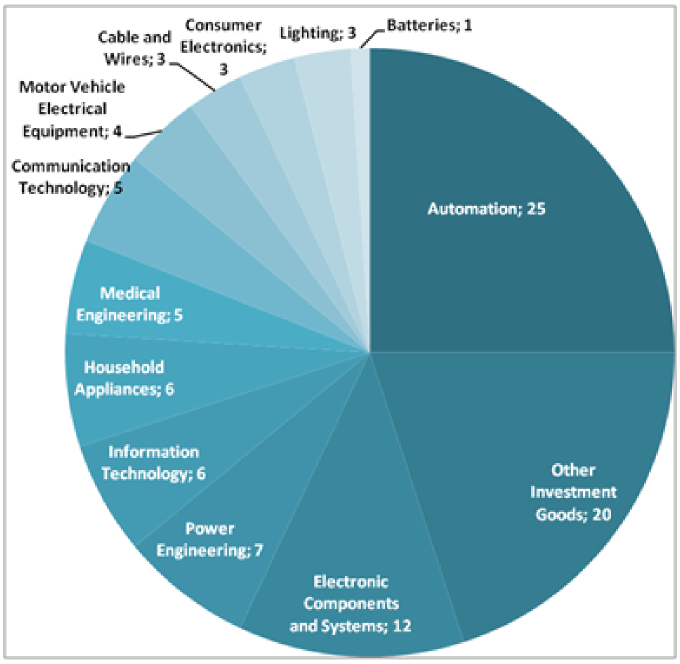
III Material Analysis

Electrical and electronic products enrich the cultural and social life and deliver essential intermediary goods in modern economies. The fast development of information and communication technologies (ICTs) changed human interaction and also economic activities. With regard to the effective and desirable transformation of economic processes towards a sustainable economy, electrical and electronic (EE) products play a crucial role. They are used in renewable energy technology for example for wind turbines or electric vehicles. Moreover, they form important parts of smart grids and provide potential to mitigate emission by better communication possibilities. Although the electrical and electronic industry (EEI) grows globally the industry faces important obstacles of material scarcity and environmental problems due to the equal growth of waste of electrical and electronic equipment (WEEE). WEEE is the fastest growing waste flow in the European Union with a low official and high unofficial collection rate. A significant amount of WEEE is treated illegally, so not in line with the EU law. The material analysis provides an adequate approach to understand the reasons and relevance of illegal WEEE treatment processes.

Key facts about the industry

The EEI is a key industry as an intermediary supplier of products and also as an industry that incorporates a large innovation potential and growth expectations. According to the German association of electrical engineering and the electronic industry (ZVEI), one quarter of the research and development expenditures in Germany is effected in connection with EE products and one third of all technology impulses come from the EEI (Zentralverband Elektrotechnik- und Elektroindustrie, 2012*b*). Owing to the technological dynamics of the industry, the research interest for technological development in this branch and the related progress of an environmentally friendlier production arise. Moreover, the industry employs a lot of workers and represents an important branch of the current developed economies. For example, in Germany the EEI is the fourth largest industry branch after the car, the mechanical engineering and the chemical industry.

Figure 2: *Electrical and Electronic Industry - share on turnover*



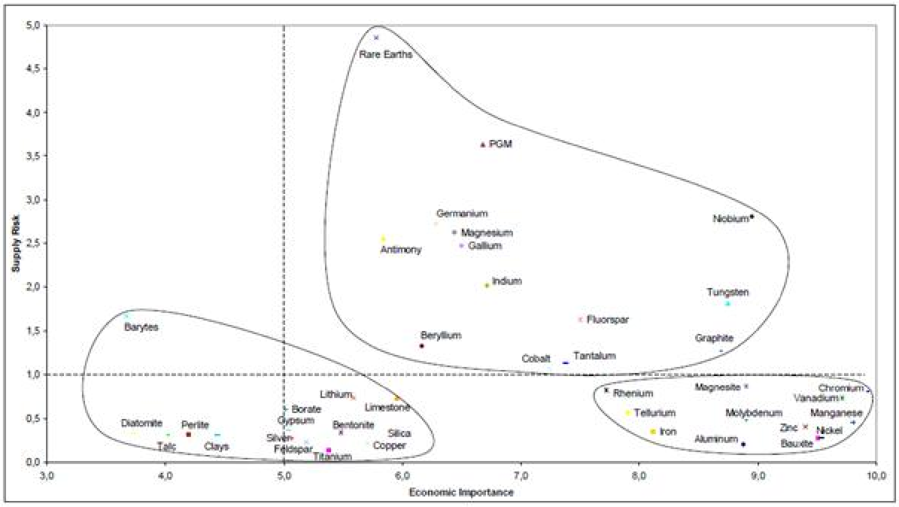
Own illustration, (Weinberg et al., 2010, p.3)

Figure 2 shows the distribution of EEE according to their use categories and generated turnover. Automation has the highest share in terms of turnover of the EEI (Weinberg et al., 2010, p.3). Electronic components and Information and Communication technologies account for 12 and 11 percent respectively. Other categories remain below a ten percent share.

III.1 Material flow analysis of electric and electronic products

Main commodities for the EEI are copper, crude iron or steel, aluminium, crude oil or natural gas, nickel, lead, cobalt, lithium, zinc, manganese and rare earths (Weinberg et al., 2010, p.3). Ferrous metals account for 50 percent of WEEE weight, non-ferrous metals for five percent, plastics around 20 to 25 percent (European Commission, 2008, p.110). Other components can be wood, oil, glass. A complete list of metals in electric and electronic products can be found in the publication of Behrendt et. al. in Appendix 2 (2007, p.55). An expert group and the European Commission assessed in a report the critical raw materials for the EU (European Commission, 2010). 'Raw material is labelled 'critical' when the risks of supply shortage and their impacts on the economy are higher compared with most of other raw materials' (European Commission, 2010, p.5). The focuses lies on the supply risk triggered by political-economic instability of production countries, by the concentration level of production, by the substitution potential and the increasing demand of raw materials (European Commission, 2010, p.5). On the other hand environmental country risk resulting from poor environmental standards in the production country was an indicator for criticality (European Commission, 2010, 5).

Figure 3: *Potential critical minerals and metals*



(European Commission, 2010, p.6)

The expert group analysed 41 different metals and minerals. The factors of criticality were summed up to indices and are represented in two-dimensional diagram of supply risk and economic importance (Figure 3). Rare earths and Platinum Group Metals have a high critical status as well as Germanium, Antimony and Beryllium (see Table 1 for the list of critical raw material).

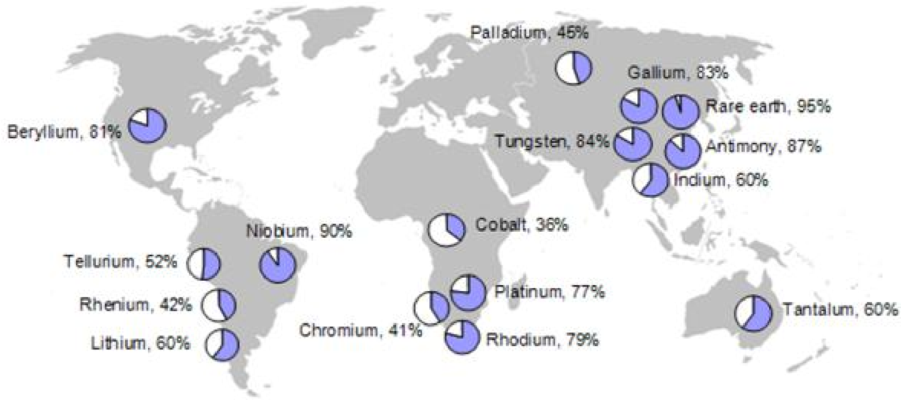
Table 1: *List of critical raw materials at the EU level (in alphabetical order)*

Antimony	Indium
Beryllium	Magnesium
Cobalt	Niobium
Fluorspar	PGMs (Platin Group Metals)
Gallium	Rare earths
Gemranium	Tanatalum
Graphite	Tungsten

(European Commission, 2010, p.6)

The supply risk arises beneath other reasons from the production monopoly of countries. Figure 4 shows some regions that dominates the production of important metals for the economies. In the case of rare earth the production is significantly concentrated with 95 percent coming from China (Figure 4). In 2009, China pulled back its exports leading to a rapid scarcity of rare earth on the world market (Kutsche, 2012, p.6). Besides the rare earths, China has a dominant position in the supply of antimony and tungsten and Russia in the case of Palladium. Moreover, South Africa delivers about 70 to 80 percent of world supply of platinum (OECD, 2010*a*, p.41). For a completed list of critical ma-

Figure 4: *Countries having a dominant mining production of some metals*



(OECD, 2010*a*, p.27)

terials and European import dependence, see the critical raw material report (European Commission, 2010, p.77-81). Due to the scarcity of metals, recycling and other recover processes of material become interesting although for example valuable metals are often used in small quantities in EEE.

The increasing demand of EE products and the concentration of production within some countries increase the relevance of WEEE and its still valuable components. The intermediary electronic products, the non-iron metals and fabricated metal products make up the largest share of material costs relative to the total material costs (Weinberg et al., 2010, p.4). Other important material cost factors are plastics, machinery and chemical products in EE products.
The weight of consumer electronic devices is in mainly defined by the materials iron, aluminium, copper and plastics. However the precious metals are relevant for the economic cost of production. For all of the consumer electronic devices listed in Figure 5, plastics take continuously a relatively high share in weight but have a low economic value. The precious metals are only used in small proportions but they are most costly. The enterprises have incentives to search for the most efficient use of the costly metals.

When analysing the potential to recover valuable materials of WEEE one has to keep in mind the diversity of inputs in EE products. The development of electronic devices goes into more complex systems in terms of material use. A mobile phone has around 500 to 1000 different components (OECD, 2010*a*, p.28). In electronic semiconductors, 12 different chemical elements were used in the 80s increasing to 16 elements in 90s up to 60 different chemical elements today (Zentralverband Elektrotechnik- und Elektroindustrie, 2012*a*, p.2). The complexity of consumer electronic devices increases using more components in smaller proportions. The application of smaller and increasingly different components hampers material recovery. Therefore a conflict may arise between an intelligent composition of their products leading to simpler recovery processes and the growing

Figure 5: *Weight versus value distribution for some consumer electronic devices*

Weight	Fe (%)	Al (%)	Cu (%)	Plastics (%)	Ag (ppm)	Au (ppm)	Pd (ppm)
TV-board	28	10	10	28	*280*	*20*	*10*
PC board	7	5	20	23	*1000*	*250*	*10*
Mobile phone	5	1	13	56	*1380*	*350*	*210*
Portable audio	23	1	21	47	*150*	*10*	*4*
DVD player	62	2	5	24	*115*	*15*	*4*
Calculator	4	5	3	61	*260*	*50*	*2*

Value Share	Fe (%)	Al (%)	Cu (%)	PM sum (%)	Ag (%)	Au (%)	Pd (%)
TV-board	4	11	42	43	8	27	8
PC board	0	1	14	85	5	65	15
Mobile phone	0	0	7	93	5	67	21
Portable audio	3	1	77	20	4	13	3
DVD player	13	4	36	48	5	37	5
Calculator	0	5	11	84	7	73	4

("PM" is Precious Metals and includes Ag, Au and Pd)

(OECD, 2010*a*, p.60)

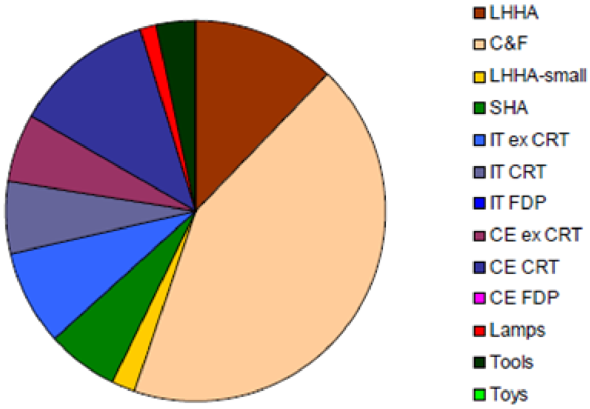
challenging demand about functional possibilities of electronic devices. Both emphasises can be realized but it requires research to build up satisfactory design, recovery possibilities and in addition raise consumer awareness of these issues. Considerable supply risks and the increasing price of metals set up incentives to improve material efficiency and recovery operations.

The growth of consumption of EEE leads to a huge accumulation of waste that enhances the importance of recovery operations in order to spare environment and human health from environmental problems arisen with the production of EEE.

III.2 Environmental Weight of Materials of WEEE

Electrical and electronic products contain hazardous substances that can seriously harm the environment and humans. As a large part of WEEE generated in the European Union is unofficially collected and treated, special attention has to be paid on the risk of environmental damage and health problems.
Figure 6 shows the environmental burden of different consumer EEE categories according to the Eco-indicator 99. The Eco-indicator'99 was developed by the consultancy agency PRé and foresees the assessment of environmental impacts of major life cycle stages for production, use and end-of-life (Goedkoop and Spriensma, 2000).

Figure 6: *Contribution of categories to environmental impacts of WEEE total (EI99 H/A)**



(Huisman et al., 2007, p.V)

*Eco-indicator'99 H/A weighted, per kg WEEE total collected

CE	Consumer equipment
C&F	Cooling and freezing
CRT	Cathode ray tube
CE	consumer equipment
FDP	Flat panel displays
IT ex. CRT	Information technology except cathode ray tubes
IT ex. FRT	Information technology except flat panel displays
LCD	Liquid crystal display
LHHA	Large household appliances
SHA	Small household appliances

With respect to the Eco-Indicator'99, cooling and freezing appliances have the highest environmental impact. The high impacts result among others from ozone-layer depletion, the global warming potential during waste treatment, from the cumulative energy demand and resource depletion (Huisman et al., 2007, p.VI). Specific IT goods have a high environmental as for instance flat panel displays. WEEE is a very heterogeneous waste stream regarding its environmental impacts so the environmental requirements should be differentiated by product categories.

The extraction of rare earth shall clarify exemplary which environmental concerns arise during the mining process of metals that are used in EEE. Rare earths are essential components for the EEI especially for upcoming economic branches as ICTs and energy technology relating to renewable energy sources and smart grids. For the extraction of rare earths drillers dig holes in porous rocks. After the extraction of big pieces, chemical fluids stay in some holes in the rocks and continue to dissolve the rocks and uncover heavy metals, radioactive materials and further rare earths (Kutsche, 2012). During mining activities, ground water passes are crossed and if the pipes are not sealed very carefully, radioactive substances will enter the ground water (Kutsche, 2012, and further facts relate to this source). The biggest mine of the world in Bayan Obo in China accumulated 150 million tonnes of waste consisting of poisonous heavy metals and radioactive thorium. The wind takes the dust along kilometres. The ground water of the villages next to the mine is polluted and the cases of cancer increase. In general, the extraction of metals necessitates high use of energy and water and often involves employment of hazardous chemical substances. Mines to extract rare earths were closed in the past in the US because of environmental considerations.

The environmental weight of a material is calculated on the basis of inputs (material and energy) and the resulting outputs (emissions to air, water and land) necessary to produce and dispose a mobile phone (OECD, 2010*a*, p.33). Figure 7 gives an insight how much greenhouse gas emissions (in CO_2 kilogram) arise and how much cumulative energy (in mega joule) is necessary for primary production of one kilogram material (f.eg. glass). Figure 7 shows in the first column the component's share on total weight of a mobile phone. Furthermore, the environmental weight of a material is measured either in energy use or in emitted CO_2 and either by kilogram used material or by mobile phone. The average weight of a mobile phone is assumed to be 70g (OECD, 2010*a*, p.29). The extraction and production of palladium and platinum lead by far to the highest GHG emissions per kg employed material. Although plastic generates relatively low 5 CO_2 kilograms per employed kilogram, it has a considerable impact as it accounts for 43 percent of mobile phone weight. On the other side, palladium takes less than 0.01 percent of the weight of a mobile phone. However, through its hazardous chemical characteristics its environmental impact is considerable even in low quantities. Magnesium has a high environmental impact relatively to the other materials which diverges depending on the consulted factor. Palladium

Figure 7: *Environmental impact of a mobile phone*

	percentage share on total weight	Cumulative energy demand MJ per kg material*	MJ energy per mobile phone**	CO2 kg per kg material*	Grams of CO2 per mobile phone**
plastic	43	108	3.251	5	0.151
glass	14	17	0.167	1.3	0.013
copper	13	102	0.928	4	0.036
iron	7	4	0.020	1.2	0.006
aluminium	5	200	0.700	12	0.042
magnesium	3	422	0.886	43	0.090
nickel	1	196	0.137	10	0.007
lead	1	21	0.015	1.5	0.001
palladium	0.0144	181940	1.835	8677	0.087
platinum	0.0004	290770	0.073	13954	0.003

Own calculations, Data from OECD report
**(OECD, 2010*a*, p.29)*(OECD, 2010*b*, p.22)

has a significant impact per mobile phone for both indicators. The environmental impact clearly changes according to the environmental factors chosen for instance CO_2 emission, energy or water use, pollution of ground water and air or health risks. If materials have a high environmental weight and are also very costly economic and environmental interest to recover those materials will coincide.

Critical metals are necessary inputs for electrical and electronic products. The scarcity of some electrical and electronic components and their environmental impact enhance the importance of efficient and effective recovery processes of WEEE.

