Handling electronic waste flows: on the effectiveness of producer responsibility in a globalizing world

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Abstract

This paper explores the present and future magnitude of global WEEE flows and investigates desirable changes in these flows from a sustainable development point of view. Quantitative estimates of present and future e-waste flows between global regions, generating and processing waste, are presented and their driving forces are analysed. Global e-waste production by households exceeded an annual amount of 20 million tons in 2005. Domestic e-waste generation in China has already climbed dramatically, now equalling the amount generated in Japan. China is second in the world after the USA in land-filling and incineration of e-waste residues. Absolute volumes of recycled e-waste are largest in the EU, followed by Japan. After a period characterized by national disposal practices, a period of global low level recovery practices has emerged. The paper analyses exogenous factors, including legislating promoting Extended Producer Responsibility, which are favouring as a next step regionalizing of (reverse) supply chains. Examples on a business level are discussed and critical success factors for applying regional high level recovery are identified. The analysis shows that the coming decades two options will compete on a global scale: (1) a further expansion of the present low level recovery system of e-waste recycling, and (2) a regional approach with higher level recovery applications. The authors argue that putting businesses, more specific the Original Equipment Manufacturers, in stead of legislators in the driver seat will strengthen the opportunities for high level recovery.

Keywords: WEEE, EPR, quantified global e-waste flows, globalization, EU-policy effectiveness

1. Introduction

Since decades, waste material and in particular Waste of Electrical and Electronic Equipment (WEEE) has been treated mainly as a cost factor in production. The resulting tendency was to look for the cheapest way of disposal at the nearest distance. Today, sustainable practices are legally imposed by governments with a key role for Original Equipment Manufacturers (OEMs). We argue that policy makers insufficiently consider whether regulatory intervention is needed and if so at which level (global versus more regional). Moreover, firms face problems when adapting their business to meet the global sustainability criteria. This paper presents the results of a first exploration.

Multinational companies have recently been encouraged to improve waste recycling practices by government policies based on Extended Producer Responsibility (EPR), (Chung and Yoshida, 2006; Sinha-Khetriwal et al. 2005, OECD, 2001). EPR is defined as 'a policy approach in which producers accept significant responsibility, financial and/or physical, for the treatment or disposal of products' (OECD, 2001). EPR policies have two distinct features: the shifting of responsibility upstream to the producer and the provision of incentives for producers to include environmental considerations in the design of their products, resulting in a life-cycle approach. Note that OEMs (or their formal representatives) are responsible for recovery, not for collection.

For e-waste (WEEE), different national recovery systems have been in place for years, for example in Switzerland, The Netherlands, Belgium and Sweden. According to Directive 2002/96/EC of the European Union all EU member states had to have an operational End Of Life recovery system for e-waste as of August 13, 2005 (EU, 2003). Non-EU member states like Norway, the Baltic States and Switzerland as well as Asian countries like South Korea, Japan and Taiwan are adopting similar legislation (Sinha-Khetriwal et al. 2005). In the USA so-called product stewardship is becoming more accepted and mandatory recycling is prescribed in some states (Nnorom and Osibanjo, 2008, Ogushi and Kandlihar, 2007, Chung and Yoshida, 2006).

Today, many globally operating companies, such as DELL, are adopting EPR worldwide by offering free recycling services, even when not mandatory prescribed by the regional authorities. Table 1 gives some examples on mandatory EPR in the automotive, packaging and WEEE industry. As Table 1 shows, all countries listed apply directives with recovery quota, imposing a strong constraint on the disposition decision. The present regulations focus predominantly on waste reduction and pollution prevention by reducing waste export and increasing recycling of materials. Quotas are currently realized by achieving material recovery as well as energy recovery.

Table 1: Recovery quota in some regions of the world for 2008 (2015)

Stream	***Options***	***EU***	***Japan***	***Korea***
Packaging	Recovery	60-75 %		
	Recycling	55-70 %		
Automotive	Recovery	85% (95%)	30% (70%)	85% (95%)
	Reuse and recycling	80% (85%)		
WEEE	White goods recovery*	80%	50%	85%
	Brown goods recovery*	75%	55%	80%

*Definitions vary but 'white goods' are usually functional (laundry, kitchen equipment), 'brown goods' leisure related (audio, TV)

The Basel Convention of 1989 established worldwide requirements for the movement of hazardous waste and obliged the parties to minimize the generation of such waste and to ensure its environmentally sound management. The European Union transposed the Convention by Council Regulation (EEC) No 259/93 (the Waste Shipment Regulation) and as from 1998 prohibited the export of hazardous wastes to non-OECD countries. Different regimes apply to shipments of wastes for disposal and for recovery, as well as to hazardous and "green-listed" non-hazardous wastes, and to some special categories in-between. Shipment of hazardous wastes and of wastes destined for disposal is generally subject to notification procedures with the prior consent of all relevant authorities of dispatch, transit and destination, while green-listed wastes, as a rule, may be shipped for recovery within the OECD like normal commercial goods and only have to be accompanied by certain information. Shipment of non-hazardous wastes to non-OECD countries depends essentially on whether the importing country accepts them and which procedures it wants to apply. Regulation No 259/93 was replaced in July 2007 by the new Regulation (EC) No 1013/2006 on shipments of waste, which streamlines the existing control procedures, incorporates recent changes of international law and strengthens the provisions on enforcement and cooperation between Member States in case of illegal shipments.

Environmental policies as described above prohibit simple waste disposal practices in OECD countries. But we will show that this has resulted in wider global waste streams towards cheap waste disposal sites abroad, including China, India and West Africa. There are strong indications that, in particular outside OECD countries, sustainability objectives are not met. Profit-driven cherry picking has led to low-quality and environmentally unsound recovery, often with poor labour conditions for the workers concerned. Receiving countries generally abstract valuable components and materials from WEEE streams before burning and dumping the residues. Export abroad has been regulated by the earlier mentioned Basel convention which aims to reduce transboundary movements of hazardous waste to limit environmental damage. However, not all countries have joined the Basel convention, for instance the USA has not. Other countries such as China are currently revising national regulation, thereby increasing quality requirements of ‘waste’ imported for recycling.