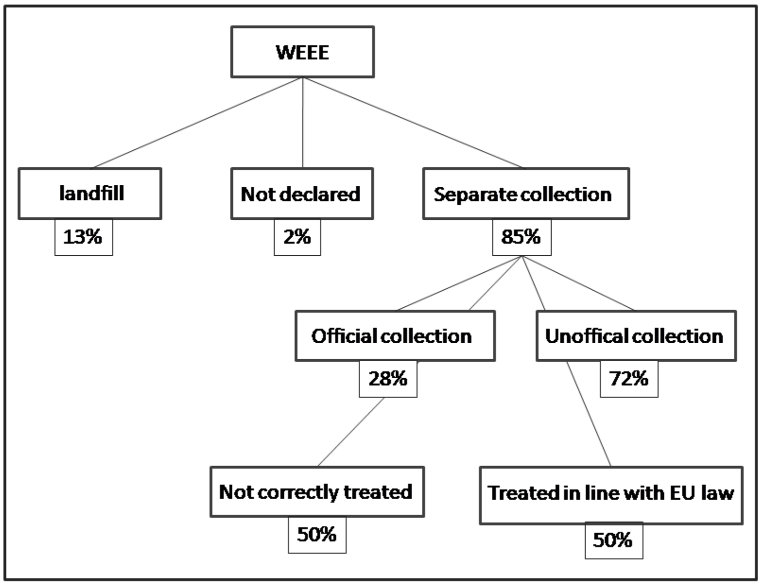
IV Concepts of waste recovery

Waste of electrical and electronic equipment (WEEE) is still economically valuable due to the tight supply of some materials and the increasing prices of metals. The significant gap between the official collection rate of WEEE and the estimated actual one in the European Union mirrors the economic relevance of WEEE. This section clarifies recovery options for WEEE and how a life cycle perspective provides a helpful approach in this regard. Furthermore, the conflict of interests between the different involved actors may also present obstacles in waste treatment processes.

IV.1 The collection scheme of WEEE

The European Commission states in an impact analysis that WEEE 'is the fastest growing waste stream in the EU' (European Commission, 2008, p.5). The electrification of household products supports this dynamic. Figure 8 shows the statistical structure of collection. Officially only 33 percent of WEEE is collected. However the actual collection rate is assumed to be around 85 percent and 13 percent of WEEE are estimated to go to landfills (Ibid.). 50% of collected and 40% of all WEEE is supposed to not be treated according to the official EU standards (Ibid.). The figure 8 enlightens that a part of the

Figure 8: *Key facts about the collection of WEEE*



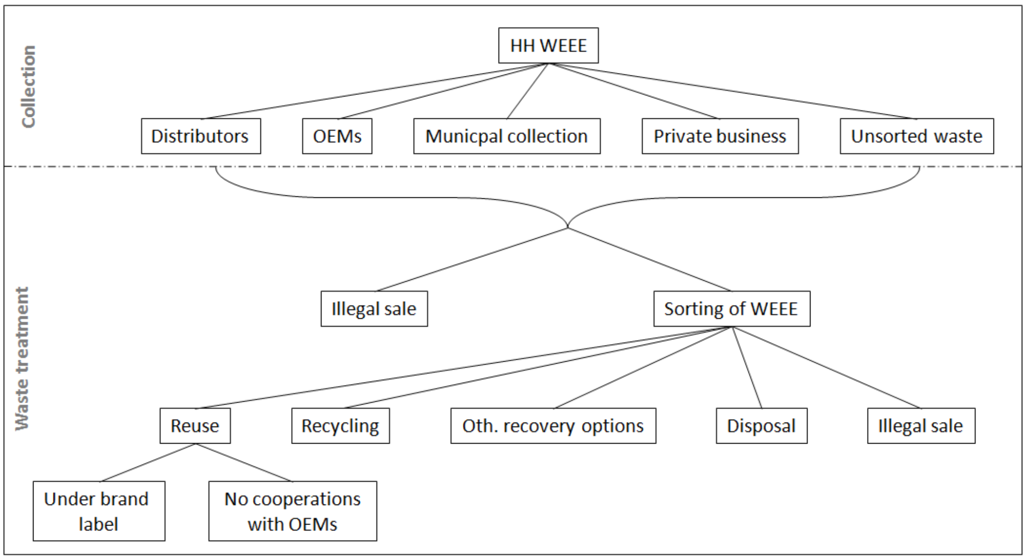
Own representation (European Commission, 2008, p.5)

unofficially collected waste is still treated in line with EU law. The collection of WEEE can still not be clearly related to collection centres and actors providing a considerable

impediment for effective regulation. The inadequately treated WEEE will rise from 3.4 million tonnes in 2005 to 4.3 million tonnes in 2020 according to a European Commission projection (European Commission, 2008, p.5).
The regulation for WEEE in the European Union prohibits the disposal of WEEE in domestic waste and foresees a separate collection system (more about legal requirements in section V. It is highly important that at the first stage of waste treatment, the collection is professionally carried out in order to sort out the equipment that can be directly reused. The Member States of the European Union (MS) set up different collection schemes (for more detail look European Commission 2008, p.92).
Figure 9 shows more concretely the treatment paths of WEEE. The flows start when the domestic and comparable industrial WEEE is entering the collection phase. The WEEE can be given to the distributors, the Original Equipment Manufacturers (OEMs), in a municipality collection station and to private businesses. In some cases, private businesses collect the WEEE directly from the consumers or the consumers give to the collection centres. One possible collection program foresees the buy-back of the product by the company, sometimes the company takes back the product for free, sometimes the equipment is donated for example to raise funds for charity organization. The collected WEEE can enter the illegal business domain followed by illegal treatment activities and WEEE exports.

Otherwise the WEEE is sorted and sent to facilities for reuse, recycling, other recov-

Figure 9: *Treatment of WEEE*



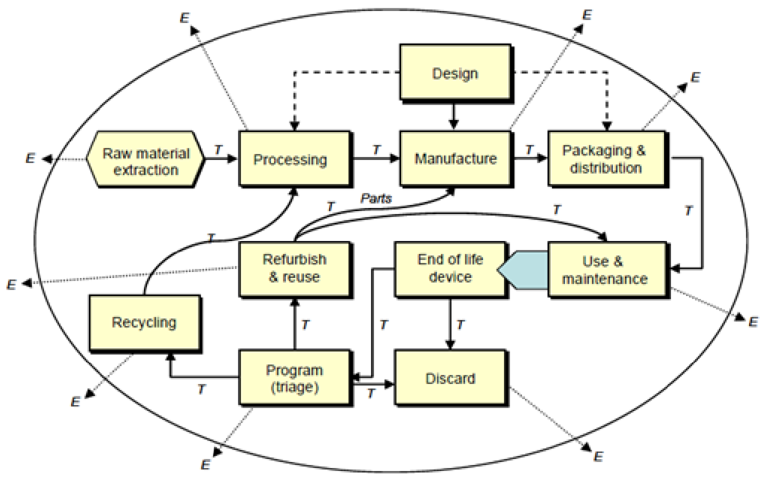
Own representation HH WEEE: Household and comparable industrial WEEE
OEMs: original equipment manufactures

ery options or final disposal. Every type of collector has different incentives to choose one option over another. In the reuse case, if the cooperation between OEMs and waste treatment companies is effectively realized the product can be sold under the brand name. If there is no cooperation the product will be probably sold under a lower price. The recycling process diverges a lot. According to the treatment facility, certain substances will be recycled and sold for reuse; others will be incinerated to deliver thermal energy for the recycling processes. The focus and the choice of material to recycle can differ between the facilities. The recycled material can be used for EEE or for other sectors. Regarding the research question of this paper further sub questions arise: which points and paths are crucial in environmental concerns and are preferable under reasonable economic costs? Which paths favour the development of technological progress? Which are key operations and strategies that enterprises of the EEI and the waste treatment industry can develop to reduce hazardous waste flows of EE products? Which are the current proceedings, trends and technological potential in this regard?

IV.2 A life cycle perspective

A life cycle analysis depicts the flows between the economy and environment on different phases of a product life. Figure 10 shows the life cycle schema of a mobile phone. Between different stages of a product life cycle transport activities occur. Within a phase emissions to the air, water and land arise, necessary water and energy supply lead to direct exchange processes with the environment. A life cycle analysis shows with variable degree of detail all flows from the environment in the economic sphere and vice versa. Key stages of a life cycle comprise design, resource extraction and processing, manufacturing, packing, distribution, retail, use, recovery options and disposal.

Figure 10: *Mobile Phone Lifecycle - Conceptual Material and Product Flows with Associated Emission and Transport Impacts*



(OECD, 2010*a*, p.38)

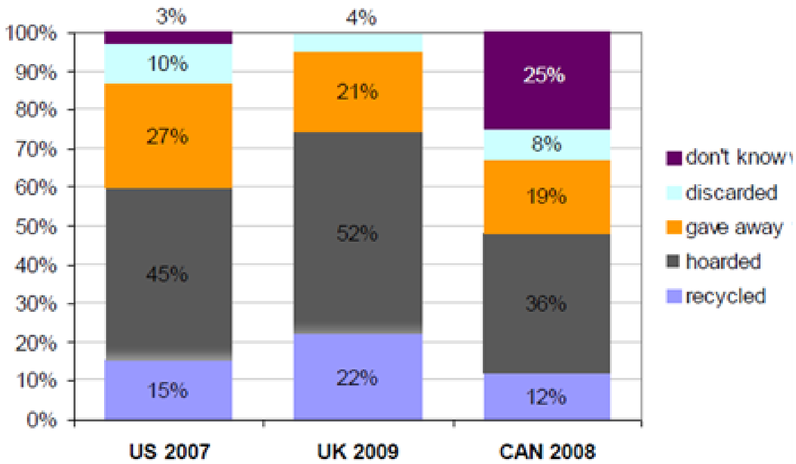
E = emissions to the environment (air, water, land), T = transport

A life cycle schema shows important points where emissions and hazardous flows appear.

The points localize options for measures of cleaning and filtering substances, liquids and air. Stages that can reduce directly environmentally harmful flows are eco-design, recycling and reuse processes. For the other stages a multitude of possibilities are present to reduce harmful flows into the environment for example using electric cars and trains to avoid transport emissions or using more energy efficient and less water intensive manufacturing technology. However, the focus of this study lies on the reduction of harmful flows generated by WEEE and emphasis is therefore put on recovery concepts.

The use and collection phase form also important parts to reduce harmful flows of WEEE and can be also influenced more directly by the user or consumer. A survey may provide a short insight how consumers deal with EE products. In Figure 11 consumer surveys conducted in the US, UK and Canada about what they do with WEEE show that around 16. 33 percent sort the mobile phones for recycling (OECD, 2010*a*, p.53). A large amount of end-of-life mobile phones about 44.33 percent are hoarded and around 22 percent are given away or sold. Around 7.33 percent of the mobile phones are discarded. The results of the material flow analysis can be integrated in a life cycle analysis. The

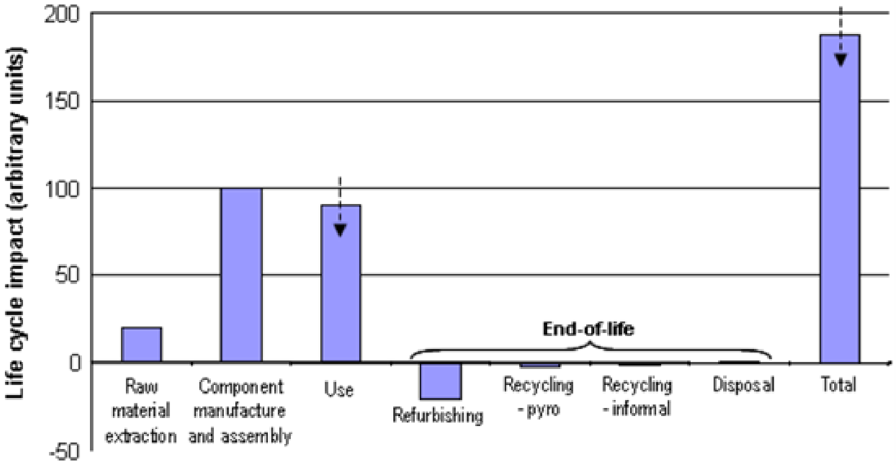
Figure 11: *Mobile Phone User Surveys 2007 to 2008*



(OECD, 2010*a*, p.53)

environmental impact of a material is assigned to the steps within a life cycle and opportunities to reduce the hazardous environmental impact become transparent. Normally, a life cycle assessment is concentrated on one product to allow precision and clarity. At the beginning, the scope and the goals of such an analysis are concretely defined. After an inventory analysis and the environmental impact assessment, interpretation allows a strategic orientation at which stages improvement potential should be realized. All steps of a product cycle are not directly managed by the manufacturing enterprise. However, the manufacturing phase encompasses the highest economic value adding process in the life cycle. So the manufacturing enterprise should be responsible to fulfil all reasonable potential to reduce hazardous flows into the environment. The responsibility of the manufacturing enterprise also includes a wide spectrum of measures and instruments for example by setting up supplier requirements. Figure 12 presents the impact of different life cycle stages of a mobile phone on the environment. The authors choose arbitrary units and

Figure 12: *Conceptual impacts for various life cycle stages of a mobile phone*



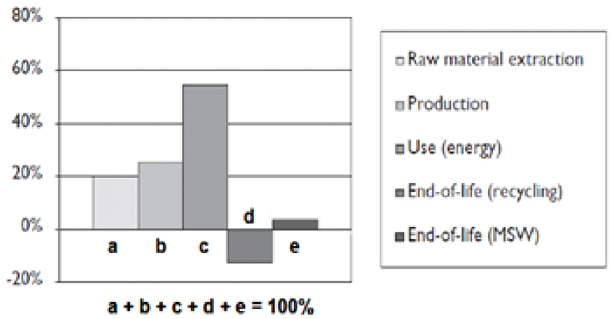
(OECD, 2010*a*, p.65)

concentrate on the comparison of environmental impact between the different life cycle stages. Around 1000 mobile phones provide the basis to measure the environmental effects. Around the half of the harmful impacts (the blue columns in the positive area) occur in the manufacture processes (around 46 percent) and ca. 41 percent in the use phase. The manufacturing process for mobile phones consists in assembling different components to a very small complex system and it requires for instance a high energy input (OECD, 2010*a*, p.64). The use phase accumulates environmental impact mainly through the energy use to operate the device.

During the end of life phase, refurbishing and recycling limit the hazardous flows from the economy in the environment (blue columns in negative field). Reuse has the largest negative impact reducing hazardous flows. Recycling conducted by professional pyrometallurgical industries is more effective than the informal recycling (OECD, 2010*a*, p.65). Emissions and other harmful flows occurring during the recovery processes are already included in the calculation for example transport emissions from collection centre to recycling facilities. Interestingly the primary production of material only accounts for around 9.17 percent of the harmful flows to the environment. Final disposal burdens also the environment. The authors suggest that if the manufacturing environmental impact is larger than the one of primary production the focus shall lie on the extension of the life span (OECD, 2010*a*, p.66).

More generally, Figure 13 shows the cumulative environmental impacts of consumer electronics during the different life cycle steps according to the end-of-life QWERTY/EE concept (Huisman, 2003). According to the author, the use of consumer electronic products has the biggest environmental impact. The raw material extraction and the production of the goods account together for around 45 percent of the total impact. The end-of-life step recycling has a positive impact because emissions and hazardous flows of extraction and production of material can be saved. In this regard the need for raw material extraction sinks with the amount of secondary raw materials in consumer electronics goods. The author focuses in this analysis on environmental burdens and costs that arise at the end of life and how they can be avoided (Huisman, 2003). To reduce negative impacts caused by

Figure 13: *Cumulative environmental impacts of consumer electronics across the life-cycle*



(OECD, 2010*a*, p.35)

transport activities during recovery operations, the material can be transported by trains. According to the OECD, transport operated through trains can decrease hazardous impact of reverse logistics by 62 to 73 percent (OECD, 2010*a*, p.52). The pollution during the use phase of EEE can be reduced by the operating of the device with electricity generated by renewable energy sources. A large potential of product innovation can certainly reduce the environmental impact during the use phase whereas the whole eco-balance (so the environmental impact throughout the entire life cycle) should be considered.

An application of life cycle analysis is the calculation of an environmental footprint of a product. The European Commission develops the methodological framework how to assess the Product Environmental Footprint (PEF) and will start the pilot phase in September 2013 (European Commission, 2013*e*). For example, Apple calculated a footprint of their products of 30.9 million metric tons of greenhouse gas emissions (Apple, 2013). The greenhouse gas emissions were calculated on the basis of ISO 14040 and 14044. 61 percent of the environmental footprint arises during raw material extraction and manufacturing, five percent during transportation, 30 percent during the use phase, two percent during recycling and two percent during final disposal (Apple, 2013). It is favourable that enterprises calculate and publish the footprints of their products because they certainly have the best information about these flows. Environmentally responsible corporate policy includes also setting up requirements for supplying firms. In this regard, Apple has often been criticized for its passive environmental policy regarding supplier firms in China where accidents causing deaths and suicides occurred (Pfluger, 2013).

A life cycle assessment provides a useful tool to assess intervention possibilities to reduce hazardous flows generated by the production, consumptions and disposal of a product. The level of detail and focus of certain phases can differ between different life cycle analysis and should be concretely adapted to scope and goals. A stakeholder analysis including the impact assessment of each life cycle stage on the workforce, managers, users and local community can depict more accurately how different groups are concerned by especially waste flows of EE products. A lot of initiatives were found to deal with WEEE problems like PACE (Partnership for Action on computing Equipment) or StEP (Solving the E-waste Problem).

IV.3 Ecodesign and material choice

Ecodesign is defined by the European Union as 'the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle.' (European Parliament and the Council, 2009*a*, p.16).

Eco-efficiency can be understood as measures that optimize the use of resources and reduce simultaneously environmental impacts. Efficiency improvement can reduce the environmental impact of economic activities however the absolute waste production and not only relative to one output unit is finally crucial for the eco-system. In this regard the complete recyclability of products would be desirable. Eco-design also refers to the way of manufacturing different components together to one product. The type of glue and of soldering material plays for example an important role for later decomposition. According to the European Commission eco-design determines 80 percent of the environmental impact of a product (European Commission, 2012, p.3). However the reduction of environmental impact depends on the efforts an enterprise to realize environmental improvement potential and to accept higher production costs.

The Directive 2009/125/EC on a framework for ecodesign covers all energy-related products and establishes a framework to harmonize the understanding of eco-design. The Directive provides only a framework and the related products. The European Commission assign initiates studies on different energy-related products and their environmental impact. After the preparatory study and the impact assessment the European Commission proposes implementing measures (European Commission, 2013*b*, p.3). There is still a huge potential and necessity of regulation on ecodesign. Some important product categories are still not separately considered, for example toner cartridges. Moreover the implementing measures focuses on energy efficiency and left over the potential for further environmental impact reduction.
The design affects also the life time of a product. In this context, the planned obsolescence and its avoidance is discussed in parliaments and society. 'Planned obsolescence' refers to intended reduction of a product's life span through for example an adapted design,

complicated construction and the lack of repair services (Oxford Dictionaries, 2013).
The average life time of an EEE varies a lot between the products. Medical electronic or electrical appliances have a functional life span of 20 to 30 years, fridges around 15 years and mobile phones 23 months. The technical life span for mobile phones is significantly higher than the actual use phase. Furthermore, the innovative dynamism and the incentives to sell more products through new functionalities and applications lead to a shorter life time of EE products particularly of ICT products. The average life time of a mobile phone decreased from three years in 1991 to 18 months in 2002 and even less today, however the technical life time of a mobile phone is about ten years (OECD, 2010*a*, p.49). Products can also be designed in such a way that new functions and applications can be easily added. The consumer can use the same product without necessarily buying new equipment. Jeremy Rifkin describes the transformation of the economy to a greener one also as a change of the buyer - seller relation (Rifkin, 2011). The relationship buyer - seller changes to user-supplier characterized by a long-term perspective where user and supplier do not meet at one point in time for the sale but develop a constant relationship (Rifkin, 2011). Developing the idea further the equipment stays in the property of the producer and the use, service and functional improvement will be the product.

Material choice - substitution

The choice of material and the way the materials are put together have a great impact on the recovery options and environmental flows into the environment. The decomposition of EE products must be conducted under specific safety requirements like air and liquid filtering and professional seal from earth contact. The more hazardous the substances are the more expensive the recovery processes in line with environmental and health standards get. Less aggressive substances can support recovery activities. The research for substitution possibilities for high poisonous material focuses on the substitutes for mercury, cadmium but also other forms of plastics.
Batteries and accumulators are essential in products of ICTs but incorporate hazardous substances. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan initiated a project to search for innovations to substitute minor elements and scarce resources. The researches try to substitute lithium and cobalt against natrium and another more abundant metals in large scale batteries (10 to 20 kWh) that could reduce the environmental impact by 1/1000 (Okada, 2012, p.29). A lot of research projects are still in the discovery and development phase and so fare away from product wide diffusion. For small devices, Aqua Power System Japan has developed batteries that functions with water and special alloys like aluminium, magnesium and cupronickel (Japan, 2013). Due to price increases of palladium substitutes were found and methods to use palladium in thinner layers (OECD, 2010*a*, p.42). Some of the platin group metals have special properties that make substitution more difficult for example platinum (OECD 2010A: 73). Moreover research on substitution possibilities led to the decreasing use of tantalum (OECD, 2010*a*,

p.29).
Another field within material research for environmentally friendlier products concern plastics. Synthetically produced plastics have often a very high life span and cannot easily be absorbed by the ecosystem. For instance PVC (Polyvinylchlorid) is a synthetically produced material that is often used because of its robustness, relatively simple production and its light weight but can effectively not be destroyed by natural decomposition processes. Therefore a lot of PVC is reused again for instance in building constructions. Apple for instance substituted lead, BFR, PVC, mercury and PVC, mercury and use arsenic-free glasses in their products (Apple, 2013).
Biologically degradable plastics are also in the discussion for the reduction of waste flows. Conventional plastics are made of crude oil. Bioplastics made of renewable sources are already used in shoes, mobile phones or shopping bags. Problems arise if biologically degradable plastics are mixed with conventional ones which are not degradable by nature (Nuernberger, 2003). There is still no clear consensus about the advantages of bioplastics comparing the eco balance of conventional and bioplastics (Nuernberger, 2003). Bioplastics are currently only used in small quantities so that bioplastic facilities are costly (European Bioplastics e.V., n.d.). Some bioplastics are directly degradable and some are not whereas the recycling techniques of non-degradable bioplastics are not yet developed in detail (Nuernberger, 2003). In order to foster recycling techniques for bioplastics, they do not have to be mixed with other plastics. The interaction between the producer deciding about the product design and material composition and waste treatment companies is crucial to get to more effective waste treatment processes.

IV.4 Reuse

Although the reuse of products is often the most favourable option from an ecological perspective the purchase of used products makes up a small part of EE demand. In the European Union 68.465 tonnes of collected WEEE were reused in 2010 making up a 1.89 percent reuse rate (Eurostat Database on Waste Electrical and Electronic Equipment 2013). A UK study on the refurbishment of washing machines and IT equipment concludes that 75% of the collected products were often still repairable (European Commission, 2008, p.36). Some reasons for the low reuse rates within the European Union are the consumers' preferences, costly repair services and safety standards.
Information campaigns about waste and essential collection issues could be promoted directly in shopping areas. With the purchase of a product, the consumer should be informed about optimal operating strategies and the necessity to return products. It is not in the interest of the retailers to advertise to return products as additional management problems arise with storing WEEE. The internet provides interesting second hand markets. In addition, incentives to buy used products can be increased by providing guarantees for the devices (Broehl-Kerneret. Al. 2012: 23). Also quality labels for used EEE could present a favourable additional guarantee (Broehl-Kerner, 2010, p.52).

For a company, important criteria to prepare a product for reuse are the type of device, the status, the brand, quality criteria as the life span expectation, the functionality as well as ecological and social criteria (Broehl-Kerner, 2010, p.52). The term 'reverse logistics' encompasses according to the European Working Group on Reverse Logistics 'the process of planning, implementing and controlling flows of raw materials, in-process inventory and finished goods, from a manufacturing, distribution or use point to a point of recovery or point of proper disposal' (De Brito et al., 2003, p.3). A major challenge of reverse logistics are the planning and dealing with uncertainties about time, location and the status of the product when it will return to the enterprise. Since it is possible to return products to the distributor under European regulation or to other collection places the local point of return is not clear. Some enterprises collect directly their products as for example the enterprise HP. Another uncertainty refers to the status of the product and the management of the next steps to repair, to rebuild or to just recycle the product. The OECD report portrays forward against reverse logistics showing the new challenges with reverse logistics for enterprises (see Figure 14).

For repair services intermediary goods of EEE are necessary. The uncertainty of the

Figure 14: *Comparison of forward and reverse logistics*

Forward logistics	Reverse logistics
Product quality uniform	Product quality not uniform
Disposition options clear	Disposition options not clear
Routing of product unambiguous	Routing of product ambiguous
Forward distribution costs more easily understandable	Reverse distribution costs more less understandable
Pricing of product uniform	Pricing of product not uniform
Inventory management consistent	Inventory management not consistent
Product life cycle manageable	Product life cycle less manageable
Financial management issues clearer	Financial management issues unclear
Negotiation between parties more straight-forward	Negotiation between parties less straight-forward
Types of customers easy to identify and market to	Types of customers difficult to identify and market to
Visibility of process more transparent	Visibility of process less transparent

(OECD, 2010*b*, p.26)

amount of reusable WEEE is translated in a more complex material, capacity, time and store planning (Ayres and Ayres, 2002).
When it comes to product design, reuse could profit from an easy decomposition of products and assemblage so that repair services are facilitated. Waste treatment processing technology could screen used products and test the situation of the components. In order to reduce treatment costs, machinery could be developed further as for instance the majority of mobile phones are sorted manually. The OECD states in a report that manual sorting cost of a mobile phone are around USD 4.17 per phone while semi-automated sorting costs amount to USD 0.83 per phone (OECD, 2010*a*, p.51). If a product is not significantly changed after repair services, the producer will still be legally responsible for the safe operating of her device during the use phase (Broehl-Kerner, 2010, p.26-32). Particularly, the increase of reuse of products depends on the cooperation and collaboration between second-hand companies, distributors and the OEMs. This will depend less

on technological progress but more on efficiently organized repair services and reselling of EEE. The state should provide incentives for the involved interest groups to exchange information and to cooperate.

Manufacturing makes up a large part of the environmental burden generated by an EE product varying between 30 to 60 percent according to the study and analysed product (Broehl-Kerner, 2010, p.36). For example the environmental burden during the use phase for washing machines and fridges is significant so that more energy-efficient products should be substituted against old once in some cases. From an environmental perspective, it is necessary that before starting preparing activities for reuse that it is also a favourable option from an eco-balance point of view. Eco balance means that the environmental burden generated by the reuse is lower compared to a new product. A study analysed the improvement potential of the reuse rate. With efficient autonomous mobile testing units, WEEE can directly be sorted at the point of collection. The authors find a possible reuse rate of 4 - 10 percent of the WEEE (Broehl-Kerner, 2010, p.36).

IV.5 Recycling

The process of recycling implies the material recovery from a used product. After the collection of products the recycling process for metal recovery involves different processing activities as 'shredding, screening, magnetic, eddy-current or heavy media separation, and further volume reduction measures' (OECD, 2010*a*, p.70). WEEE is recycled in large plants able to recover nearly 100 percent of certain metals. Recycling processes are a profitable business and essential for the material supply in the EEI.

The challenge of plastic recycling

A lot of products already use recycled plastics. The sport textile enterprise Dakine sells packs that are made out of 100 percent recycled plastic bottles (Dakine, 2013). Technological development in the waste treatment sector has been advanced the recycling processes leading to metal recycling quotes of nearly 100 percent. However the recovery of plastics in WEEE is still in its infancy and has an interesting technological potential. Current standard recycling methods of plastic are very energy intensive as much as creating new plastics so that thermal recovery sometimes seems the preferable option from an environmental point of view (European Parliament and the Council, 2008, p.96). Enterprises do research and development investments to find better plastic recycling technologies. Metals are simpler to recycle because of their different densities, electrical and magnetic properties and colours, for plastics these characteristics are very similar for different plastic types (Biddle, 2013). As an example, the enterprise Unisensor Sensorsystem GmbH has developed machines in which plastics are analysed according to their composition on the basis of laser spectroscopy (Unisensor Sensorsystem GmbH, n.d.). As shredded plastics are visually not well differentiable the physical footprint allows sorting out non desired materials. Also other firms are developing plastic recycling plants and are able to deliver plastics out of WEEE that are equal to new plastics made from oil (Biddle 2011). Using recycled plastics instead of new one saves up to 80 to 90 % of the energy use and 1 to 3 tons of CO_2 per ton plastic (Biddle, 2013).

The recycling of metals of WEEE is already well developed. For some metals, metallurgical plants recover more than 95 percent of the metal of a product (OECD, 2010*a*, p.58).Cooper can be recycled up to 100 percent from WEEE. In addition, recycled metals are identical to material from primary production (Huisman, 2003, p.93) and can re-entering the life cycle of a product a lot of times. Recycled metals increase significantly the supply of metals on the global market. The supply of recycled platinum and palladium formed 14 percent of the total supply in 2007 (OECD, 2010*a*, p.58). Still metal recycling can be refined by focusing on small proportion in WEEE as the rare earths. The development of recycling technologies will be directed to reach smaller proportion of metals. Another trend is to reach metals not well recyclable yet like neodymium and other rare earths (Schröder, 2012). Also certain product types constitute challenges for recycling as batteries. Research is carried out to facilitate refilling of batteries. For example, it is possible to recycle batteries with the help of spectrum analyser to grade batteries, testing methods and refilling of new liquids (Eco Battery Australia, n.d.).

Biomining is a technique to acquire metals from sulphurous ore rocks with the help of microorganisms. Also WEEE can be treated with microorganism allowing more efficient recycling processes and the recovery of also small quantities of precious metals. The recycling of WEEE was only operated in laboratories and is yet not used in industrial plants (Röhrlich, 2013). The procedure biomining is highly discussed because of its toxic environment and the potential harm that arise in case of accidents even in developed countries (Röhrlich, 2013). The mining company Talvivara employs the technique of biomining in Finland and toxic metals were found in the ground water nearby mining location (Röhrlich, 2013).

The use of recycled materials presents an interesting option for enterprises that want to reduce the environmental footprint of their products. In a life cycle perspective, recycled aluminium leads to 95% energy savings, copper 85%, lead 65%, zinc 60%, paper 64% and plastics more than 80% (European Commission, 2008, p.46). Compared to primary steel production, recycled ferrous metal can save 74 percent of energy, mitigate around 76 percent of water pollution and about 86 percent of air pollution (European Commission, 2008, p.96). The supply of recycled material in relation to total supply is estimated to increase by two percent per year (OECD, 2010*a*, p.58).

Environmental risks and advantages of recycling processes

Despite the reduction of hazardous environmental flows due to material recycling, these processes demand a lot of energy input and generate also emissions. During the final disposal and the recycling processes hazardous emissions, liquid discharges and solid residues occur (OECD, 2010*a*, p.60). For example during the shredding of mobile phones very unhealthy beryllium dust emerges (OECD, 2010*a*, p.44). Around recycling facilities in China the increased concentration of lead and copper augments health risks for the workers and the surrounding population (OECD, 2010*a*, p.60). Polychlorinated dibenzodioxins are substances that decompose only slowly and represent health issues as disruption of the thyroid or skin if consumed in specific quantities. High tech metallurgical plants have high environmental standards and are for instance certified by ISO 14001 (OECD, 2010*a*, p.57). ISO 14001 is a certification for an environmental management where enterprises control the environmental burden generated by their economic activities and improve their environmental performance. For instance gas that emerges during recycling processes can be used as energy source through heat exchangers before leaving the plant. Emissions are cleaned for example with baghouse or electro filters or other scrubbers (OECD, 2010*a*, p.57). In metallurgical plants for example copper smelters can establish feedstock control and control system to regulated emissions (OECD, 2010*a*, p.45). In order to support officially recovery processes their eco-balance should be positive so that benefits of its activities should outweigh other recovery processes.

Other recovery options and final disposal
Another recovery option is thermal recovery. Plastic components of EEE are sometimes recycled and sometimes used as thermal energy supply for the plant's processes. The last stage of a product life cycle, if it does not enter in another cycle, is the final disposal. The waste is stored or incinerate. The incineration of WEEE is submitted under high environmental standards as it contains ozone-depleting substances and set up human health risks if emitted in air, water or land. For instance cooling and freezing equipment contains ozone depleting substances that can be released if not dispose correctly (European Commission, 2008, p.96). Printed circuit boards are typical components of ICT and contain hazardous substances as arsenic, antimony, beryllium, cadmium and lead. A report of the Scientific Committee on Emerging and Newly Identified Health Risk states its concern about possible hazardous flows while treating products containing nanomaterials and asks for further research and treatment specifications (European Parliament and the Council, 2012, p.40). The European Union still collects data and initiates scientific studies about the effects that recovery processes have on the environment and human health.

IV.6 Conflict of interests

The European Union establishes a priority hierarchy concerning WEEE and favours in its waste policy prevention, then reuse, recycling and finally other recovery options. The preferences for recovery options differ among the involved actors. The reuse of products may be contradictory to the producer's interest when it competes with new products.

With a growing amount of qualitatively high used products consumers may buy less new products. From an ecological perspective, the saving of natural resources and the reduction of material throughput are favourable. For the producer less revenue and profit may be generated. Concerning products of the same brand the price of a used product will be below the new one. Depending on the quality and the brand, used brand products can have the same or a higher price compared to no name products. Then it depends on the cost structure how much profit a producer can make by reselling brand-own products. However, the challenge of reverse logistics and the willingness to pay for used products reduce the expected revenue compared to the sale of new products. The competition between old and new products is in general not in the interest of the producer. Although it will not be clear if the consumer actually substitutes reused against new products. Used products purchased by enterprises as intermediary goods are certainly substitutes for new ones.
Sometimes firms of the waste treatment industry build up contracts with the OEMs in order to have necessary spare parts and then sell the repaired product again under the brand name assuring high quality standards (OECD, 2010*a*, p.55). The OEMs may try to avoid the reuse of their products with the help of design adaptation or complex manufacturing. Producers of printers build foams and little walls in the toner or cartridge in order to avoid refilling. Some of these incentives are tried to be avoided by EU regulation on WEEE and ecodesign (look section V).The producer prefers in most cases recycling over reuse to prevail the reputation of the branded products and avoid competitive interference between own products. Another reason is that recycling of the WEEE brings more metals on the market, so the price of their inputs decreases. Also the waste treatment industry may prefer recycling over reuse because the precious materials in WEEE have a higher value then the price of the product on the second hand market. It is simpler to recycle than to negotiate contracts with the OEMs, organize original components and follow case-by-case operations that are more cost-intensive. A recycling plant has certainly higher fix costs but generates higher profits in the long run. The statistics about WEEE treatment indicates this preference as the recycled amount is 27 times higher than the reuse of WEEE in average in the EU in 2010 (see the following section). Other reasons for the high recycling and low reuse rates besides organizational and profit-orientated arguments lie in the quality of products when they are returned to the collection centres.

A moral hazard problem also rises from the perspective of municipal energy supplying companies which may foster waste incineration for heating motives instead of the reuse of products. In addition waste treatment industry and municipalities compete with each other for the WEEE. A German law for closed loop management (Kreislaufwirtschaftsgesetz) become effective in June 2012.
The interpretation of that law by some German municipalities has been criticised by the waste treatment industry (Lettenbauer, 2013, next information also refers to this source). Some municipalities prohibit the collection of WEEE from private and business parties. In

some municipalities waste collecting and waste treating firms have to ask the permit of the municipalities to collect and treat. Individuals can give up their waste in the municipal collection centres. If the waste requires more sophisticated treatment it will be sold to the waste treatment industry. Some municipalities generated profit with the waste collection and decreased the general waste taxes for households. An advantage of an obligatory collection by state authorities is the possible effective sort out of reusable products during the first collection so that the amount of reusable collected products is maximized. However, private firms may cover a higher share of WEEE by collecting also directly from the households. WEEE collection by private business includes more transportation activities and decrease so the potential reuse rate and maybe increase also improper treatment of WEEE. In both cases moral hazard problems get effect when prioritizing profitable recycling or thermal recovery over reuse. From a consumer perspective, it is important that data security is prevailed even in the case of a product's reuse.