OEMs today operate on a global scale, but recent tendencies are to organize e-waste handling on a more regional level for a number of reasons. General factors in favour of a global approach include economy of scale and low out-of-pocket costs for the exporting party. Factors favouring the regional recovery option include reduced transport costs, reduction of CO2 emissions and avoiding congestion and treatment capacity problems in for instance Asia.

From a WEEE-flow perspective, a regional approach will also improve controllability and reduce illegal practices as well as unnecessary transportation. However, initial costs may be high due to investments and costs and proceeds should be calculated over the entire product life cycle. Against the background of legal regulations implemented over the last years, the following issues are dealt with in this paper (see also Figure 1):

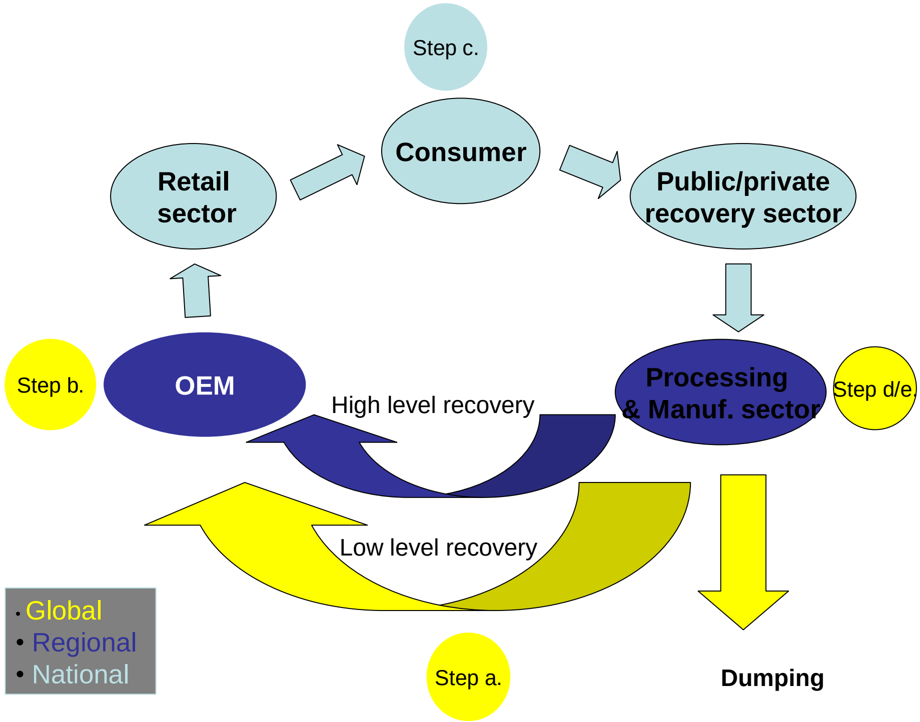
- **a.** Analysis of the gaps between the policy objectives and the actual global WEEE-flows;
- **b.** The scale of OEMs operations and government enforcement (global/regional);

c. Case studies and surveys of successful business applications in recovery;

d. Lessons learned from cases, supported by literature and scenarios including a better span of control and a higher quality of recovery.

e. Future research

Figure 1: Conceptual framework for WEEE handling and research steps(a till e)



Objectives and approach

This paper explores in section 2 the magnitude of global WEEE flows and investigates desirable changes in these flows from a sustainable development point of view. We collect data on "source and sink", i.e. waste generation and reuse, on a macro level. Next we map the different routes followed by WEEE and discuss results in section 3. More viable and compliant alternatives as well as their possible impacts on global WEEE streams are presented in section 4. We present alternatives on a business level and we distil, based on a number of illustrative cases, critical success factors for applying regional high level recovery. The studies are carried out by applying the so-called WARM method, which uses semi-structured interviews, surveys and workshops. The alternative options are supported by extensive literature study and validated by a larger survey amongst companies in various sectors. Subsequently we return in section 5 to the regional and macro level and discuss the impact at those higher geographical levels of the lessons learned. In this context two options will compete: (1) a further expansion of the present low level recovery system of waste electronics recycling, and (2) a regional approach with higher level recovery applications.

The role of industry (more specific the OEM) is emphasized. Putting businesses in stead of legislators in the driver seat will strengthen the opportunities for small and medium-sized enterprises (SMEs).

However, governments should play an active role in creating optimal conditions for the market by e.g. setting standards in order to optimize e-waste flows globally from a sustainable development point of view.

2. Global WEEE flows: sources, destinations and volumes

This section aims to provide a better insight into global WEEE flows in order to identify future risks and challenges for the global waste handling system and to provide a context to assess the potential for wider EPR application.

Although WEEE has been transported globally for decades, the quantitative characteristics are still poorly understood and monitored. This is partly due to the interest of traders in avoiding disclosure of the exact destiny of the goods they handle. New legislation, such as in the EU since 2007 and described more in detail in the next chapter, is forcing traders and waste treatment businesses to provide better information.

This section offers the best available estimates of global WEEE streams between the major regions in the global system, comprising Europe, North America and Asia. We aim to specify waste flows for the quantitatively most important waste categories as specified in the EU WEEE Directive.

Estimating waste flows is not an easy task. After estimating waste generation, the distribution of the flow across different waste handling routes, both domestically and abroad, has to be determined on the basis of often scarce information. But even the first step of estimating waste generation is troublesome. Different methods have been proposed for e-waste generation (Widmer et al., 2005, Lohse et al., 1998), such as:

1. the consumption and use method, which is based on extrapolation from the average amount of electrical equipment in a typical household;
2. the market supply method, which uses production and sales data for a certain region;
3. the old-for-new method, applied in Switzerland, which assumes that for each new appliance bought an old one reaches its end-of-life.

As long as the use in private households is not saturated, the growth of electronic equipment use and the lifespan of this equipment have to be taken into consideration.

In this study we have also used, when better alternatives were lacking, what one could call the "bridging indicator method". In this method, e-waste generation quota (kg e-waste per capita) that are typical for a region are calculated on the basis of other general indicators that are likely to correspond with e-waste generation, such as ICT investment per capita or the volume of discarded PCs per capita. In the future more detailed models to predict e-waste generation will be able to provide more accurate data for regions or countries.