IV.7 Comparison of recovery options and conclusion

Figure 15 shows statistics of officially collected WEEE (measured in tons) within the European Union in 2010. Most of WEEE is collected in Germany, Italy and UK and France. Recycling is the preferred option of recovery. United Kingdom, Belgium and France have the highest reuse rate in 2010. Malta, Cyprus, Lithuania and Poland have high final disposal rates staying above 20 percent of the collected WEEE.

Figure 15: *Comparison of recovery, recycling and reuse rate in the European Union in 2010*

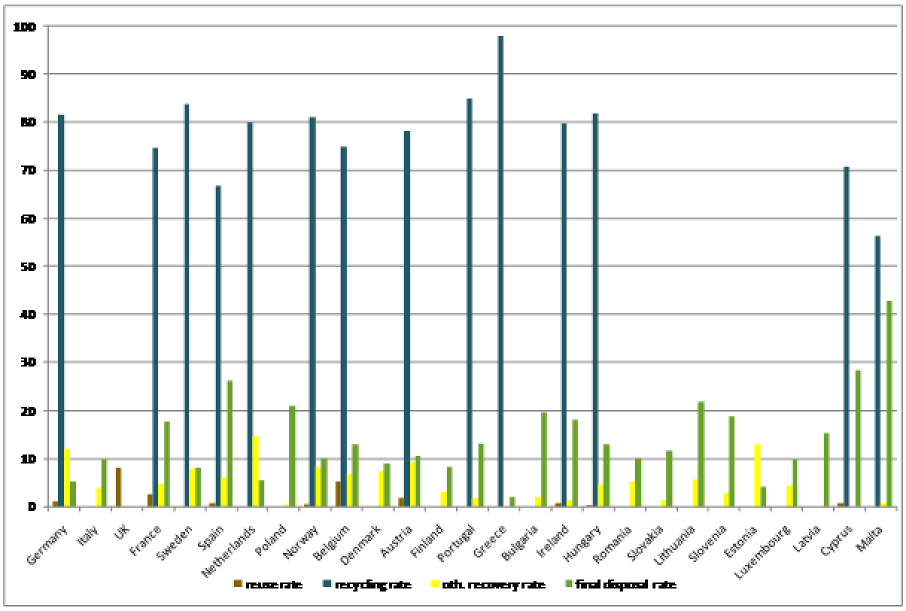
	Waste collected	Reuse	Recycling	oth. Recovery	final disposal	reuse rate	recycling rate	oth. recovery rate	final disposal rate
	Tons	Tons	Tons	Tons	Tons	in %	in %	in %	in %
Germany	777.035	8.873	634.206	93.242	40.714	1,14	81,62	12,00	5,24
Italy	582.482	n.a.	n.a.	23.184	57.006	n.a.	n.a.	3,98	9,79
UK	479.356	39.080	n.a.	n.a.	n.a.	8,15	n.a.	n.a.	n.a.
France	433.959	11.524	324.467	20.667	77.301	2,66	74,77	4,76	17,81
Sweden	161.444	202	135.288	12.760	13.194	0,13	83,80	7,90	8,17
Spain	158.099	1.040	105.531	9.924	41.604	0,66	66,75	6,28	26,31
Netherlands	128.119	1	102.324	18.759	7.035	0,00	79,87	14,64	5,49
Poland	112.246	n.a.	87.711	643	23.552	n.a.	n.a.	0,57	20,98
Norway	107.767	475	87.401	9.059	10.832	0,44	81,10	8,41	10,05
Belgium	105.556	5.496	79.152	7.245	13.664	5,21	74,99	6,86	12,94
Denmark	82.931	n.a.	n.a.	6.135	7.515	n.a.	n.a.	7,40	9,06
Austria	74.256	1.292	58.055	7.024	7.885	1,74	78,18	9,46	10,62
Finland	50.867	n.a.	44.821	1.563	4.300	n.a.	n.a.	3,07	8,45
Portugal	46.673	14	39.644	893	6.122	0,03	84,94	1,91	13,12
Greece	46.527	0	45.598	0	929	0,00	98,00	0,00	2,00
Bulgaria	45.056	n.a.	35.305	868	8.883	n.a.	n.a.	1,93	19,72
Ireland	44.431	315	35.373	654	8.089	0,71	79,61	1,47	18,21
Hungary	40.521	131	33.220	1.885	5.285	0,32	81,98	4,65	13,04
Romania	26.247	n.a.	n.a.	1.366	2.643	n.a.	n.a.	5,20	10,07
Slovakia	21.916	n.a.	18.708	285	2.542	n.a.	n.a.	1,30	11,60
Lithuania	8.928	n.a.	n.a.	516	1.944	n.a.	n.a.	5,78	21,78
Slovenia	8.674	n.a.	n.a.	244	1.624	n.a.	n.a.	2,81	18,73
Estonia	5.630	n.a.	n.a.	734	241	n.a.	n.a.	13,05	4,28
Luxembourg	4.823	n.a.	n.a.	215	475	n.a.	n.a.	4,46	9,84
Latvia	4.287	n.a.	3.629	0	658	n.a.	n.a.	0,00	15,35
Cyprus	2.609	21	1.848	0	740	0,82	70,83	0,00	28,36
Malta	1.535	0	865	12	658	0,00	56,35	0,78	42,87

Author's calculation, (Eurostat Database on Waste Electrical and Electronic Equipment 2013)

Only in UK, Belgium, France, Austria and Germany, the reuse rate is over one percent of total collected WEEE. Final disposal also includes thermal recovery (Eurostat Database 2013).

Figure 16 illustrates graphically the different recovery options. Recycling has the highest

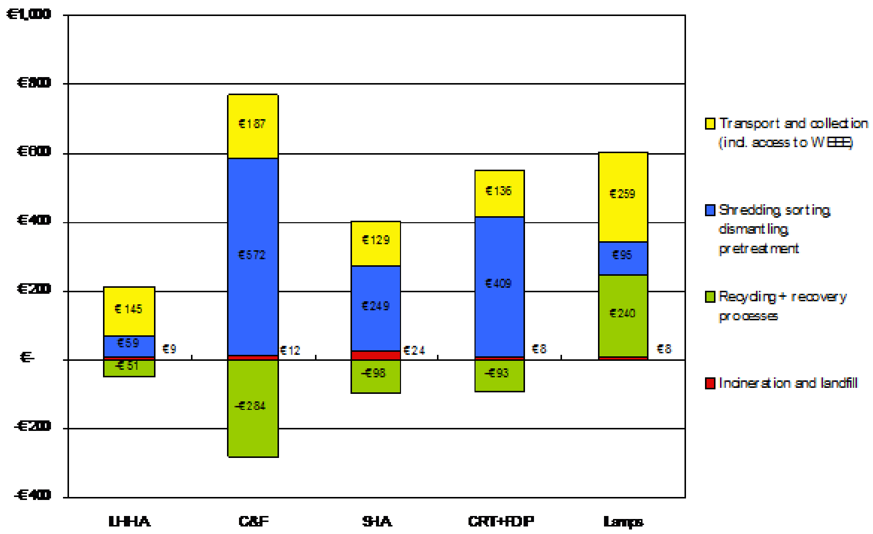
Figure 16: *Comparison of different recovery and disposal rates within the EU 27*



Own calculation,(Eurostat Database on Waste Electrical and Electronic Equipment 2013) share followed by final disposal including thermal recovery. Interestingly Greece has the highest recycling rate with 98 percent. Analyzing this data one has to consider the high amount of unofficially collected WEEE.

Figure 17 provides an insight about the costs (in Euro per tonne) of waste treatment processes of several categories in 2005 (Huisman et al., 2007, p.ix). The cost calculation

Figure 17: *Breakdown of the cost of collection and treatment of WEEE equipment categories*



(European Commission, 2008, Figure taken from p.42)

includes collection and recycling including revenues for secondary materials (Huisman et al., 2007, p.viii). For large household appliances transport costs are the main cost factor. Pre-treatment costs form a major part of the total treatment costs for cooling and freezing equipment and CRT and FDP due to the sophisticated withdrawal of hazardous substances (Huisman et al., 2007, p.ix). The overall cost of waste treatment processes are higher for the category lamps compared to the other devices. The picture would change when the price increases in 2007 where considered leading to an increase of revenues by 50 to 100 Euros per tonne compared to 2005 (Huisman et al., 2007, p.ix). The authors underlines that the costs of WEEE treatment will mainly depend on the development of new technologies (Huisman et al., 2007, p.viii). The recycling process is the most profitable option of recovery if the recovery options are analysed separately. The collection and pre-treatment are highly cost-intensive and according to the study, they are not compensated by revenues generated through recycling or other recovery processes.

In general, electrical and electronic waste treatment activities are subject to economies of scale. For instance around 2.5 percent of collected mobile phones are treated in the five largest tech pyro-metallurgical recycling plants in the world (OECD, 2010*a*, p.57). Precious metals occur often in small concentrations in ICT products so only large material amounts to recycle are profitable. The lower is the material concentration in the waste goods the higher are the recovery costs (Ayres and Ayres, 2002, p.407). In addition as prices of metals fluctuate large companies have a wider margin to operate. Geyer and Blass analyse the cost and revenue conditions for mobile phones concerning reuse and recycling operation and calculated an average profit margin about 15-21 USD per phone (OECD, 2010*a*, p.54).

V Inducing green technological progress

Different regulatory instruments provide incentives to foster technological progress that reduces the material throughput during the life cycle of EEE. Nevertheless the high amount of illegal treatment of WEEE creates obstacles for technological progress and the effective implementation of WEEE regulation. The focus of the current regulation on WEEE lies on standards, quota and the first steps to an establishment of the polluter-pays-principle. Environmental Management Systems, labels, taxes and subventions are some possible tools to promote technological progress.
Regulatory instruments and rules can be set up on different institutional levels. Requirements can be defined on a branch level so that a branch has to fulfil a certain quota for example the reduction of a specific amount of CO_2 emissions. In addition regulation may directly address enterprises for example to implement production standards and proceedings or management structure like an Energy Management System. The object of regulation has a wide span from processes, over products to technologies and behavioural aspects. Which tools are the most adequate to foster technological progress?

V.1 Current regulation on WEEE

Prohibited substances
The European Union or state can prohibit substances in EEE. Prohibition makes sense in the case of hazardous substances that have considerable effects on humans and nature and that are not absolute necessary for the society or substitutes do exist. The Directive on restricting the use of hazardous substances in electrical and electronic equipment (RoHS, 2002/95/EC) banned the employment of some heavy metals or limited the concentration of specific substances. The Directive was recast in 2011 limiting the following maximum concentration by weight in homogeneous materials in EEE (European Parliament and the Council, 2011, p.100):

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominateddiphenyl ethers (PBDE) (0,1 %)

These restrictions apply for EEE put on the market after July 2006 and for reused EEE after July 2016 with some exemptions for particular devices (European Parliament and the Council, 2011, p.93 and Annex III). One exemption is for example lead in liquid crystal on silicon (LCoS) displays (European Parliament and the Council, 2011, p.106). The firms whose products fall under the exemptions shall provide an analysis about alternatives substances, design favouring life-cycle aspects and other research activities. The prohibition of substances leads directly to the search of substitutes to continue the production.

Standards

The EU or the state establishes standards to prioritize life cycle stages and proceedings of waste treatment. The EU lists a hierarchy between the different life cycle steps. The first priority is the prevention of waste followed by reuse, and recycling (European Parliament and the Council, 2008, p.10). Other recovery options like thermal recovery are last priorities before final disposal with incineration and landfill as last resort.

Current regulation on WEEE is defined in the revised Directive on waste electrical and electronic equipment (Directive 2012/19/EU) published in July 2012 (EU 2012). In general, distributors are obliged to take old EEE with some exemption for smaller retailers. Special applications have to be made for large WEEE components from industry sites.

The regulation states that no harmful liquids and substances should enter the environment and harmful flows for humans during waste treatment processes or should be cleaned before emitted. Annex VII lists components and substances of EEE that have to be removed before further WEEE treatment as for example batteries, toner cartridges but in such a way that it still allows the reuse and recycling of EEE (European Parliament and the Council, 2012, p.63). Further treatment standards are listed in Annex VIII of the Directive. They relate to the storage and treatment security requiring impermeable surfaces, weatherproof covering and cleaning processes before emitting into the environment (European Parliament and the Council, 2012, p.65). However concrete targets of treatment processes and standards like a limited amount of CO_2 particles in the air are not fixed. Within the regulation,a compulsory environmental quality standards for waste treatment processes could provide a helpful benchmark and drive technological diffusion.

Targets - Quota

A target formulates a concretely specified and desired goal. A quota is a fixed or limited share of a measurable amount of goods, people or a group. A policy goal can be specified via a quota in order to provide an orientation how to implement the policy. Quotas are set in cases in which the object of regulation is relatively clear or well known or the technologies seem mature. Targets and quota help to specify more concretely policies on the basis of measurable aims and implementation strategies. For instance the European Union has set targets in the Europe 2020 strategy to reduce greenhouse gas emissions by 20 to 30 percent relative to 1990, to provide 20 percent of energy production from renewable energy sources and to increase energy efficiency by 20 percent (European Commission, 2013*a*). Concerning WEEE policies the Directive on WEEE (2012/19/EU) defines concrete collection targets. Table 2 provides an overview from which date on specific targets shall be at least implemented and how the collection targets are defined. The collection target is defined as 'percentage of the average weight of EEE placed on the market in three preceding years' in the Member State (European Parliament and the Council, 2012, p.45).

The Directive does not define how to organize the collection and if it is done by munic-

Table 2: *Collections targets*

Compulsory from	Collection target
01.01.2016	Rate of separate collection of at least 4kg on average per inhabitant per year of WEEE from private households or a minimum collection rate of 45% of weight of WEEE collected in the 3 preceding years in MS
01.01.2019	65% of the average weight of EEE placed on the market in the 3 preceding years in the MS concerned or 85% of WEEE generated on the territory of that MS
For Bulgaria, Czech Republic, Latvia, Lithuania, Hungary, Malta, Poland, Romania Slovenia, Slovakia	
14.08.2016	Collection rate higher than 40% of the average weight of EEE placed on the market in the 3 preceding years
14.08.2021	Collection rates of the EU apply

Source: Article 7 (European Parliament and the Council, 2012, p.45)

ipal agencies, by the producers or other private businesses (European Commission, 2008, p.45,for the actual collection scheme in EU Member States look Annex 3). The difficulty of determining concrete collection targets lies in the different lengths of life cycles of EEE and non-saturated markets so that the amount of EEE put on the markets increases. Table 2 shows the compulsory recovery and recycling rate set up by the WEEE directive. The recovery or recycling target describes the WEEE weight that enters a recycling or recovery facility divided by the weight of all separately collected WEEE and is expressed in percentage (European Parliament and the Council, 2012, p.47).

The targets already indicate the expected improvement of a five percent increase of recy-

Figure 18: *Recovery and recycling targets I*

Categories of Annex II		Minimum targets from 13.08.2012 - 14.08.2015		Minimum targets from 15.08.2015 - 14.08.2018	
		recovery rate	recycling rate	recovery rate	reuse and recycling rate
Large household appliances (refrigerators, freezers etc.), automatic dispensers	1,10	80%	75%	85%	80%
IT and telecommunications equipment, Consumer equipment and photovoltaic panels	3,4	75%	65%	80%	70%
Small household appliances (toasters, electric knives, clocks), lighting equipment, electrical and electronic tools (sewing machines), toys, leisure and sport equipment, medical devices, monitoring and control instruments	2,5,6,7,8,9	70%	50%	75%	55%
gas discharge lamps			80%		80%

(European Parliament and the Council, 2012, p.54-57,60)

cling and recovery rates over three years. The Directive does not establish specific reuse rates which however would be the most beneficial recovery option from an environmental perspective. Around 70 to 80 percent of the collected WEEE shall be recovered from 2015 onwards. However the collection rate of 45 percent of the weight of EEE products put on the market in the last three preceding years is relatively low. Ambitious recovery rate can be set up but if the collection rate is poor the absolute amount of recovered WEEE will remain minor. One reason for the low collection target is the illegal collection, transport and recovery operations of WEEE (concerning the illegal WEEE treatment look section V.b). Figure 19 indicates the recovery, recycling and reuse rates effective from 2018 onwards.

In section IV Figure 15 shows the reuse and recycling rates in the European Union in

Figure 19: *Recovery and recycling targets II*
and recycling targets II.png

Categories of Annex III		Minimum targets from 15.08.2018	
		recovery rate	reuse and recycling rate
Temperature exchange equipment, large equipment	1,4	85%	80%
Screens, monitors	2	80%	70%
Small equipment, small IT and telecommunication equipment	5,6	75%	55%
Lamps	3		80%

(European Parliament and the Council, 2012, p.58,60)

2010. Germany and Austria with recycling rates of about 82% and 78% already fulfil the EU requirements of the Directive.

Polluter-pays-principle

The Directive establishes the polluter-pay-principle: 'Producers should finance at least the collection from collection facilities, and the treatment, recovery and disposal of WEEE' (European Parliament and the Council, 2012, p.41). The WEEE refers to WEEE from private households but also includes WEEE 'from commercial, industrial, institutional and other sources which, because of its nature and quantity, is similar to that from private households' (European Parliament and the Council, 2012, p.44). This obligation can be charged indirectly to the consumer by a higher price however at least this legislation shifts the cost of waste treatment (as collection may be pursued by municipal authorities) from tax payer to the consumers. In order to provide also incentives to change consumer preferences towards more environmentally friendly products, the waste charge should be indicated on products. However the current regulation does not foresee an obligatory indication on EE products. The Directive tries to integrate standards for product design which facilitates reuse and operations of WEEE recovery (European Parliament and the Council, 2012, p.44) and refers to the eco-design Directive 2009/125/EC.

Additional comments are made for instance that the producer should integrate recycled material as well as the freedom of the Member States to define minimum standards for environmental protection (European Parliament and the Council, 2012, p.40,46). Further voluntary options are proposed as a financial guarantee that is orientated to the difficulty of collection and treatment operations and to the value of WEEE or the introduction of an eco-management and audit scheme (EMAS) (European Parliament and the Council, 2012, p.41,47). The lack of generally binding standards and targets in the WEEE regulation hampers efforts to set up effective standards. WEEE trade within the European Union is then encouraged if there is a steep gradient of environmental standards between the different Member States.

The Extended Producer Responsibility (EPR) refers to an approach that goes beyond the coverage of financing of waste treatment processes but aims to set up incentives for the producer. The original producer and seller of a product are involved in the end-of-life of a product and the related activities in order to decrease waste management costs and foster the recovery of material (OECD, 2006). Besides the OECD and others, also the European Union analyses this topic. The European Commission has initiated a research project on how EPR is operated in the EU with the goal to identify best practices (European Commission and BIO Intelligence Service 2013E).

Information transfer

The Directive wants to establish information transfers from the producer to waste treatment facilities. The producer shall provide adequate information about the components of EEE and hazardous substances to facilitate reuse and recovery operations (European Parliament and the Council, 2012, p.49). The producer shall provide the information within one year that the product is on the market. Furthermore it shall be possible to relate a product directly to the producer. Every EEE producer and EEE supplier shall register in the Member State of production if not already registered in another Member State. Member States shall assess information about the weight of WEEE, its components when leaving the collection facility, entering and leaving different treatment facilities (European Parliament and the Council, 2012, p.47). The implementing of the Directive is conferred to the EU Commission. However Member States implement the producer pays principle by setting up a register of EEE producers, organizing the financial guarantee of the producers and penalties. It will be interesting if the producers cooperate effectively with the waste treatment industry and product concepts and sensitive information are actually exchanged. However regulation is only as effective as there are controls and threatening penalties.

Technological focus in regulation

The technological progress has only limited importance in the EU Directive on WEEE. The main focus of the Directive lies in the establishment of standards and of the producer pays principle. The Directive mentions that not all risk emerging during WEEE treatment processes are assessed. The Directive set up normative statements that for instance best available technologies for recovery and recycling should be used. Adoption according to technological progress remains vague and is left over the Commission and the Member States (European Parliament and the Council, 2012, p.42). A great milestone is the obligation of the producer to deliver information about her products to the waste treatment industry. The obligatory information transfer about the composition of EE products facilitates the separation of products and the control during treatment processes of hazardous substances. Research and development activities start directly on the separation of known components for instance testing dissolution of specific substances. However, only a trustful and professional cooperation between producer and treatment facility will enable the potential of technological and economic improvement of recovery. The fulfilment should be followed by reporting of the waste treatment industry about the actual information transfers and its quality. The prohibition of hazardous substances certainly pushes more directly the research for less hazardous substitutes.

V.2 Legal and illegal waste treatment

The illegal treatment of WEEE is a major concern in the discussion about regulation. The official collection rate of WEEE is one third, whereas the real collection rate is supposed to be around 85%. It is assumed that 50 percent of the collected WEEE is not treated in line with European regulation (European Commission, 2008, p.5). Often developing countries are chosen due to their low and sometimes non-existing environmental standards and cheaper labour work. Recycling a computer in the US or Europe costs about 30 USD and in China and developing countries the costs fall to two USD (OECD, 2010*a*, p.58). WEEE contains hazardous substances and has to be treated with caution whereas in developing countries often no precautionary measures are taken. 'The process in these plants typically consists of melting the solder from circuit boards over coal fires and then removal by hand of the various electrical components' (OECD, 2010*a*, p.60). Open burning as it is done on WEEE disposal sites in developing countries has serious consequences on the health of the people and can raise persistent problems for example through polluted ground water. Synthetic materials can release carcinogenic substances when they are simply burned in open area. Metals from primary production as well as recycled metal are internationally traded allowing recycling abroad and selling in the European Union (OECD, 2010*a*, p.71). In addition illegal waste treatment is not so efficient than recovery activities in official sophisticated facilities. For some metals the recycling rate goes up to 95 percent in high tech plants and for the informal sector the recycling rate for gold for example is estimated to 50 percent (OECD, 2010*a*, p.58). Table 3 compares informal and legal recycling activities of printed wiring boards. The professional recycling industry would perform better due to higher extraction rates. The cost and profit relation differ among products. The collection and treatment according to official standards however requires sophisticated technology that may only amortize in large facilities and huge amounts of treated material. These conditions may provide reasons for the high share of illegally treated WEEE.

Table 3: *Cost-benefit analysis for two recycling scenarios of Printed Wiring Boards (Euros per tonne)*

Variables	Informal sector	Pyrometallurgical operation
Sales of recovered metals	1300	4600
Transport costs		600
Operational costs	800	1100
Profit	500	2900

(OECD, 2010*a*, p.59)

Despite the continuous development of EU regulation on WEEE the effectiveness of law is poor. In order to assess the problems of effectiveness the European Commission initiated an impact assessment report with the focus of more effective regulation and impacts of WEEE. The results are integrated in the new Directive. If the financial charge is paid respective to the products put on the markets the producers will have no incentives to collect their used products if the turnover of waste treatment activities does not cover the costs. If the financial charge for treatment activities was high enough and treatment activities generated high profits producers would have higher incentives to pursue an effective collection and sophisticated treatment process. As analyzed in the previous section, profit can be generated for some products for some recovery processes but in general the costs of collection and pre-treatment activities exceed the earnings. In this case the producers collecting their products may have a higher incentive to sell it to business of the illegal economy or export it for improper treatment.

V.3 Fostering green technological progress

The electrical and electronic industry and the waste industry are both dynamic economic sectors that have a huge potential for technological progress to decrease environmental burdens of their activities. The previous sections illustrated the state of the art and trends of activities to reduce the hazardous flows generated by the electrical and electronic products. The current regulation focuses mainly on some eco-design requirements, collection targets and the financing of the recovery processes. In the following, further regulatory tools are discussed aiming to direct technological progress and providing incentives so that enterprises develop their environmental performance.

Environmental labels

An environmental label focuses on the assessment of environmental flows within a life cycle of product and aims to decrease the harmful environmental impacts generated by the product. A label or certificate assures specified product and proceeding standards and facilitates the purchase decision of a consumer with environmental preferences. Environmental labels establish credibility since external parties control and monitor a company

and its production. A multitude of eco-labels are available with different focuses for instance some emphasis more on energy or water use or on the used material. The labels set up assessment methods and goals and measures that include for instances the reduction and elimination of environmentally sensitive materials, materials selection, design for end of life, product longevity, energy conservation, end of life management and other aspects (EPEAT, 2012, p.27).
Well established labels for EEE are for example Electronic Product Environmental Assessment Tool (EPEAT) supported by the US government and the EU Ecolabel. EPEAT ensures a more environmentally friendly production chain of electronic products and tries to bring different actors (supplier, manufacturers, distributors) together to share information and improve continuously to a more environmentally friendly product (www.epeat.net). Although the environmental standards are valuable improvements to an ignorance of environmental consequences of production the standards set up in the label could still be more ambitious. For instance, Apple's products are all certified with the best possible grade of the label, however, serious environmental and health incidents arise in the supplier firms of Apple in China. Another label is the EU Ecolabel that reduces the environmental impact of a product through its life cycle (European Commission, 2013*d*, p.27)(for further explications of eco-design labels see IVIV.3.

The requirements vary between the different labels. Some demand a high environmental performance and ambitious commitment and investment of firms. Others just cover one environmental aspect and let the enterprise chose their environmental performance and goals. Some labels just require reporting. According to the different requirements, environmental labels can foster the use of technology that enhances environmental quality of production. The control of the fulfilment of European eco-design requirements is left over to the Member States. Compulsory labels that fulfil the regulatory requirements for EE products could shift the control from the Member State agencies to private businesses.

EMS - Environmental management system

Another regulatory tool provides an environmental management system which implies the systematic assessment of environmental flows and impacts generated through activities of an enterprise. After the assessment the enterprise formulates own goals how to improve its environmental performance.
Different EMS- types exist on the international level. Two important EMS are the ISO 14001 and the EMAS. The International Organization for Standardization (ISO) establishes the internationally recognized EMS standard ISO 14001. The European Union set up a framework for an EMS named EMAS eco-management and audit scheme (European Commission, 2013*c*). The management of a company has to set up an environmental policy as basis of the EMS. After the assessment of environmental flows, the most important goals are defined and then options and actions are deduced. The implementation

of measures is evaluated afterwards to control the fulfilment of defined goals. Licensed environmental verifiers pursue the audit and validation tasks within the EMAS. The audit and evaluation have to be positive or prospective actions to achieve the defined targets are promising so that the enterprise receive the EMAS or ISO 14001 standard. According to the current regulation, the enterprises of the European Union can participate voluntarily in an eco-management and audit scheme (EMAS) (European Parliament and the Council, 2009*b*).
An EMS raises the employees' and managers' awareness for environmental effects of economic activities. Furthermore an EMS will generate spill-over effects. The implementation of a certified environmental management system has positive effects on environmental product innovations (Pfluger, 2013, non-technical summary). The authors questioned several firms of the German manufacturing sector. According to the study, waste treatment activities and product take-back systems play also an important role for environmental product innovations (Pfluger, 2013, non-technical summary). The key factors of environmental product innovation are environmental policy, technology push and market pull. As the management systematically assesses flows of the environment to the economic sphere and vice versa potentials clarify and can be integrated in the business management process.
An EMS can become compulsory for enterprises of the EEI as well as for the waste treatment industry. When the producers register in a Member State as already foreseen by the WEEE they shall provide a certificate of a recognized verifier. Member States give permits to firms to participate in the waste treatment industry which provides a good node for regulatory intervention. EMS are already been discussed in the European Union in the context of energy tax remissions for energy-intensive industry in order to avoid carbon leakage (local displacement of emissions) and competitive disadvantages. Energy tax remission could be guaranteed under the introduction of an EMS. The EEI and the waste treatment industry belong both to energy-intensive industries. However, it is very doubtful that an EMS can be well controlled in every EE producing country in the world whereas products standards can partially be controlled on the product itself.

Environmental tax

Environmental taxes aim to charge activities and products for their external effects by putting an additional fee on them and thus finance mitigation. Products, waste streams (f.eg. emissions) and used materials serve as calculation base for taxation. Moreover, environmental taxes establish the polluter-pays-principle. The tax increases the production costs and can be reduced by improving environmental performance of production.
Negative externalities arise if activities of a person or a group have a negative impact on other persons or groups. In addition, the utility generated by consumption or profits on one side and the harm generated by the environmental and social impacts of WEEE on the other side are unequally distributed. The current regulation emphasizes generally the

economic internalization of the negative externality since only the financial obligation of the producer is concretely established.
However, as the financial charge is not differentiated according to non recoverable waste but according to products put on the markets, the regulation does not really provide incentives for the EE producers to reduce waste streams by eco-design concepts or material choice.
Nevertheless, the financial charge could be differentiated according to the recovery option, for instance reuse would imply a lower financial guarantee. Although a part of the amount prepared for reuse and recycling lies outside of the producer's operating range for example the qualitative status of an EE product at the time of collection. However such a regulatory instrument would provide incentives to become more efficient, to build up more robust products, to research for substitutes and alternative production processes to avoid these costs. An environmental tax aims to change behaviour and does not favour a specific technology but is open enough to let the enterprises chose the most efficient technology, material and processes. It allows to mitigate in a cost-effective way and to adapt quickly to changes. The charge focuses on one still not economically well integrated cost factor of EE products and opens new fields of competition. In the Netherlands a waste treatment association that organized waste treatment for ICTs adapted a system for computers that assessed the brand and the recycling costs for each product and charged accordingly cite[p.29]OECDC. This waste treatment concept is quite costly and a lot of products could not be related to any producer and were later assigned to each producer according to their market share.

Government consumption

In general this analysis focuses on activities and operations that can be pursued by businesses to reduce environmentally harmful flows. In regard to the research questions the state can also foster green technological progress by stating its preference in its consumption. For instance, a government can require certified environmental products and initiate alternative consumption patterns. The state can lease or rent equipment instead of buying it and can engage furthermore in the durability of the use of devices cite[p.50]OECDA. The US government claims that 95 percent of all electronic products used in state agencies shall be certified by EPEAT (US Environmental Protection Agency, 2010). State agencies, universities and huge institutions could trigger a scale effect with their demand leading to a wider diffusion and cost degression.

Cooperation

The Directive on WEEE establishes mandatory data exchange between the producers and waste treatment facilities. Among others, three key issues lie in the recovery cooperation between waste treatment enterprises and EE producers: the eco-design of products, repair services knowledge and practices and the reuse of recycled material.

Eco-design cooperation aims to use material in concentration and possibly not mixed so that products can be more easily treated. Less hazardous substances, biologically degradable material are used and products are manufactured in a way that favours the decomposition of the products. Less hazardous substances allow a recycling process that can be more easily pursued because the safety standards are not so high and the treatment processes are probably less ambitious. Biologically degradable material should not superficially shorten the life span of a product. Degradable material is sometimes not adequate for instance in the construction of cars. The repair services activities are mainly operated by OEMs or by small enterprises but not the usual big waste treatment industrial plants as necessary for recycling processes. The cooperation between the producers and small & medium enterprises shall allow an exchange of brand products so that the reuse of product can be provided under the highest quality. The state in this respect shall more efficiently foster the priority of prevention, reuse and then recycling and disposal. During the collection phase firms of repair services and distributors should be constantly integrated and questioned about the cooperation with OEMs. However the reuse of EE products is often associated with lower quality and consumer preferences are more directed towards new products leading to relatively small market.

The waste industry is characterized by an operation structure that includes economies of scale. The collection and treatment infrastructure is occasionally subject to cartels. Agreements between waste treatment company and producer can be exploited to build up market barriers.

The integration of collection and waste treatment in one enterprise may present competitive disadvantages. In addition, market concentration of market will increase if only a small number of licensed companies are allowed to organize waste treatment operations. The European Commission accused the Austrian company ARA for uncompetitive behaviour by setting up market entrance barriers due to its collection network and compulsory agreements with its contacting partners (European Commission and BIO Intelligence Service, 2013). Moreover, association that collection and treat the WEEE for the producers may also hampers incentives set up by the state or the EU. In general, this association determines a fixed price according to the products of a producer sold on the market. Then the waste charge does not provide any incentives to the producer to pursue ambitious environmental policies.

Other possible regulatory tools are for example the establishment of environmental targets through fixed environmental footprint reductions, tax reduction in the case of the employment of the best available technology as for instance in the UK for energy efficiency investments of the energy-intensive industry. The states should invest in research and development projects and foster proto-typing maybe also of cost-intensive technologies which have a high cost degression potential through for example high learning effects or large scale effects of production as typical economic barriers for technological progress (see section II). Regulatory tools to induce environmental friendly technologies include also the decrease of administrative burdens and costs of enterprises that want to improve their environmental performance. The strategies should be integrated in existing policies. The state should use already established bureaucratic infrastructure to minimize administrative burdens and costs.

VI Model of the electrical and electronic industry with induced technological change

In this model, the electrical and electronic industry (EEI) produces one homogenous good. The production function represents an aggregate of different production technologies and an average of diverse products of the enterprises within the EEI. All enterprises of the EEI need labour, capital and resources to produce their input. In this model, special attention is paid to technological progress. The enterprises influence these dynamics through R&D investments and continuous learning activities. In addition to the output good of the EEI, the enterprises produce also hazardous waste which is not recovered and comprises harmful substances for the environment and the society. The hazardous waste is produced by using capital and resources and decreases by a part of technological progress that foster environmental performance of production processes. Material substitution achieving to use less hazardous material and an ecological intelligent design which allows the repeated use of a product and production technologies constraining waste flows provides some examples of possible paths of green technological progress. In the following, the optimization problem of the EEI gives an insight on the investment decision and the related reduction of hazardous waste.

The model shall provide an insight of how the enterprises invest over time and how an environmental tax on waste affects investments, technological progress and output. Under which conditions will the EEI generate waste under the environmental threshold? How does the EEI invest over time? How does the industry accumulate knowledge and progress potential? Which impact has the waste tax on each variable?
Furthermore, all variables depend on time.

Table 4: *Variables and parameters of the model*

Variables	
Y	Output, homogeneous good of the EEI
A	Technological progress, quality of products and production, stock of knowledge
X	Inputs for production
RD	Research and development investments
θ	Hazardous waaste
Z	Accumulated stock of waste
s	Share of revenue invested in research and development
p_X	Price index of inputs
q	Costate or adjoint function
λ	Current value of costate or adjoint function
t	time
Initial and threshold values of variables	
A_0	Technological and scientific state of the art (f.eg. quality standards)
X_G	Global demand and supply of inputs (capital and resources)
Parameters	
β	Scale parameter of technological progress
η	Scale parameter of resource and capital inputs
τ	Tax rate on waste
δ	Depreciation rate
μ	Share of production which is environmentally hazardous
γ	Positive impact of research and development investments on technological progress
l	Share of technological progress which leads to more environmentally friendly production and so reduces waste
k	Learning-by-doing parameter
m	Ecosystem absorptive capacity of waste stock
η	Share of renewable resources
General notions	
S	Set of all possible shares of investment
Ψ	Set of all possible combinations of labour, capital and resources
∂	Partial derivate
d	Total differential
$\dot{v}$	The derivative of the variable w.r.t. time

VI.1 Production functions

The EEI produces one product with the inputs labour L, capital K as for example machines and resources R like commodities and metals. A is the stock of knowledge and develops according to technological progress. The production function of the EEI:

$$Y(t) = Y(A(t), K(t), R(t), L(t)) \tag{1}$$

Can also be written as

$$Y(t) = Y(A(t), KL(t), R(t), L(t)) \tag{2}$$

$KL(t)$ is the product of labor and capital and whose proportional demand stays the same over the time horizon. Furthermore, it is assumed

$$X(t)^{\eta} = X(R(t), KL(t)) \tag{3}$$

The transformed production function:

$$Y(t) = A(t)^{\beta} X(t)^{\eta} \tag{4}$$

Labour in $KL(t)$ relates to labour not linked to the knowledge stock so without researchers. $X(t)^{\eta}$ is a function of resources, capital and labour of which the relationship remains constant along the period. Assumptions for the parameter:

$$\beta \neq 0 \text{ and } \beta \neq 1$$
$$\eta \neq 0 \text{ and } \eta \neq 1$$
$$\beta + \eta \neq 1$$

Waste production function
The hazardous impact of the use of capital and resources is characterised by μ. Hazardous waste can be reduced by 'green' technological progress represented by the parameter l which measures the environmentally favourable impact of technological progress on waste.

$$\theta(t) = \mu X(t) - lA(t) \tag{5}$$

The firms of the EEI spend a part from their revenue to research and development investments:

$$RD(t) = s(t)p_Y(t)Y(t) \tag{6}$$

$$\text{with } p_Y(t) = 1$$

For simplicity, the price of the product of the EEI is normalized to one.

$$RD(t) = s(t)Y(t) \tag{7}$$

The hazardous waste θ increases with the use of capital and resources including waste flows from the distribution of products. For instance mining activities to extract necessary metals have a damaging impact on the environment and can be included in these flows as well. θ decreases through the environmental friendly impact of knowledge and so through technological progress. One of these flows in the environment passes for example through the choice of material composites of EE products. The discussion of how far the 'green' progress of technology and quality actually affects the waste flows of EEI has already been analysed in the previous sections. The functional form of this relationship differs according to the focus of the model or the empirical study.
The change of the waste stock:

$$\dot{Z} = \theta(t) + (1 - me^{\frac{-Z(t)}{\bar{Z}}})Z(t) \tag{8}$$

$$\text{with } Z(t) \leq \bar{Z} \text{ for all t}$$

$$Z(t) = \int_0^t \theta(k)\, dk \tag{9}$$

The stock of waste changes according to the difference between waste produced in that period and accumulated waste which is incinerated and absorbed by the ecosystem (inspired by *Conrad*, 2010,p.200). The capacity of the ecosystem to absorb waste diminishes as the waste stock increases. The waste stock has to be under the threshold $\bar{Z}$ above which the ecosystem services of absorption will collapse and environmental conditions will change dramatically so that normal production cannot be pursued in the provided model framework. As the enterprises maximize profits they do not consider the environmental damage incorporated in their products so that only through regulative intervention the waste can be hold under the critical level of $\bar{Z}$.