To arrive at estimations of international WEEE flows, amounts of waste that are processed regionally were derived using recovery and disposal options as defined by Thierry et al. (1995).

2.1 Developing a basic fact sheet for WEEE flow estimation

Generally speaking, the availability of data and the existence of regulations is most advanced in regions such as the EU where the regulations have been in place since 2003. Evaluation of the effectiveness of the legislation is prescribed after five years. For this purpose, a Technical Report on the implementation of the WEEE directive in the EU (Savage et al., 2006) and a Review study of the WEEE Directive by the United Nations University (Huisman et al., 2007) provide important information that is lacking for most other regions. This necessitates making rough estimations for the other regions.

Basic data requirements to estimate WEEE streams

In view of a possible extended use in the future, it is important to set up a database that can be used for multiple purposes. This ideally incorporates the following characteristics:

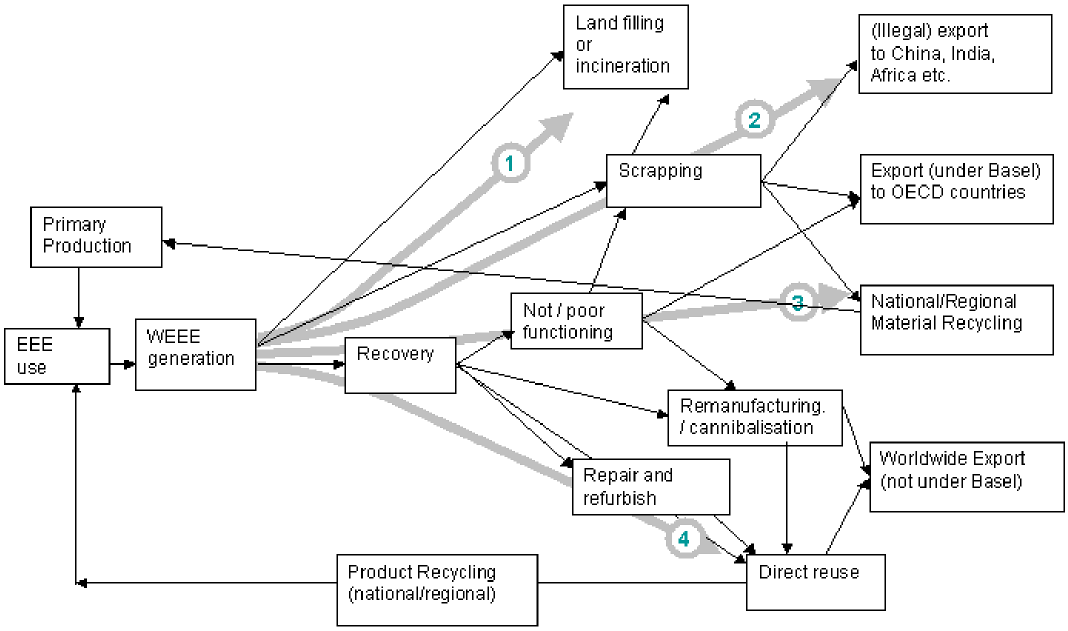
- Waste characterization: the 10 categories of EU WEEE directive
- Geography: country
- Periodicity: yearly, if possible more frequently
- Waste recovery process: municipal sites, in-store retailer take-back, recycle shop, producer take-back, % of recovery of total WEEE supply
- Reuse in the country or region: % and possibly specification of type of recovery process (collective association, metal industry, traders)
- Resulting export: if possible, specification of the receiving country and the type of waste processing
- Projections for coming years: based on past data and economic growth estimations.

Figure 2 presents a flow scheme of national WEEE generation and processing. From an overall point of view, four main options are available: 1. Landfilling and incineration, the simplest form of waste handling; 2. Export to low-cost regions like Africa and Asia; 3. Regional material recycling and 4. Direct reuse, either domestically or abroad. We will return to this in section 5.

The basic data specified above show that a large database is needed for detailed projections of global WEEE streams. Such a detailed approach is not yet feasible as such information is lacking at industrial sector or governmental level, and because WEEE streams are not consistently defined and monitored in different countries and regions. In addition, there are considerable problems with free riders and illegal traders while the level of enforcement differs significantly from country to country, also within the EU. This is currently improving as a result of the new EU monitoring requirements and increased collaboration among enforcement agencies in the EU member states since 2007.

Consequently, simplifications and approximations have been made using available data as much as possible.

Figure 2: Flow scheme of national/regional WEEE generation and processing



Visualizing the following stage of development: 1. do nothing; 2. Export and dump; 3. Global material recycling and low level recovery/second hand reuse; 4. regional high level recovery. See § 5 for detail.

Starting with a simplified approach

The simplification results in a selection of 4 out of the 10 categories of the EU WEEE Directive, representing the largest share (90% or more) of the volume produced. Some country-specific indicators will be used to estimate regional total waste streams.

Following this simplification, for each region estimates have been made of

- the total volume of four WEEE categories generated annually
- the amount recycled (incl. incineration) and land-filled in the region
- the (resulting) amount exported/imported by the region.

Data presented in the next section are based on this format.

2.2. Estimation of WEEE streams generated by the EU, North America and Asia

Estimation of WEEE streams is not easy as direct data from nations or regions are not or to a limited extent available. Estimations therefore had to be based on indicator values and comparisons between countries. A detailed description of the assumptions applied is given in Appendix 1.

Table 2. Global household WEEE production, disposal, recycling and import/export estimates[1] (2005)

Country/region	Annual household production in mln tons	Land-filling, storage and incineration in mln tons	Domestic recycling in mln tons[2]	Annual export in mln tons	Annual import in mln tons
USA	6.6	5.2	0.13	1.3	-
EU-25	7	1.6	3.5[3]	1.9	-
Japan	3.1	0.6	1.9[4]	0.62	-
China	3.1	3.6	1.5	-	2.0
India	0.36	0.85	0.36	-	0.85
West Africa	0.05	0.45	0.17	-	0.57
Total	20,21	12,3	7,56	3,82	3,42

The data from Appendix 1 can be summarized as presented in Table 2. This table indicates that the global WEEE production by households exceeded an annual amount of 20 million tons in 2005, as data presented do not fully take into account all nations and all streams. Still excluded are nations such as Canada and nations on the South American continent. Business to business (B2B) streams are often not included. They are estimated to be 25% of the stream generated by households in the EU (Huisman et al., 2007). In this paper we focus on the household generated waste streams.