VI.2 The mathematical conditions for an infinite time horizon problem

The EEI maximizes its profit over an infinite time horizon. It sells products and spends a part (s) of its revenue to research and development investments (RD). The firms buy their inputs to an exogenous price p_Y. They have to pay taxes τ on the hazardous waste which they produce. Waste rises with the use of capital and resources and decreases with 'green' technological progress. Since K and L are used in fixed proportions and KL and R as well, if L increases the waste will also increase however only by the additional use of K and R required with an increase of L. $\dot{A}$ is the derivate of A with respect to time. The technological progress or the quality of the production process and the products changes over time through learning-by-doing (parameter k). So the dynamics of technological process is driven on one side by the knowledge embodied in human capital and positive spill-over externalities, for example new environmentally friendly production processes and behaviour. On the other side RD investments lead to innovation and improve the production and products. Progress does not only relate to technology but also encompasses the behaviour of the workforce, of the management, the processes and intelligent solutions.

VI.2.1 Optimization problem and constraints over an infinite time horizon

The industry maximizes the profits with respect to the dynamics of technological progress. This optimization problem can be solved with the help of the optimal control approach. The initial level of technology and quality of production is supposed to be known. The terminal condition states that the level of technological progress at the end of the period should at least be as high as the starting value of the optimization (cf. equations (12) (13)). The EEI maximizes her profits over an infinite time horizon by choosing the optimal

level of inputs and the share of revenue spent to R&D.
The profit maximization:

$$\max_{s,X} \Pi = \int_0^\infty e^{-\delta t}([1-s(t)]Y(t) - p_X(t)X(t) - \tau\theta(t))\,dt \tag{10}$$

$$s.t.\dot{A} = kA(t) + \gamma s(t)Y(t) = g(s(t), X(t), A(t)) \tag{11}$$

$$\text{Initial condition:} A(t) = A_0 \tag{12}$$

$$\text{Terminal condition:} \lim_{t\to\infty} A(t) \geq A_0 \tag{13}$$

$$Y(t) > 0 \tag{14}$$

$$\tau \geq 0 \tag{15}$$

$$p_X(t) > 0 \tag{16}$$

$$\delta, \mu, \gamma, l, k > 0 \tag{17}$$

$$s(t) \in [0,1] \tag{18}$$

Optimal control theory provides the mathematical tool to picture dynamic processes of a system. In this model the development of technological progress can be controlled by a control variable which is the share of the revenue spent to RD investments.
The control variable s is an element of the convex set S and X is an element of the convex set Ψ which are subsets of the real numbers and the control regions of the optimal control problem. Both control variables can be summarized in a vector function

$$u(t) = U(s(t), X(t)) \tag{19}$$

with $s \in S$ and $X \in \Psi$

$$u(t) \in U \subset R^{Sx\Psi} \text{U is a given set in} R^{Sx\Psi} \tag{20}$$

A is the state variable. We search a pair of the vector functions

$$(u(t), A(t)) = (s(t), X(t), A(t)) \tag{21}$$

defined for all t that maximizes the profit function subject to the dynamic constraint, initial and terminal conditions (cf. (10)-(18)).

The pair $(u(t), A(t))$ is admissible for an optimal solution of the maximization problem if $u(t) = u(s(t), X(t))$ is piecewise continuous (Sydsaeter et al., 2005, p.360). $u(t)$ takes values of U and $A(t)$ is the continuous function that satisfies the conditions (cf.(11)-(13)). Beneath all admissible pairs an optimal pair is searched that maximizes the profit with respect to the constraints.

q is the adjoint function of the state variable. The Hamiltonian is then given by

$$H(s, X, A, u, q, t) = q_0\pi(t) + qg(s(t), X(t), A(t))(u(t), A(t)) = (s(t), X(t), A(t)) \quad (22)$$

The current value Hamiltonian
The current value principle of Sydsæter et al. is applied (Sydsaeter et al., 2005, p.364ff). For simplicity t is omitted keeping in mind that all variables still depend on time. Current value of the costate:

$$\lambda(t) = e^{dt}q(t)$$
$$\dot{q} = e^{-\delta t}(\dot{\lambda} - \delta\lambda)$$
$$\dot{\lambda} = \delta\lambda - \frac{\partial H^C}{\partial A} \quad (23)$$

For the following theorems and throughout the section **??**, the formulations are taken by (Sydsaeter et al., 2005, Chapters 9 and 10) [1].

VI.2.2 Mathematical theorem

Theorem I
The maximum principle of a standard end constraint problem with a finite time horizon is used to provide the necessary conditions (Sydsaeter et al., 2005, Theorem 10.1.1., p.361ff.). Suppose $(u^*(t), A^*(t))$ is an optimal pair for the standard end-constrained problem (cf. (10)-(18)) with changed (13) such as $A^*(t_1) \geq A_0$ with t_1 as a terminal point in time in a finite optimal control problem. Then there exist a constant $q_0 = 0$ or $q_0 = 1$ and a continuous and differentiable adjoint function q(t) such that for all t in $[t_0, t_1]$, one has $(q_0, q(t)) \neq 0$ and:

1. The control function $u^*(t) = (s^*(t), X^*(t))$ maximizes the Hamiltonian $H(t, s^*(t), X^*(t), A^*(t), q(t))$ for all u in U, i.e.

$$H(t, s(t), X(t), A^*(t), q(t)) \leq H(t, s^*(t), X^*(t), A^*(t), q(t))\text{for all u in U} \quad (24)$$

2. Wherever $u^*(t)$ is continuous, the adjoint function satisfies

$$\dot{q} = \frac{\partial H(t, s^*(t), X^*(t), A^*(t), q(t))}{\partial A} \quad (25)$$

3. Corresponding to the terminal condition (13), one has the respective transversality conditions:

$$q(t_1) \geq 0 \text{ and } q(t_1) = 0 \text{ if } A^*(t_1) \succ A_0 \quad (26)$$

[1] The formulations are copied from the book as they represent standard theorems of the optimal control theory. They are only adapted to the variables in order to fit to the problem set of this model. The following section can partially be seen as an adapted quote which becomes transparent through page quotation.

In order to test for optimality define (Sydsaeter et al., 2005, p.371)

$$D_u(t) = \int_{t_0}^{t_1} \Pi(\kappa, u^*(\kappa), A^*(\kappa))\, d\kappa - \int_{t_0}^{t_1} \Pi_0(\kappa, u(\kappa), A(\kappa))\, d\kappa \tag{27}$$

The pair $(u^*(t), A^*(t)$ is CU optimal if for each admissible pair $(u(t), A(t)$ and every $\epsilon > 0$ there exists a number $T_{u,\epsilon}$ such that $D_u(t) \geq \epsilon$ whenever $t \geq T_{u,\epsilon}$ (Sydsaeter et al., 2005, p.371).

Theorem II

For an infinite time horizon, the maximum principle of a standard end constraint problem changes as follows(Sydsaeter et al., 2005, Theorem 10.3.1.,p.372):
Suppose $(u^*(t), A^*(t)$ satisfies the differential equation (11), the initial condition (12) and terminal condition (13). If this pair is catching up (CU) optimal, then it musts satisfy all conditions in Theorem I of the maximum principle with a finite time horizon.

In order to provide sufficient conditions for infinite time horizon the Theorem II is used (Sydsaeter et al., 2005, Theorem 10.3.2.,p.372). Consider problem (10) with the terminal condition (13). Suppose that the pair $(u^*(t), A^*(t)$, together with the continuous and differentiable adjoint function $\delta(t)$, satisfies the conditions (24) and (25) with $\delta_0 = 1$ for all $t \geq t_0$. Suppose that U is convex, that

$$H^C(t, s, x, A, \delta) \text{ is concave in A and} \tag{28}$$

$$\lim_{t\to\infty} (\lambda A(t) - A^*(t)) \geq 0 \text{ for all admissible } A(t) \tag{29}$$

Then the pair $((u^*(t), A^*(t))$ with $u^*(t) = (s^*(t), X^*(t))$ is CU optimal.(For the proof look Sydsæter et al. 2008,p.372) The concavity of the Hamiltonian is checked with respect to A:

$$\tfrac{\partial^2 H}{\partial^2 A} = (1 - s(t) + q(t)\gamma s(t))\beta(\beta - 1)A^{\beta-2}X^{\eta}$$

The second derivative of the Hamiltonian with respect to A is smaller than zero if beta is smaller than 1. In this case the Hamiltonian is concave with respect to A so that the sufficient condition of Arrow's theorem is fulfilled (Sydsaeter et al., 2005, p.363). These conditions provide that a solution exists and that it will be optimal.

VI.3 Profit maximization of the EEI

So the EEI maximizes its discounted profits over an infinite time horizon by choosing the optimal share s and inputs X while respecting the dynamics of the technological progress.

$$\max_{s,X} \Pi = \int_0^{\infty} e^{-\delta t}([1 - s(t)]Y(t) - p_X(t)X(t) - \tau\theta(t))\, dt \tag{30}$$

$$s.t. \dot{A} = kA(t) + \gamma s(t)Y(t) \tag{31}$$

$$\text{Initial condition} A(0) = A_0 \tag{32}$$

$$\text{Terminal condition} \lim_{t\to\infty} A(t) \geq A_0 \tag{33}$$

$$H(s(t), X(t), A(t), \lambda(t)) = (1 - s(t))Y(t) - p_X X(t) - \tau\theta(t) + \lambda(kA(t) + \gamma s(t)Y(t)) \tag{34}$$

First order conditions [1]

$$\lambda = \frac{1}{\gamma} \tag{35}$$

$$X = (\frac{p_X + \tau\mu}{\eta A^\beta})^{\frac{1}{\eta-1}} \tag{36}$$

Costate equation

$$\dot{\lambda} = \delta\lambda - \frac{\partial H}{\partial A} \tag{37}$$

$$A = (\frac{(\delta - k) - \tau l\gamma}{\gamma\beta X^\eta})^{\frac{1}{\beta-1}} \tag{38}$$

$$A^* = (\frac{p_X + \tau\mu}{\eta})^{\frac{\eta}{\eta+\beta+1}}(\frac{\beta}{\frac{\delta-k}{\gamma} - \tau l})^{(\frac{\eta-1}{\eta+\beta+1})} \tag{39}$$

$$X^* = (\frac{p_X + \tau\mu}{\eta})^{\frac{\eta+\beta-\eta\beta-1}{(\eta-1)(\eta+\beta+1)}}(\frac{\beta}{\frac{\delta-k}{\gamma} - \tau l})^{\frac{-\beta}{\eta+\beta-1}} \tag{40}$$

A and X only depend on parameters and on p_X which is an exogenous variable and so also Y.

$$Y^* = (\frac{p_X + \tau\mu}{\eta})^{\frac{\eta}{\eta+\beta+1}}(\frac{\beta}{\frac{\delta-k}{\gamma} - \tau l})^{(\frac{-\beta}{\eta+\beta+1})} \tag{41}$$

Then the share of revenue spent to R&D investments s can be defined:
Given the problem set, s contributes to the dynamics of technological progress:

$$\dot{A} = kA + \gamma sY \tag{42}$$

$$s^* = \frac{\beta}{\delta - k - \tau l\gamma}[(\frac{\eta}{\eta + \beta - 1})\frac{\dot{p_X}}{p_X + \tau\mu} - k] \tag{43}$$

[1]In order to simplify, we proceed with the current value Hamiltonian and sometimes 't' is omitted however all variables depend on time.
$\frac{\partial Y}{\partial X} = Y'_X$ means the first partial derivative of Y with respect to X
$\frac{\partial^2 Y}{\partial^2 X} = Y''_X$ means the second partial derivative of Y with respect to X

The equations of motion depict how the varibles change over time.
Equations of motion:

$$\dot{A} = (\frac{\eta}{\eta+\beta-1})(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l})^{\frac{\eta-1}{\eta+\beta-1}}(\frac{p_X+\tau\mu}{\eta})^{\frac{1-\beta}{\eta+\beta-1}}(\frac{\dot{p_X}}{\eta}) \tag{44}$$

$$\dot{X} = \frac{\eta+\beta-\eta\beta-1}{(\eta-1)(\eta+\beta-1)}(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l})^{\frac{-\beta}{\eta+\beta-1}}(\frac{p_X+\tau\mu}{\eta})^{\frac{3\eta+2\beta-2\eta\beta-\eta^2-2}{(\eta-1)(\eta+\beta-1)}}\frac{\dot{p_X}}{\eta} \tag{45}$$

The growth rates of the model:

$$\frac{\dot{A}}{A} = \frac{\eta}{\eta+\beta-1}(\frac{\dot{p_X}}{p_X+\tau\mu}) \tag{46}$$

$$\frac{\dot{X}}{X} = \frac{\eta+\beta-1-\eta\beta}{(\eta-1)(\eta+\beta-1)}(\frac{\dot{p_X}}{p_X+\tau\mu}) \tag{47}$$

$$\frac{\dot{Y}}{Y} = \frac{\eta}{\eta+\beta-1}(\frac{\dot{p_X}}{p_X+\tau\mu}) \tag{48}$$

The growth rate of A is the same for Y and bigger than the one of X. An interesting point is that only the scale parameters β and η, the price of inputs, the change of the input price and the hazardous effect of the inputs as well as the waste tax determine the growth rates. The other parameters do not interfere in the determination of growth.

After optimization with respect to the constraints of the problem set, optimal values of A^*, X^* and s^* are found that satisfy the conditions and optimize the profit of the industry over an infinite time horizon. The solution provides insights on how do the parameter and the price of inputs impact the technological progress, quantities of inputs and the share of revenue spent to RD investments. The dynamics of the variables arise through the price of inputs p_X the only term still depending on time.

We assume that $\beta + \eta \neq 1$. Without this assumption the variables A and X could follow the same curve leading to an infinite range of solutions.

VI.4 Impact of parameters - a static comparative analysis

The assumption about the discount rate affects a lot the results of the parameter impact analysis. If $\delta < \tau l\gamma + k$, the scale parameter of technological progress β has to be negative in order to have a positive output Y. However technological progress in general has a positive effect on the productivity so the assumption would not be very realistic.

So in all cases it is assumed that $\delta > \tau l\gamma + k$. Y,A and X react identically due to a parameter change in the case of decreasing and increasing returns to scale. Actually the impact of β and η is never unambiguous because they appear in the exponents. However their impact is analyzed whenever they appear in the numerator or denominator.

VI.4.1 The case of decreasing returns to scale

Figure 20: *Decreasing returns to scale**

β; η ε]0,1[β+η < 1	Y	A	X	s	growth rate A	growth rate X	growth rate Y
η	+	+	+	+/-	+/-	+/-	+/-
β	+	+	+	+/-	-	+/-	-
δ	-	-	-	-			
μ	-	-	-	-	-	-	-
γ	+	+	+	↑			
τ	+(l) -(μ)	+(l) -(μ)	+(l) -(μ)	+(l) -(μ)	- (μ)	- (μ)	- (μ)
k	+	+	+	+/-			
l	+	+	+	+			
px	-	-	-	-	-	-	-
px point				-	-	-	-

No entry means that the parameter does not affect the variable. To allow a relatively clear interpretation of the impact of the parameters, futher assumptions has to be made about the parameters: $(\eta/(\eta+\beta-1))(\dot{p_X}/(p_X+\tau\mu)) > k$ and $\eta+\beta-1 < \eta\beta$. In order to have positive growth rates and a positive share s of revenue spent to R&D, the price index of inputs should be defined as follows: $\dot{p_X} < 0$.

The arrows indicate the direction of change of the variables (columns) due to a change of one parameter (rows). If for example η increases, 'Y' would also increase in the case of decreasing returns to scale. If we assume decreasing returns to scale, η (scale parameter of X), β (scale parameter of A), k the learning-by-doing parameter, γ the parameter of successful RD, the waste tax τ and l the waste reducing impact of technological progress have a positive impact on the technological progress A, the inputs X and the output Y. The price of inputs p_X, τ, μ the adding influence of the use of inputs on waste and the depreciation rate δ have a negative impact on the variables Y, X and A.
The waste tax has an ambiguous influence on the variables as it increases the cost of production shown by the negative impact of the tax via μ. But equally the waste tax enforces green technological progress via l and reduces costs in this way.
Interestingly the share s is only positive if the price of inputs decreases over time ($\dot{p_X} < 0$).