In Europe alone, the annual volume of e-waste generated by households is estimated at approximately 7 million tons per year (Huisman et al., 2007, Van Wassenhove et al., 2004). Global WEEE streams may change considerably if disposal (land-filling and incineration) in North America is reduced and exports to the developing world are increased. A total amount of 3.8 million tons (about 20% of the global WEEE stream) was exported in 2005. Part of this stream will ultimately be land-filled in developing countries.

It is surprising how domestic e-waste generation in China has already climbed dramatically, now equalling the amount generated in Japan. China is second in the world after the USA in the land-filling and incineration of e-waste residues. Volumes of recycled e-waste are largest in the EU, followed by Japan.

Table 3 details the estimates of the WEEE flows between nations and regions. Although one might assume that the differentiation in four WEEE categories given for the export remains the same, it is in fact likely that importing countries have preferences that will increasingly be reflected in the composition of the waste streams imported. However, the present database does not allow for such a detailed analysis of the import streams. It is therefore assumed that no selective preferences exist in the import of WEEE categories in Asian and African countries.

[1] From the recovered stream part that is disposed within the country/region (see estimate), part is exported to the developing world (see estimate) and the remainder is reused directly or through different types of processing like refurbishment and remanufacturing.

[2] It is assumed that 30% of the waste generated and imported is recycled in China, India and West Africa.

[3] It is assumed that 50% of the waste generated is recycled in the EU-25.

[4] It is assumed that 60% of the waste generated is recycled.

According to these estimates, most WEEE export (50% or 1.9 mln tons) is generated in the EU, with the ports of Rotterdam, Hamburg and Antwerp playing an important role in the export. Most of the total export flow ends up in China (53%) and India (22%).

Table 3 Global export and import per EU-WEEE category, estimations for 2005

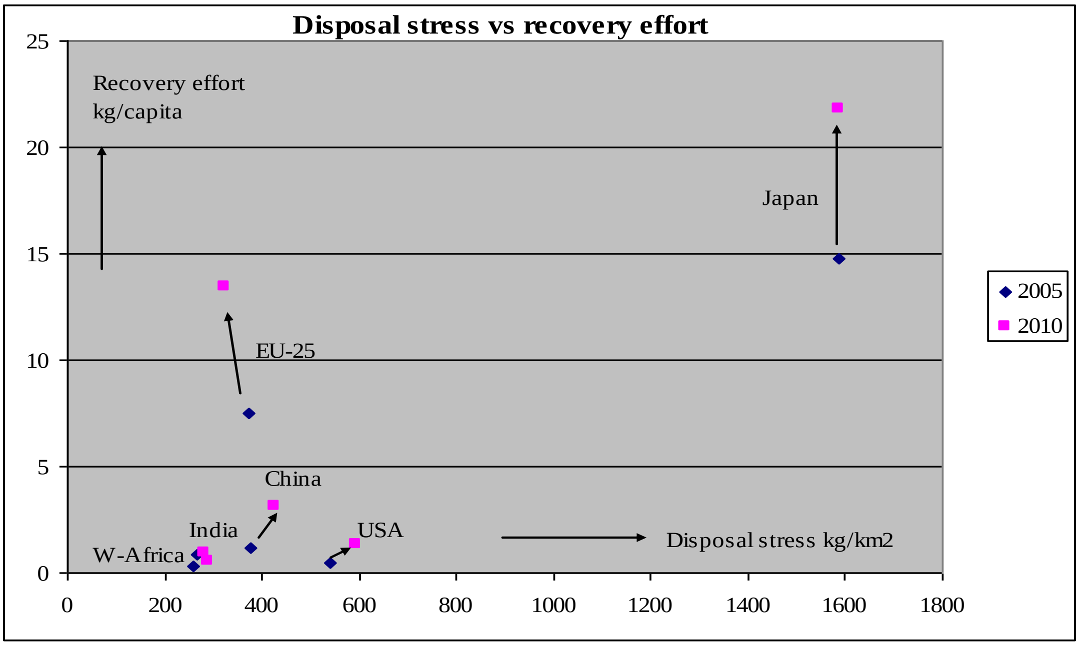
WEEE category	Other nations Import	China import	India import	W.Africa Import	Total mln tons 2005
EU export	0.38	0.74	0.40	0.38	1.90
cat 1	0.19	0.39	0.2	0.19	0.97
cat 2	0.038	0.07	0.04	0.038	0.19
cat 3	0.076	0.14	0.08	0.076	0.37
cat 4	0.076	0.14	0.08	0.076	0.37
USA export		0.91	0.26	0.13	1.30
cat 1		0.55	0.16	0.08	0.78
cat 2		0.073	0.021	0.01	0.1
cat 3		0.146	0.042	0.021	0.21
cat 4		0.168	0.042	0.021	0.21
Japan export		0.38	0.18	0.06	0.62
cat 1		0.21	0.1	0.03	0.34
cat 2		0.032	0.017	0.005	0.054
cat 3		0.066	0.033	0.011	0.11
cat 4		0.066	0.033	0.011	0.11
Total export/import	0.38	2.03	0.84	0.57	3,82
cat 1	0.19	1.15	0.46	0.3	2.1
cat 2	0.038	0.18	0.078	0.053	0.35
cat 3	0.076	0.35	0.16	0.11	0.69
cat 4	0.076	0.37	0.16	0.11	0.69

2.3 Future projections

In Figure 3, disposal stress (kg/km2), which is the sum of land-filling, storage and incineration, divided by the land surface of the region, is plotted against the recovery effort (kg WEEE/capita). The data for 2005 and 2010 are given in Appendix I. Figure 3 shows a high disposal stress in Japan of 1600 kg/km2, followed by the USA at approximately 600 kg/km2. China and Europe have similar disposal stress levels of approximately 350 kg/km2. It is noteworthy how fast domestic household production is expected to rise in China, equalling the production of Japan in 2005 and exceeding Japan's production in 2010 by 40%. Japan will probably manage to keep the disposal stress at the same level in the period 2005-2010 by moving towards stage 4 (see Figure 2), achieving 70% recovery of household WEEE production.

The EU-25 is the first region that will probably reduce disposal stress in this period by strongly improving its recovery effort from 50% to 66%. Besides disposal stress, the strong policies to promote sustainable development are probably a factor in explaining the expected doubling of the recovery performance in the EU between 2005 and 2010. The USA is lagging far behind, reflecting the already described stage 1 position of this country.

Figure 3. WEEE disposal stress and recovery effort of regions worldwide, estimates 2005/2010.



Although recovery efforts are likely to increase, the main recovery option for the near future remains global material recycling. The goal of a sustainable society that is less material-intensive still seems far away, when the WEEE production forecasts are considered.

Figure 4. WEEE production of regions in the world as a function of GDP/capita

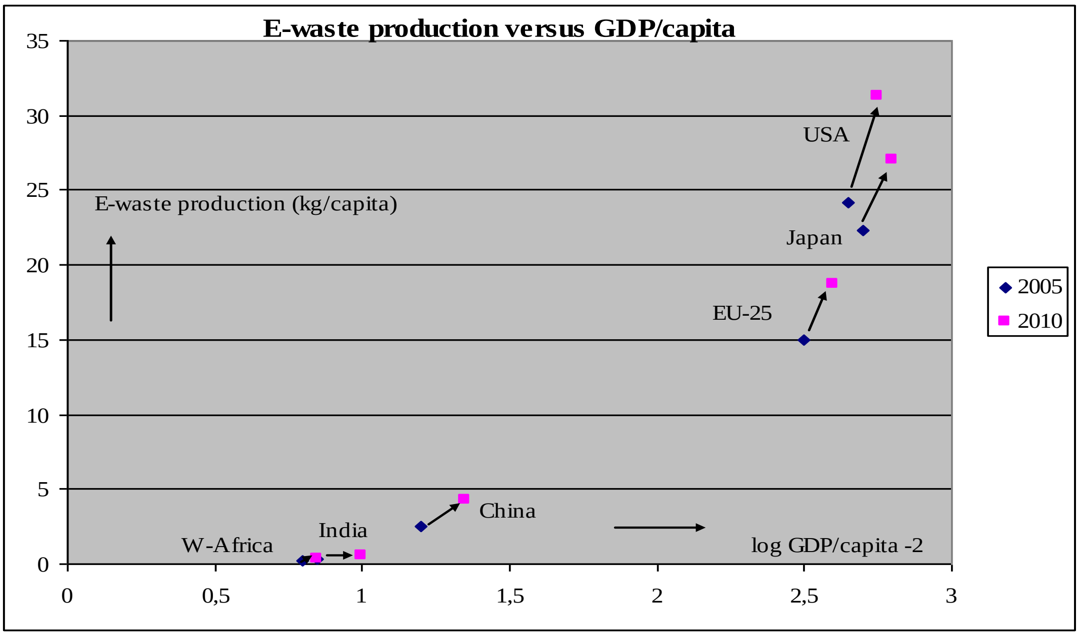


Figure 4 gives an overview which shows the impact of GDP on WEEE production volumes. Although China's WEEE production is still relatively low in terms of kg/capita, the absolute quantities are large. China is already the third biggest WEEE producer in the world and will probably become the biggest around 2020. All countries and regions still show a fast increase in e-waste production, a trend which is not likely to be reversed in the foreseeable future.

3. Analysis of global e-waste flows

The data presented give cause for some reflection and interpretation. First, several authors (Hammond & Beullens, 2007; Huisman et al. 2006; Krikke et al., 2003), argue that the EU policies based on EPR may lead to low quality and environmentally unsound solutions. As part of the 'open-loop' problem, illegal exports remain a problem while the reuse and transportation add to the energy use. Our data confirm that EU-directives do indeed stimulate recovery, but mostly via alternative applications in what is euphemistically described as "cascade markets". Moreover, the collectively organized systems make that the incentives for individual OEMs to apply eco-design are limited. We can see that, although profitable for some actors in the playing field, there is still an overall deficit for many recyclers. Apart from tradable commodities such as scrap and waste paper, quality and hence economic proceeds are often low. Waste reduction is not achieved, given the ever increasing volumes presented in Table 2 and Figure 4.

Moreover, disassembly and recycling in receiving countries often takes place under poor working conditions (SwedWatch, 2009). The EU Directive for Transboundary Movement of Waste Materials may hinder but not prevent export, as economic forces often win from than enforcement.

Waste export mostly is the result, not just of low labour costs and dumping, but of the need in industrially developing countries such as China and India for materials. They recognize the value of streams that are seen as just waste by the developed countries. On the other hand, growing economic

prosperity in Asia will make this region a major WEEE producer in the future, as Table 2 and Figure 4 show.
Although it is difficult to trace origins and destinations of all flows, it is fair to assume that large parts of WEEE travel long distances. Globalization certainly has its merits but also increases energy use and hence CO2 emissions. Global is not green (Nathan, 2007). Moreover, as environment is becoming an economical factor, global sourcing is being reconsidered. Rubin and Tal (2008) show how steel industry is already regionalising on a large scale, where Mexico has gained large portions of the USA market and Chinese exports have dropped by 20%. (Out-) sourcing strategies have also led to complex supply chain networks, with different locations for different activities.
Illegal WEEE trading will remain common, given its profitability. This will probably result in a redirection of the WEEE streams to those countries where requirements are lowest (race-to-the-bottom effect). For this reason we expect West Africa to be an increasingly popular destination among illegal exporters from the EU and Japan and still legal exporters from the USA. In the second place, certain areas in Eastern Europe are still used as dumping sites. As a counterforce, governments are tightening the enforcement which will reduce illegal trade in this region (VROM inspectie[5], 2006). Additional measures to help prevent illegal trade will be necessary, however, such as a guarantee from the remanufacturer/exporter to take back discarded equipment. Regionalizing recovery leads to less transportation and to recovery close to the market, which increases control for the OEM and government enforcement agencies. Governments can encourage business intentions in this direction through legal and financial incentives, though this is more common in the EU than in North America where a free market approach dominates.