To assure a positive share of revenue spent to RD with an increasing price ($\dot{p_X} > 0$) the depreciation rate have to be $\delta < k + l\tau\gamma$. But then $A(t)^*, X(t)^*, Y(t)^*$ would be negative. In addition the growth rates of Y, X and A are also only positive if the price of inputs decreases over time. The optimal level of output is chosen according to the constraints. Without the assumption of continuous decrease of the input price and with decreasing returns to scale there will be no possibilities to further increase profits and the dynamic problem gets the similar results as in a static optimization problem. No further profits are possible through specialization.
Only if the price of inputs decreases over time, the costs of production will sink over time creating potential for further profitable growth. Under a profit maximizing behaviour firms will only invest in R&D if other production costs decrease over time. Otherwise firms just use the accumulated knowledge and quality stock of their production and consume these until nothing is left over and A decreases over time in case of ($\dot{p_X} < 0$).

VI.4.2 The case of increasing returns to scale

Figure 21: *Increasing returns to scale**

β; η ϵ]0,1[β+η > 1	Y	A	X	s	growth rate A	growth rate X	growth rate Y
η	-	-	-	+/-	+/-	+/-	+/-
β	-	-	-	+/-	-	+/-	-
δ	+	+	+	-			
μ	+	+	+	-	-	-	-
γ	-	-	-	+			
τ	+(μ) -(l)	+(μ) -(l)	+(μ) -(l)	+(l) -(μ)	- (μ)	- (μ)	- (μ)
k	-	-	-	+/-			
l	-	-	-	+			
px	+	+	+	-	-	-	-
px point				+	+	+	+

No entry means that the parameter does not affect the variable. To allow a relatively clear interpretation of the impact of the parameters, futher assumptions has to be made about the parameters: $(\eta/(\eta+\beta-1))(\dot{p_X}/(p_X+\tau\mu)) > k$ and $\eta+\beta-1 < \eta\beta$. In order to have positive growth rates and a positive share s of revenue spent to R/D, the price index of inputs should be defined as follows: $\dot{p_X} > 0$.

If we assume increasing returns to scale, the p_X price of inputs,τ, μ and δ will have a positive impact on Y, X,A and $\eta, \beta, k, \tau, l, \gamma$ a negative one. If p_X increases A will be more

productive relatively to the others factors and increases. The development of technological progress is already described by the dynamic state equation and positive with a positive share of revenue spent to R&D investments and the learning by doing parameter k. A higher stock of knowledge leads to positive externalities. If k increases an additional unit of A will be more valuable as before and less A is needed to accumulate the same level of profit over time. With increasing returns to scale the higher the depreciation rate is the more valuable gets a current unit of Y, X and A. If γ increases the higher will be the possibility that R&D investments actually contribute to the technological progress, the less A will be demanded to increase the dynamics of A. If τ and l increase less A will be demanded to reduce the waste amount of one unit.
If p_X, μ, τ and δ increase, X will increase. If η, β, k, τ, l and γ increases X will decrease. The tax has an ambiguous impact on X. The impact of the political control parameter τ on the variables is counter-intuitive for X and Y. τ leads to an increase of the production costs. So in order to decrease them more A is demanded. As A and X are both necessary to produce the output good Y also X increases. However the cost reducing impact of τ through the green technological progress has a negative impact of the demand on the variables Y, X and A. The higher the environmentally damaging effect of inputs (μ) the more has to be invested in environmental improvements so A increases and with it through the dynamics of the production function also the variable X and consequently Y.

If l, γ, p_X increases s will increase as well. However δ, p_X and μ have a negative impact on s. As the inputs become more expensive the accumulation of A should be enforced and so a higher share of revenue is spent. The impact of β, η, τ and k on s is ambiguous. If the tax on waste increases the production will get more costly and less revenue can be dedicated to RD investments. However, it gets more profitable to invest in green technology to reduce waste. In regard, if l gets larger, more revenue will be spent on RD investments. With an increase of the learning-by-doing parameter k less effort is necessary to drive the dynamics of technological progress. One unit of successful RD investments can be accumulated over time through learning-by-doing. Both dynamics explain the ambiguous impact of k on s.

The price of inputs has a direct negative effect on the growth rate of Y, X and A due to increased costs of production. However, as the demand of EEI products increases more inputs for production of Y are necessary. As the resources are scarce and more expansive sources have to be exploited, the price of resources included in the input price index p_X increases over time. Moreover, due to a higher demand Y will also increase. Furthermore, one has to keep in mind that p_X is the real price $\frac{p_X}{p_Y}$ in terms of p_Y the price of the output good Y. So if p_Y decreases due to a higher demand of Y, the real price $\frac{p_X}{p_Y}$ will increase. The same logic applies to A and X as factors of production of Y. Another explication for the positive impact of an increase of $\dot{p_X}$ is that the firms produce even more to limit the rise of marginal costs in absolute terms through economies of scale. The waste tax only effects negatively the growth rates through the environmental cost parameter μ.

VI.5 Transversality condition

In order to satisfy the sufficiency conditions, it has already been shown that (28) $H^C(t, s, x, A, \delta)$ is concave in A. To fulfil (29) $\lim_{t\to\infty}[\lambda(t)(A(t) - A^*(t))] \geq 0$ for all admissible $A(t)$, the transversality condition is set up in discounted terms:

$$\lim_{t\to\infty}[e^{-\delta t}\lambda(t)A^*(t)] \geq 0 \tag{49}$$

The limit depends on the dynamics of the price function of the inputs (resources, capital and labour) and the parameters. We assume a price function

$$p_X(t) = X_G^{\frac{1}{\xi}}t \tag{50}$$

X_G stands for the global demand of inputs necessary to produce Y but also includes the demand of these inputs by other industries. Both demands, the one of the EEI and of other global industries, affect the price of the inputs. X_G stands for the input demand at the beginning of the optimization and develops according to the inverse of ξ a parameter indicating the impact of population growth on demand. As time increases, non-renewable resources of the finite planet become scarce and more expensive to exploit so the price increases. In an infinite time perspective, substitution possibilities are restricted or the production framework changes in such a way that the present model would not fit any more.

$$\lim_{t\to\infty}[e^{-\delta t}\lambda(t)A(t)^*] = \lim_{t\to\infty}[e^{-\delta t}(\frac{X_G^{\frac{1}{\xi}}t + \tau\mu}{\eta}^{\frac{\eta}{\eta+\beta-1}})]\frac{1}{\gamma}(\frac{\beta}{\frac{\delta-k}{\gamma} - \tau l})^{\frac{\eta-1}{\eta+\beta-1}} \tag{51}$$

The transversality condition (51) implies that the present value of the technological progress in the fare future has no impact on current behaviour of the firms. Showing that the discounted value of the state variable goes to zero as time t goes to infinity:
Cases

i) $\beta, \eta \in]0, 1[\text{and}\beta + \eta < 1$ As the price function and the discount factor appear in the denominator the limit (51) tends to zero and the transversality condition is fulfilled.

ii) $\beta, \eta \in]0, 1[$ and $\beta + \eta > 1$

The price function appears in the nominator. Since the discount factor $e^{-\delta t}$ is in the denominator and $e^{\delta t} > 0$ so the discount factor has a greater impact as the direct impact of time in the price function, the whole term tends to zero when t goes to infinity.
For A_0 the sufficient condition (28) will be fulfilled as well, as equation (13) $\lim_{t\to\infty} A(t) \geq A_0$ is the starting value and defines the values of $A(t)$ which are admissible for the optimal control problem. According to the Maximum Principle and the sufficient conditions the

solution $\Pi(A(t)^*, X(t)^*, s(t)^*)$ is optimal and solves the problem (10)-(18).

VI.6 The waste production and environmental constraints

The production of the EEI good is only possible if the hazardous waste stock is kept below the threshold of the absorptive capacity $\bar{Z}$. Up to this waste stock level the conditions of the environment remains relatively the same such that production can be pursued as described by the model.

$$\dot{Z} = \theta(t) + (1 - me^{\frac{-Z(t)}{\bar{Z}}})Z(t) \text{ with } Z(t) \leq \bar{Z} \text{ for all t} \tag{52}$$

$$Z(t) = \int_0^t \theta(k)\, dk \tag{53}$$

$$Z(t) \geq 0 \tag{54}$$

$$\theta(t) \geq 0 \tag{55}$$

VI.6.1 The dynamics of the waste stock under a profit maximizing perspective

The change of waste stock $\dot{Z}$ follows the currently produced waste $\theta(t)$ and diminishes according to the absorptive capacity of the ecosystem m. As $Z(t)$ approaches the threshold $\bar{Z}$, the absorptive capacity decreases driven by the formulation of the exponential function. The waste production within one period with the chosen levels of X and A by the EEI:

$$\theta(t) = \mu X(t)^* - lA(t)^* \tag{56}$$

$$\theta(t) = \mu(\frac{p_X + \tau\mu}{\eta})^{\frac{\eta+\beta-\eta\beta-1}{(\eta-1)(\eta+\beta-1)}}(\frac{\beta}{\frac{\delta-k}{\gamma} - \tau l})^{\frac{-\beta}{\eta+\beta-1}} - l(\frac{p_X + \tau\mu}{\eta})^{\frac{\eta}{\eta+\beta-1}}(\frac{\beta}{\frac{\delta-k}{\gamma} - \tau l})^{(}\frac{\eta-1}{\eta+\beta-1}) \tag{57}$$

With the assumotion of the following price function:

$$p_X(t) = X_G^{\frac{1}{\xi}} t \tag{58}$$

$$Z(t) = \int_0^t \theta(k)^*\, dk \tag{59}$$

By substituting for $r = X_G^{\frac{1}{\xi}} k + \tau\mu$ and $\frac{dr}{dk} = X_G^{\frac{1}{\xi}}$ the integration over the accumulation of waste is possible. The waste stock is thus defined:

$$
\begin{aligned}
Z(t) = & \left(\frac{\mu}{\eta^{\frac{\eta+\beta-1-\eta\beta}{(\eta-1)(\eta+\beta-1)}} X_G^{\frac{1}{\xi}}}\right)\left(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l}\right)^{\frac{-\beta}{\eta+\beta-1}}\left(\frac{(X_G^{\frac{1}{\xi}}(t-1)+\tau\mu)^{\frac{\eta}{\eta+\beta-1}}-(\tau\mu)^{\frac{\eta}{\eta+\beta-1}}}{\frac{\eta}{\eta+\beta-1}^{\frac{\eta}{\eta+\beta-1}}}\right) \\
& -\left(\frac{l}{\eta^{\frac{2\eta+\beta-1}{(\eta+\beta-1)}} X_G^{\frac{1}{\xi}}}\right)\left(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l}\right)^{\frac{\eta-1}{\eta+\beta-1}}\left(\frac{(X_G^{\frac{1}{\xi}}(t-1)+\tau\mu)^{\frac{2\eta+\beta-1}{\eta+\beta-1}}-(\tau\mu)^{\frac{2\eta+\beta-1}{\eta+\beta-1}}}{\frac{\eta}{\eta+\beta-1}^{\frac{\eta}{\eta+\beta-1}}}\right)
\end{aligned} \quad (60)
$$

With decreasing returns to scale, $Z(t)$ becomes negative however the waste stock cannot become negative. With increasing returns to scale, the waste tax through its cost-adding effect decreases the waste stock by inducing technological change (through A) but increases the waste stock because less revenue can be spent on R&D investments.

The positive effect of the waste tax by making the input factor A more productive has

Figure 22: *Impacts of parameter on waste stock accumulation*

β; η ε]0,1[β+η < 1	Z(t) via X	Z(t) via A
τ(μ) and β+2η < 1	-	-
τ(μ) and β+2η > 1	-	+
τ(l)	+	-
β; η ε]0,1[β+η > 1		
τ(μ)	+	-
τ(l)	-	+

a negative effect on the waste stock through X and positive effect through A. The waste tax has a positive impact on the profit as it enhances the positive effect of green technological progress. Enterprises with a higher environmental performance have a competitive advantage as they reduce their production costs. However the general positive impact on the profits triggers a higher production and thus more waste. It would be interesting to see in a simulation the actual scale of effects.

VI.6.2 Criterion for sustainable production

For sustainable production the newly accumulated waste should be absorbed by the ecosystem. This condition has not to be fulfilled for every period but over the time the balance shall be assured.

$$\lim_{t\to\infty} \theta(t)^* + (1 - me^{-\frac{Z(t)^*}{\bar{Z}}})Z(t)^* \leq 0 \quad (61)$$

$$\lim_{t\to\infty}\{\frac{M}{\eta^h}\left[(X_G^{\frac{1}{\xi}}t+\tau\mu)^h+\frac{(X_G^{\frac{1}{\xi}}(t-1)+\tau\mu)^{h+1}-(\tau\mu)^{h+1}}{X_G^{\frac{1}{\xi}}(h+1)^{h+1}}\right]$$

$$-\frac{N}{\eta^j}\left[(X_G^{\frac{1}{\xi}}t+\tau\mu)^j+\frac{(X_G^{\frac{1}{\xi}}(t-1)+\tau\mu)^{j+1}-(\tau\mu)^{j+1}}{X_G^{\frac{1}{\xi}}(j+1)^{j+1}}\right]-me^{-\frac{Z(t)^*}{\bar{Z}}}Z(t)^*\}\leq 0 \qquad (62)$$

with

$$M=\mu\left(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l}\right)^{\frac{-\beta}{\eta+\beta-1}} \text{ and } N=l\left(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l}\right)^{\frac{\eta-1}{\eta+\beta-1}}$$

$$h=\frac{\eta\beta-1-\eta\beta}{(\eta-1)(\eta+\beta-1)} \text{ and } j=\frac{\eta}{\eta+\beta-1}$$

With decreasing returns to scale $\eta,\beta\in]0,1[$ and $\eta+\beta<1$, the price function of inputs, the waste tax and the waste parameter $(X_G^{\frac{1}{\xi}}t+\tau\mu)$ appear in the denominator. As 't' increases to infinity, the first two summands of equation (62) converge towards zero.
For increasing returns to scale, the fulfilment of the environmental constraint is not so clear.

$$\lim_{t\to\infty}\left(\frac{M}{\eta^h}\left[(X_G^{\frac{1}{\xi}}t+\tau\mu)^h+\frac{(X_G^{\frac{1}{\xi}}(t-1)+\tau\mu)^{h+1}-(\tau\mu)^{h+1}}{X_G^{\frac{1}{\xi}}(h+1)^{h+1}}\right]\right)\leq$$

$$\lim_{t\to\infty}\left(\frac{N}{\eta^j}\left[(X_G^{\frac{1}{\xi}}t+\tau\mu)^j+\frac{(X_G^{\frac{1}{\xi}}(t-1)+\tau\mu)^{j+1}-(\tau\mu)^{j+1}}{X_G^{\frac{1}{\xi}}(j+1)^{j+1}}\right]+me^{-\frac{Z(t)^*}{\bar{Z}}}Z(t)^*\right) \qquad (63)$$

$j>h$ and if $M<N$ then the constraint (63) is also fulfilled.

$$M<N \text{ if}$$

$$\mu\left(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l}\right)^{\frac{-\beta}{\eta+\beta-1}}<l\left(\frac{\beta}{\frac{\delta-k}{\gamma}-\tau l}\right)^{\frac{\eta-1}{\eta+\beta-1}}$$

$$\tau>\frac{\delta-k}{l\gamma} \qquad (64)$$

The waste stock constraint leads to a minimum level of waste tax rate above which the infinite growth of the waste stock can be restricted. The tax rate increases with the depreciation rate as firms evaluate the present higher than the future and will possibly build up a higher stock of waste. The tax rate will decrease if the firms learn faster (higher k) and build up higher potential of eco-innovations (higher γ) and the technological progress gets more productive regarding environmental concerns (higher l).
The firms of the EEI do not take into account the waste stock threshold. Therefore the state should intervene to assure continuous production and a stable environment. The state shall keep in mind the strategic and profit maximizing behaviour of the firms and adapt the tax accordingly.

VI.7 Cohesion and contradictions between the WEEE analysis and the model results

The following section discusses to what extent the developed model can be applied to the EEI and to what extent the qualitative relations within the model mirror essential arguments of the previous sections.

Around 60 percent of the operating expenditures of the EEI in Austria are spent on material, about 22 percent on labour and rest on other expenditures (Heiling, 2012, p.23). The large share spent to materials underlines how important a higher supply of resources in form of recycled metals could be for the EEI. About 61 percent of the total investment is spent to real investments, 3.8 percent to immaterial investments (like research and development activities) and ca. 36 percent to financial investments (Heiling, 2012, p.24).
The model includes the essential inputs of the EEI: resources, labour and capital. In the model, it is assumed that investment in capital is pursued to hold the level of capital constant in the firms. In Austria the investment rate to renew the depreciated capital is around 100 percent in the years 2008 to 2010 (Heiling, 2012, p.25). As the focus of the model lies on technological progress and waste production, capital accumulation over time is left out. The waste production function however presents a disadvantage by summarizing all input factors labour, capital and resources in one variable X. An increase in labour would also lead to an increase of hazardous waste depending on the functional relation of inputs in X. However, the hazardous waste streams occur from material requirement, capital and processing operations and are generally not related to labour.
One of the model's central results was that only with increasing returns to scale endless growth can be pursued. In the model, the EEI can reduce waste flows generated by their products through different operations such as enhanced eco-design adaptations or recovery operations. The EEI comprises also waste treatment operations in this model framework. In the waste treatment industry increasing returns to scale is a reasonable assumption as economies of scale become effective and lead to cost reduction at least in recovery plants. The electrical and electronic industry is certainly structured by several large enterprises with a large market shares but a lot small firms pursue also innovative activities and persist on the market. In Austria ten enterprises form 55 percent of the revenue of the EEI and one third of the market revenue is generated by three enterprises (Heiling, 2012, p.17).

The decreasing returns to scale will only lead to positive growth rate if the price of inputs decreases over time. If the price of inputs increases over time increasing returns to scale are necessary to improve efficiency and productivity potential. These dynamics are not directly related to the environmental tax but result from the production function and problem formulation of the optimization with the process of technological progress. With decreasing returns to scale and a negative growth rate, the waste production also decreases.

In general, increasing returns to scale imply market failures so that monopolies arise and the perfect competition concept erodes. However, increasing returns to scale do not necessary lead to monopolies if the growth of an industry is endogenously driven by technological progress. Technological progress generates positive externalities between the enterprises of the EEI providing in aggregate the increasing returns to scale. With increasing returns to scale, the state should set a tax on waste to guarantee that the waste stock remains under the critical threshold level. The waste stock of the EEI contains hazardous substances as analysed in the previous sections so that a growth of waste stock proportional to the growth of sold EE products cannot be sustainable in the long run.

The EEI is a very dynamic industry. One third of the innovations in the manufacturing sector occur in this industry in Germany (Weinberg et al., 2010, p.3). Technological progress certainly contributes to the success of the enterprises of EEI. The description of technological progress within the model by a learning-by-doing process and RD investments mirrors in a realistic way the development of technology and ideas in this branch. Innovative capacity is built on human capital that initiates technological improvement through the application of knowledge and represented in the model by the learning by doing impact (k). On the other side, firms deliver huge investments on research and development to push production processes, new product concepts further which is expressed in the model through the share s and the innovation effect (γ). Also green technological progress applies to these dynamics. An EMS for example clarifies through a systematic assessment the potential to improve environmental performance. The established knowledge leads to behavioural change and ideas for further options, measures and represents a learning approach. In order to get certified by eco-labels enterprises pursue research and development for example to find substitutes for PVC or mercury which is only allowed in small proportions under the WEEE Directive. The taxation of hazardous flows can be directly related to a possible compulsory financial guarantee that a producer could have to pay according to the recyclability of her products.
The EU Directive on WEEE provides recovery rates that correspond to a possible threshold limits for the hazardous waste in the model. The increase of collection and recovery rates as foreseen in the Directive reflects the development and improvement of organizational efficiency and effectiveness but also technological progress.
In the model, the EEI is represented in an aggregated form which does not capture the arbitrage between different technologies of a vintage model. But the model considers the difference between green and total technological progress. Additionally to the demanding assumption of increasing returns to scale, the abstraction by putting EEI and waste treatment industry together in one optimization problem represented by a joint production function erases the conflicts of interests. Another crucial point of discussion is the extremely high share of illegal WEEE treatment and how to consider the informal sector within a model framework.

VII Conclusion

The electrical and electronic industry exhibits great dynamics in product innovation and provides essential parts for the transformation to a greener economy. The transformation of current economies to more sustainable ones includes among others further development of information and communication technologies, renewable energy supply and alternative mobility concepts - economic fields whose developments rely on electrical and electronic products.

To induce the transformation to a more sustainable life cycle of electrical and electronic products, different operating fields emerge. In a life cycle approach, one focus lies on the resource efficiency trying to use less material input for an output unit. The minimization of transportation also leads to less harmful environmental impacts of EEE. During manufacturing, the throughput of energy, water and air could be reduced by the efficient use of technologies but also requires new concepts of eco-design and further technological and organizational development towards environmentally friendlier processes.
As WEEE is the fastest growing waste stock in the European Union, main emphasis of this thesis was put on recovery possibilities. The recovery options have different impacts on the environment and a different technological potential to reduce the hazardous flows of the EEI. Reuse is certainly favorable from an environmental point of view if reused products are actually substituted against new products. Recycling is probably preferred by the waste treatment industry and the producers.

Different regulatory tools can be set up to reduce environmentally harmful flows arisen from WEEE and enhance supporting technology. A compulsory environmental labelling of EE products certainly drives eco-design concepts and material selection. The obligatory introduction of an EMS would induce a 'greening' of the manufacturing processes themselves. For companies of the waste industry, an EMS clarifies the potential for improvement of environmental performance. Among the different EMS, the requirements vary. In this regard, environmental problems the occur within the supply chain should be included. The producer-pays-principle established by the WEEE Directive put emphasis rather on the financing of waste treatment processes than on effective incentives. A financial charge adapted to the product's capability of recovery would provide incentives for eco-design. In general, the financial burden has to be sufficiently high so that enterprises actually take these costs into account and react as shown in the model. Concrete and higher standards for emission targets during manufacturing and waste treatment certainly direct green technological development.

The research question of this thesis includes different goals as the reduction of waste and the release of technological potential to improve environmentally friendlier product life cycle. In this regard, a combination of regulatory instruments seems adequate to achieve these aims. Effective incentives mainly depend on the implementation of collection schemes and how the financial charge on the producers is set up. If no general European agreement can be reached, ambitious standards for environmental pollution during manufacturing and waste treatment may foster directly environmental performance. However, in order to encourage producers and companies of the waste industry to develop technology that reduces hazardous flows, other instruments, such as environmental labels and EMS, are necessary.

The developed model taking up the essential economic drivers of the EEI and waste treatment industry shows that in the case of growth the state should intervene by setting up incentives to keep the waste under a reasonable level. It would be interesting to model more concretely the conflict of interests between the EEI and the waste industry and to simulate the model.

The vast amount of WEEE illegally treated represents a serious regulation problem. How to trigger environmental performance and technological development if the basis of regulation erodes? Increasing controls and a better involvement of different actors: municipalities, producers, waste treatment enterprises and consumers may reduce the illegal treatment of WEEE.

VIII Abbreviations

CE	Consumer equipment
C&F	Cooling and freezing
CRT	Cathode ray tube
FDP	Flat panel displays
f.eg.	For example
EE	Electrical and electronic
EEE	Electrical and electronic equipment
EEI	Electrical and electronic industry
EMAS	Eco-management audit scheme
EMS	Environmental management system
EPR	Extended producer responsibility
GHG	Greenhouse gas
ICT	Information and communication technology
IT	Information technology
LCD	Liquid crystal display
LHHA	Large household appliances
MS	Member State of the European Union
NACE	Nomenclature générale des activités économiques dans les Communautés Européennes
OEM	Original Equipment Manufacturers
PCB	Polychlorinated biphenyls
RD or R&D	Research and development
SHA	Small household appliances
WEEE	Waste electrical and electronic equipment
w.r.t.	With respect to
ZVEI	ZentralverbandElektrotechnik- und Elektroindustrie

IX References

Acemoglu, D. (2011), *Diversity and Technological Progress.* National Bureau of Economic Research, Working Paper No.16984.

Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D. (2008), 'The environment and directed technical change', *American Economic Review* .

Anger, N., Braun, M., Duckat, R., Santarius, T., Schmid, S. and Schüle, R. (2005), *JET-SET Die Einführung von Emissionshandelssystemen als sozial-ökologischer Transformationsprozess, Makroökonomische Wirkungen des Emissionshandels.* BMBF Förderinitiative "Sozial-ökologische Forschung".

Apple (2013), *The story behind Apple's environmental footprint, Apple and the Environment.* In: http://www.apple.com/environment/our-footprint/, Access 02.04.2013.

Arrow, K. J. (1962), 'The economic implications of learning by doing', *The Review of Economic Studies* **29**, 155–173.

Ayres, R. U. and Ayres, L. (2002), *A handbook of industrial ecology*, Edward Elgar Publishing Inc.

Biddle, M. (2013), *We can recycle plastic.* TED talks July 2011, TEDGlobal 2011, In: $http://www.ted.com/talks/lang/en/mike_biddle.html$, Access 08.04.2013.

Broehl-Kerner, H. (2010), Anforderungen an produktgestaltung, informationsflüsse und steuernde instrumente aus sicht des produkt- und komponentenrecycling, *in* 'Fachgespräch zur Ökodesign-Richtlinie, Federal Environemental Agency'.

Camatsos, S. (2012), *Fracking reaches point-of-no-return for EU legislators.* New Europe Online on 11.05.2012, In: http://www.neurope.eu/article/fracking-reaches-point-no-return-eu-legislators, Access: 06.04.2013.

Dakine (2013), *Dakine JEWEL Rucksack Girls 26L Savanna.* In: http://www.dakine-shop.de/products/de/Dakine-Schulrucksack/Schulrucksaecke-Girls/Dakine-JEWEL-Rucksack-Girls-26L-Savanna.html, Access: 18.03.2013.

De Brito, M., Dekker, R. and Flapper, S. (2003), *A Framework for Reverse logistics.* ERIM Report Series Research in Management, Erasmus Research Institute of Management.

Di Maria, C. and Valente, S. (2006), *The Direction of Technical Change in Capital-Resource Economies*, mpra munich personal repec archive edn. ETH Swiss Federal Institute of Technology Zurich, Working Paper(05/50).

Eco Battery Australia (n.d.), 'Fracking reaches point-of-no-return for eu legislators'. In: http://www.ecobatteryaustralia.com.au/rejuvenation-process/,Access 08.04.2013.

EPEAT (2012), *Environmental Benefits Report 2011.* In: http://www.epeat.net/learn-more/environmental-benefits/environmental-benefits-resources/, Access 02.04.2013.

European Bioplastics e.V. (n.d.), 7th european bioplastic conference, *in* 'Conference Brochure 6/6 November 2012, Maritime prorate Hotel Berlin'. In: $www.en.european-bioplastics.org/conference_2012/Conference_Broshure_all_you_need_to_know.pdf$, Access: 30.03.2013.

European Commission (2008), *Commission staff working paper accompanying the proposal for a directive of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE) (recast) - Impact Assessment.* In: $http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52008SC2933:EN:NOT$, Access 13.01.2013.

European Commission (2010), *Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materials.* Enterprise and Industry Directorate-General, Report Version of 30th of July, In: $http://ec.europa.eu/enterprise/magazine/articles/industrial-policy/article_10514_en.htm$, Access 07.04.2013.

European Commission (2012), *Ecodesign Your Future. How Ecodesign can help the environment by making products smarter.* In: $http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/index_en.htm$, Access 08.04.2013.

European Commission (2013*a*), *The 5 targets for the EU in 2020.* In: $http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/targets/index_en.htm$, Access 28.02.2013.

European Commission (2013*b*), *Eco-design of Energy-Related Products.* In: $http://ec.europa.eu/energy/efficiency/ecodesign/eco_design_en.htm$, Access 20.04.2013.

European Commission (2013*c*), *EMAS.* In: http://ec.europa.eu/environment/emas/, Access 11.04.2013.

European Commission (2013*d*), *The EU Ecolable.* In: http://ec.europa.eu/environment/ecolabel/, Access 11.04.2013.

European Commission (2013*e*), *Product Environmental Footprint.* In: $http://ec.europa.eu/environment/eussd/smgp/product_footprint.htm$, Access 21.04.2013.

European Commission and BIO Intelligence Service (2013), *Development of guidance on Extended Producer Responsibility (EPR).* In: http://epr.eu-smr.eu/stakeholder-consultation, Access 13.04.2013.

European Commission and the Joint Research Centre-Institute for Environment and Sustainability (2013), *Life Cycle Thinking and Assessment.* In: http://lct.jrc.ec.europa.eu/assessment/projects, Access 10.03.2013.

European Parliament and the Council (2008), 'Directive ec 2008/98/ec: On waste and repealing directives', *Official Journal of the European Union* pp. 312/3– 30.

European Parliament and the Council (2009*a*), 'Directive 2009/125/ec establishing a framework for the setting of ecodesign requirements for energy-related products', *Official Journal of the European Union* pp. 285/10–35.

European Parliament and the Council (2009*b*), 'Regulation (ec) no 1221/2009: On the voluntary participation by organisation in a community eco-management and audit scheme (emas)', *Official Journal of the European Union* pp. 342/1–45.

European Parliament and the Council (2011), 'Directive 2011/65/eu : On the restriction of the use of certain hazardous substances in electrical and electronic equipment', *Official Journal of the European Union* pp. 174/88 –110.

European Parliament and the Council (2012), 'Directive 2012/19/eu: On waste electrical and electronic equipment (recast)', *Official Journal of the European Union* pp. 197/38–71.

Gerlagh, R., Kverndokk, S. and Rosendahl, K. (2009), 'Optimal timing of climate change policy: Interaction between carbon taxes and innovation externalities', *Environmental and Resource Economics* **43(3)**, 369–390. European Association of Environmental and Resource Economists.

Gerlagh, R. and Van der Zwaan, B. (2004), 'A sensitivity analysis on timing and costs of greenhouse gas abatement emission reductions', *Climatic Change* **65**, 39–71. Kluwer Academic Publisher.

Goedkoop, M. and Spriensma, R. (2000), *The Eco-indicator 99. A damage oriented method for Life Cycle Impact Assessment. Methodology Report*, publikatiereeks produktenbeleid edn, PRe Consultants.

Heiling, M. (2012), *Die wirtschaftliche Lage der Elektro- und Elektronikindustrie August 2012*, Kammer für Arbeiter und Angestellte für Wien, in collaboration with Biehl, K. and Delapina, T. and Marterbauer, M. and Russinger, R. and Schwalm, C. and Zuckerstätter, S.

Huisman, J. (2003), The QWERTY/EE Concept- Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products, Dissertation, Deflt University of Technology.

Huisman, J., Magalini, F., Kuehr, R., Maurer, C., Ogilvie, S. and Poll, J. (2007), *2008 Review of Directive 2002/96 on Waste Elektrical and Electronic Equipment (WEEE) Final Report*, United Nations University,AEA Technology, Gaiker, Regional Environmental Centre for Central and Eastern Europe, Delft University of Technology.

IIAE Internationales Institut Österreichische Schule der Nationalökonomie (1996), *The Essence of J.A. Schumpeter.* The International Library of Austrian Economics, Manz Verlag.

Japan, A. P. S. (2013), *NoPoPo and Asyl Battery.* Product Information, In: http://www.aps-j.jp/english/apsj011.html, Access: 08.04.2013.

Karshenas, M. and Stoneman, P. (1995), Technological diffusion, *in* P. Stoneman, ed., 'A Handbook of the Economics of Innovation and Technoligcal Change', Blackwell, p. 265.

Kettner, C., Köppl, A. and Schleicher, S. (2008), *Technological Change and Learning Curves in the context of the Tran.Sust.Scan modeling network*, wifo austrian institute of economic research edn. preliminary version.

Kutsche, J. (2012), *Seltene Erden und schmutzige Geschäfte*, Deutschland Radio. In: www.dradio.de/dlf/sendungen/dossier/1653595, Access: 17.02.2012.

Lettenbauer, S. (2013), *Streit um den wertvollen Schrott. Kommunen wollen am lukrativen Altmetall verdienen*, Deutschland Radio. Umwelt und Verbraucher on the 02.04.2013.

Lucas, R. E. (1988), 'On the mechanics of economic development', *Journal of Monetary Economics* **22**, 3–42.

Nuernberger, D. (2003), Bei plastik ist "bio" nicht automatisch "öko", *in* 'Konferenz zu Biokunststoffen in Berlin', Deutschland Radio, Umwelt und Verbraucher on 7.11.2012.

OECD (2006), *EPR Policies and Product Design: Economic Theory and Selected Case Studies*, OECD Environment Directorate,Working Group on Waste Prevention and Recycling.

OECD (2010*a*), *Materials Case Study 1: Critical Metals and Mobile Devices*, OECD Environment Directorate. In: http://www.oecd.org/environment/resourceproductivityandwaste/46132634.pdf, Access: 09.10.2012.

OECD (2010*b*), *Materials Case Study 1: Critical Metals and Mobile Devices Annexes*, OECD Environment Directorate. In: http://www.oecd.org/env/waste/46133561.pdf, Access: 09.10.2012.

Okada, S. (2012), *Invention of Eco-friendly Post Li-ion Secondary Batteries*, novel carbon resource science newsletter edn. Vol.7, 29-34.

Oxford Dictionaries (2013), *Planned obsolescence*, Oxford University Press. In: http://oxforddictionaries.com/definition/english/planned%2Bobsolescence, Access 20.04.2013.

Pfluger, B. (2013), *Apple könnte enormes Zeichen setzen*, Standard on the 29.03.2013. In: http://derstandard.at/1363706491787/Apple-koennte-enormes-Zeichen-setzen, Access: 07.04.2013.

Röhrlich, D. (2013), *Mikroben als Bergleute und Recyclingfachkräfte, Abbau von Metallen durch Biomining*, Deutschlandfunk, Umwelt und Verbrauch on 07.01.2013.

Rifkin, J. (2011), *Die dritte industrielle Revolution - die Zukunft der Wirtschaft nach dem Atomzeitalter*, Campus-Verlag.

Schröder, A. (2012), *Der Wert des Elektroschrotts, Recycling Seltener Erden und strategischer Metalle*, Deutschland Radio, Emission: Umwelt und Verbraucher on 06.02.2013.

Sydsaeter, K., Hammond, P., Seierstad, A. and Strom, A. (2005), *Further mathematics for economic analysis*, Financial Times Prentice Hal.

Unisensor Sensorsystem GmbH (n.d.). In: www.unisensor.de, Access 30.03.2013.

US Environmental Protection Agency (2010), *Environmentally Preferable Purchasing (EPP): Electronic Product Environmental Assessment Tool.* In: www.epa.gov/epp/pubs/products/epeat.htm, Access 30.03.2013.

Weinberg, E., Briesemann, D., Gontermann, A., Giehl, P. and Polzin, J. (2010), *Zur Rohstoffsituation in der Elektroindustrie*, Commerzbank und Zentralverband Elektrotechnik- und Elektroindustrie.

World Commission on Environment and Development (1987), *Our Common Future*, oxford university press edn.

Zentralverband Elektrotechnik- und Elektroindustrie (2012*a*), *Rohstoffe - Daten, Fakten, Positionen Januar 2012.* In: http://www.zvei.org/Verband/Publikationen/Seiten/Rohstoffe-Daten-Fakten-Positionen.aspx, Access 7.04.2013.

Zentralverband Elektrotechnik- und Elektroindustrie (2012*b*), *Wie innovativ ist die deutsche Elektroindustrie?* Video of the ZVEI- Innovation Congress 2012, In: http://www.zvei.org/Presse/Mediathek/Videos/Seiten/Wie-innovativ-ist-die-deutsche-Elektroindustrie.aspx, Access 7.04.2013.