The economic principle underlying the situation at the end of the first decade of the 21st century is that out-of-pocket costs are minimized and that the materials recovered can compete (at least in price) with virgin materials. Although there is a lively trade in recyclable materials, proceeds for the OEM are low and recyclers may charge traders and logistics service providers. Costs are directly passed on to the customer either as a non-visible part of the cost price or as an explicit removal surcharge. In addition to economic disadvantages, ‘open loop’ recycling is hard to enforce and to monitor for governments. Discarded products are also quite an undervalued source of parts for maintenance and the assembly of new products, however. To this end, higher level recovery options should be applied and a life cycle perspective should be developed (Krikke et. al, 2004).
Referring to the four options in Figure 2, the world as a whole is at the end of the first decade of this century in a transition from stage 1 to 2, with EPR pushing for development to stage 3. To achieve sustainability that is profitable, one has to move to more high-level recovery options, hence downward in Figure 2. How to move towards stage 4 is discussed in the following section. The potential impact of the latter transition on global WEEE streams will subsequently be assessed.
It is important to note that recovery denotes all forms of recuperation for reuse. Basically, six *recovery options* are given at a conceptual level, namely: (1) direct reuse, (2) repair, (3) refurbishment, (4) remanufacturing, (5) cannibalization and (6) recycling (adapted from Thierry et al., 1995). Direct reuse

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[5] VROM inspectie: Inspectorate of the Dutch Ministry of Housing, Spatial Planning and Environment

concerns checking and cleaning activities, e.g. the refill of toner cartridges; repair restores a product to working order; and refurbishing entails an upgrade and replacement of some critical modules/parts. All these options concern product reuse, which is not included in the EU WEEE directive quota, but is seen as trading flows under the EU Directive for Transboundary Movement of Waste Materials. Remanufacturing produces as good as new products partly from old components and materials; cannibalization involves the selective retrieval of components and modules (others are scrapped) mainly for spares applications; and material recycling is seen as the 'lowest' form of recovery. There are many publications proving that higher quality recovery (read remanufacturing) should be encouraged both from an environmental and a viability point of view. In the next section we discuss this and present some illustrative options.

4. Options for a different approach

The challenge from a sustainable development point of view is to develop *closed loop* supply chains, i.e. maximum recovery for reuse in the original supply chain, or some cascade segments also under control of the OEM. Typical recovery options include remanufacturing, cannibalization (spare parts) and refurbishment.

4.1 Encouraging high-level recovery on a regional basis

High-level recovery aims to substitute new production in order to be economically viable and ecologically sound. Recovery often proofs to be cheaper than new production, as it avoids the use of virgin material, often saves energy resources and avoids other costs which are invested in the recovered products.

Economic viability

Direct reuse, refurbishing, parts cannibalization and remanufacturing usually recover more value than just the materials, as happens in recycling. It is economically profitable because, when leaving equipment and parts as much as possible in their original form, the total value present in discarded products is used. Labour invested, logistics and many other organizational and administrative costs make up the price of a product, in addition to the costs of the materials used. Materials often form only a small part of the total cost. Studies (Gray et. al, 2007; Giuntini, 2003; Lund, 1996) indicate that up to 90% of the total original costs are 'recuperated' during reuse, which is sometimes felt as 'counter-intuitive'. One assumes that the extra work for collecting, disassembling, controlling, cleaning, repairing etc. must be prohibitive because of high costs of labour, whereas new production elsewhere is cheap. However, recovery for high-level reuse entails far less work than new production starting from scratch. Much value is locked up in the product, including labour, material and energy costs, quality control costs etc., which can be reclaimed.

Remanufacturing can be as efficient as virgin production and assembly, if not better. Practice proves that even cheap (€15/piece) and somewhat complicated electrical motors can be refurbished and adapted for 50% of the new price (Comperen, 2006). For parts with a higher value or a simpler construction, this ratio becomes even more advantageous (cannibalization). So if other costs, e.g. for collection and disassembly can be kept low, reuse is profitable for many products and companies. If done on a much larger scale than presently practised, it would effectively control the various streams of discarded products in a much more economical way. Last but not least, quality standards also in Asia are expected to rise (HbR, personal communication).

The viability of high-level closed-loop recovery was proven in our program with SMEs (Appendix II), but is also mentioned in other studies (Gray et. al, 2007; TRI, 2006; Ginsburg, 2001; Steinhilper, 1998). Products involved include office photocopiers, vending machines, electrical motors and compressors, industrial food processing equipment, computer and telecom equipment, air-conditioning units and truck engines. In the USA it is estimated that a total of 73,000 firms are involved in some form of remanufacturing (as service to OEMs) in 46 product areas, employing 480,000 people and with company sales around $ 53 billion (Giuntini, 2003). In the UK the remanufacturing industry employs more than 50,000 people with company turnover of around £5 billion (Gray et al., 2007).

Ecological soundness

There is clear evidence from the studies mentioned that high-level closed-loop recovery is also more environmentally-friendly then most present practices, as energy efficiency improves compared to virgin production (Krikke & Zuidwijk, 2008; Hischler et al., 2005). Kerr and Ryan (2001) indicate that remanufacturing can reduce resource consumption and waste generation during production. E.g. over the life cycle of a photocopier this reduction can reach up to a factor of 3, with greatest reductions if a product is designed for disassembly and remanufacturing. The advantage lies in the fact that not just materials are recovered but that energy is saved as well, thus cutting CO_2 emissions. It is estimated that remanufacturing only needs 15% of the energy compared to manufacturing from scratch (Giuntini, 2003). Recovery of materials alone generally is still less energy-intensive than primary production (Berkel, 2007; Krikke, et al., 2003). Wright et al. (2002) estimate the energy benefits for secondary metal production for aluminium at 94%, for copper at 75%, for lead at 70% and for steel at 40%. Energy consumption and in particular the environmental impact of the scrapping, separation and treatment of the discarded equipment is still extensive and the costs are therefore high (Huisman et al., 2007; Huisman, 2003). Contrary to recycling, high-level recovery also recovers the energy used during the manufacture of all components and subcomponents, of the assembly process and of much of the transport required. Moreover, part of the materials is irretrievably lost during processing, which is not the case for reuse. Moreover, involvement of the OEM and other supply chain members guarantees quality standards and may help to prevent illegal exports, as discussed earlier (Krikke et al., 2003). Application of high-level recovery in many cases also reduces the eco-footprint (Hischler et al., 2005). Substitution, the saving of resources by using recovered items, materials and energy, thus replacing virgin production processes, is an important cause of this reduced foot-print. In general, substitution is favourable as it saves energy, materials and costs. To achieve this effect, the reverse logistics channel must be competitive with the new production of components and materials.

Transport issues

The exodus of the western make-industry to the Far East and Central America, has also led to amongst other things increased distances, complicating supply and communication lines. To some degree, however, the global outsourcing trend since 2000 may backfire due to the competition for raw materials, increasing pollution problems in the Far East and international shipping constraints. A capacity shortage at the world's major hubs causes delays, a lack of effective shipping capacity and hence higher tariffs.

Regional recovery is complementary to this and additionally reduces risk and CO2 emissions as well as cost of (transport) energy. Eastern Europe, Mexico, Brazil, Ukraine, China and some of the more advanced African countries may prove to be factories of the region. Remanufacturing fosters local sourcing, where suppliers are often at the OEMs site. However, a good market in Asia for recyclable non-hazardous commodities will probably remain.

4.2 Overcoming obstacles to high level recovery at business level by applying the WARM approach

Regional remanufacturing is in our opinion still insufficiently recognized as a feasible proposition. Main obstacles are e.g. the envisaged complexity of the reverse logistics, doubts about the quality of recovered parts and changes that need to be made in design and set-up of production facilities. Better and more detailed insight into the actual cost structure of products is required and companies need to adapt the way products are marketed. Nevertheless, new regulations such as the EU WEEE Directive and the growing scarcity of raw materials are prompting OEMs to reconsider their position in this matter. Besides, remanufacturing offers new business and job opportunities and can stimulate local and regional economies, as demonstrated in the USA. Authorities can promote it as an alternative for the materials recycling route commonly chosen. As SME's miss the capabilities and information to introduce high-level recovery, they need structural support. Our program, the so-called 'WARM approach' (which stands for Waste And Recovery Management), described in Appendix II, aims to develop methods and instruments that can help SME's.

This study was split into two major groups of companies: one group dealing with fairly advanced companies and a second group with less advanced companies. In the first group in-depth semi-structured interviews were combined with a 'pressure cooker' workshop to identify critical success factors for high level recovery. The examples below[6] show that remanufacturing, recovery and refurbishment are also viable and highly profitable propositions. All companies are SMEs, which are active in limited geographical areas. The second group of less advanced companies was surveyed to research the wider potential of reuse in order to validate the findings.

The first case, a typical example of refurbishing, is **Ecotax Security Technology** at Willemstad (NL). It sells fences with electronic touch detection and protection systems. Fence parts and security equipment frames, used for instance on temporary building sites, are overhauled completely, with

[6] The experience and cases described are the result of our research program described in Appendix II. It concerned case-based research and involved interviews with managers of companies and pilot projects to identify options and constraints in introducing reuse.

minor parts replaced, but reassembled in the original form and function. Practically everything is reused in some form. Overall production costs are considerably less and at the same time new jobs are created through the recovery activities, while new markets for lower-prized systems are developing.

An example of remanufacturing is **Sweere Food Processing Equipment BV** at Zevenbergen (NL). It sells crop harvesting equipment. It imports new equipment from the USA but also remanufactures discarded equipment, usually 10 years old or more. Collected equipment originates from all over Europe. The equipment is disassembled to main parts that are cleaned, controlled and if necessary repaired and modified to make them suitable for reuse in new equipment. Remanufactured equipment is sold at a price of 50 to 60% of new equipment to customers who cannot afford to buy new versions. In this way they have expanded their market substantially. The original manufacturer fully cooperates because this benefits his companies too, e.g. by supplying the spare parts.

Cannibalizing concerns the use of recovered modules and parts for repairs and replacements, if necessary after refurbishment, in still-functioning equipment. **Coffee3** at Udenhout (NL) is a typical example. It supplies coffee dispensing appliances for office use. Returned appliances are disassembled and parts are checked and cleaned. When servicing and repairing, customers are offered the choice between new parts or refurbished parts as a cheaper alternative. The company is planning to offer equipment made mostly of reused parts and modules, leading to whole-scale remanufacturing. It would open a new market with customers that cannot afford or do not need new and latest model equipment.

These cases illustrate an often-seen sequence of events. Companies start with refurbished parts to service equipment. Once this activity grows and proves to be profitable, actual remanufacturing becomes attractive.

4.3 Lessons learned

The introduction of high-level recovery in e.g. SME's can be realised in two or three years time. As is illustrated with the cases presented the concept is applicable to a wide set of product-groups. Different strategies for reuse and remanufacturing are relevant for producers and suppliers and for different phases of development.

In most cases profit is clearly the prime incentive and environmental benefits are a spin-off. The value recovered is compared with the costs of collecting, dissembling, refurbishment and control. Furthermore, production costs can be reduced because production lines profit more and longer from existing and proven designs, set-ups and equipment parts. Time involved in re-designs and production lines also proves to be shorter.

Closed-loop recovery stimulates a remodelling of customer relations, with novel market strategies and advantages for customers and producers. Concepts like product lease with extended customer services, such as fast replacement of older equipment, are common now in the copier business. This benefits overall quality as well, since returned products provide a lot of information on products' weak spots and design flaws. Designs and performance can consequently be optimized. The main points of attention, which are at the core of the WARM approach, include the following:

- A reliable and steady stream of returned equipment for a sufficient stock of parts. The volume of equipment and products that will be involved in high-level recovery is uncertain. Reverse logistics to handle this is an evolving business field attracting many companies (Thierry et al., 1995). It will take some years before a sufficiently large and reliable reverse stream of products exists. It depends of course on the average lifetime of a product. A producer can to a certain extent influence this when lease is involved and through trade-in by stimulating the exchange of older products for new ones.

- The need to measure and control the condition, wear and remaining lifespan of equipment and parts to guarantee sufficient quality for reuse. Visual control and simple tests often suffice. For more complex structures such as electronic parts, particular methods for testing are required and are being developed (Di Bucchianico, 2004). Depending on the sturdiness of design and materials applied, the history of used equipment and parts can be categorized as 'as good as new' or as lower grade. On the basis of the outcome the corresponding quality and lifetime can be guaranteed.
- Rapid changes in technology and 'fashion' can make perfectly functioning parts unfit for reuse. This often concerns only specific parts, e.g. electronics or the visible outer layer.
- Customers and sales departments may fear lower quality or reputation damage. In reality high-level recovery is incorporated already in many production processes without any adverse consequences. Many appreciate and even require the reduced costs and the 'sustainability aura' provided by remanufacturing.
- The relationship with suppliers of original equipment and parts may be jeopardized, as they may fear losing business. Looking for mutual benefits helps to overcome these fears.
- Products with high obsolescence rates (such as computers) have problems to create closed loops, because new production can not be substituted by recovery.
- Material recycling requires huge economies of scale to be profitable. Its open-loop markets are therefore globally oriented. High-level recovery requires less scale but higher responsiveness and therefore suits regional sourcing. In combination with ongoing technology developments, the quality, sustainability and viability of recovery is rapidly improving.
- Design for recovery enables a whole set of recovery options, ranging from remanufacturing to material recycling and energy recovery. Product modularity and commonality also increase the potential for high-level recovery options. Moreover, regional high-level recovery options will make it easier to identify and remove hazardous materials close to the source of the waste.
- Life cycle costing. Initial cost are high due to for example product design changes and the set up of collection systems Revenues come later in the product life cycle. Accounting systems are not geared for this and have to be adapted. In fact, a more long term focus on costs and revenues is needed.

In conclusion, there are several critical success factors for achieving high level regional recovery. All success factors are in the hands of companies. A major consequence of our analysis is that industry should take the lead encouraged by standards and other facilitating actions from governments such as removing unnecessary legal constraints.

4.4 Wider impact

Table 4 displays the benefits when applying high level closed loop recovery using indicators similar to those defined earlier in par. 4.2. It is based on a larger survey of companies in the same business sector as described earlier and three additional branches of industry. In most cases synergy exists between economic and ecological goals, but for low priced exports it proves difficult. Proceeds are good, but the environment is not well off. This can be explained by the fact that most of the exports are internationally and even globally oriented, and are not connecting to the urge to regionalize.

A broader sustainability lesson therefore is that closed-loop recovery systems clearly favour regional approaches over global ones. The companies involved in our research program contracted often the refurbishment of parts and modules out to specialist firms, to reduce costs. Short distances which foster direct contact and cooperation is seen as crucial to reach high quality in the remanufacturing process. OEMs expect to better control their responsibilities and ambitions in this way. This clearly stimulates regional economics as a growing number of companies enter this market.

Table 4 Different reuse strategies found in practice, with economic and environmental impact

Equipment type	Existing market, reuse in new equipment, for overall cost, materials and energy reduction	Renew market, cascade options, as alternative for own 'new' products reducing energy and material use	Low priced export leading to increased waste and energy use and more profits	Service for customers, lower priced replacement for faulty equipment	Lower prized spare parts
Large office equipment	++	+			+
Computers, small printers etc.			+/-	+	
Vending machines	++				
Agricultural equipment		++	+/-		+
Coffee and drinks dispensing machines		+		+	++
Medical equipment	+	+		+	

4.5 Global scenarios

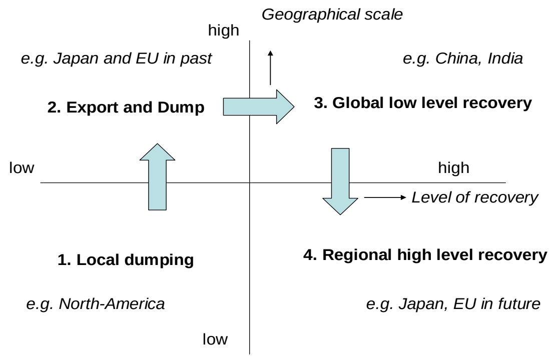
In summary we propose the following four global scenarios, as illustrated in Figure 5 to describe past and possible future developments:

1. *Local dumping*: the result of no active policy is local disposal (landfill and incineration). This scenario is the first development stage which unfortunately still applies to large parts of the world, e.g. parts of the USA. Once local and regional landfills are full, developed countries will be looking for cheap ways to get rid of their waste and in doing so may move to the next stage.

2. *Export and dump:* Export and particularly dumping in developing countries is a logical follow-up from development stage 1 as legal constraints have to be met. Smart traders will make money two ways, charging the local disposer on the one hand and selling some valuable recyclables abroad. What is left finds its way to the cheapest country. West Africa may become the centre of this flow in the future. The geographical scale thus expands to the global level and recovery quality remains low.
3. *Global low level recovery:* Commodity trading markets are resulting from the previous development stage, especially in Asia. The open-loop development is partly the result of EPR-based legislation and partly due to a strong demand for materials in the Far East. This stage is also global and the level of recovery of valuable component or materials improves by applying open-loop recycling which is not yet achieving high level closed-loop recovery.
4. *Regional high-level recovery:* Component and module based reuse is achieved in closed-loop developments using regional high-level recovery options, of which the first examples can be found in the EU and Japan.. The business cases presented earlier illustrate this concept. Businesses take the initiative using the critical success factors mentioned earlier as steering variables.

Development stages towards a more sustainable situation in the future can be defined using two critical dimensions: geographical scale and level of recovery. These two characteristics determine whether or not e-waste returns are processed in the region of origin and if reuse and recycling take place in the original supply chain (high-level recovery) or some alternative supply chain (low-level recovery). Many companies are still in stage 1 or 2, but Basel convention regulation and its follow-up are rapidly promoting stage 3. EPR based regulations recently advocate stage 4 which allows a better sustainability performance (Krikke and Zuidwijk, 2008, Hischler et al. 2005). As discussed before high-level recovery tends to favour markets on the same continent, due to low labour intensity, low energy and materials intensity and the lack of this type of recovery option in the Asian markets which are more geared towards material recycling.

Figure 5: Global scenarios in sustainable WEEE recovery and examples of regions representing such scenario's



National regulations and recovery infrastructures however concentrate on a recycling route requiring cooperation by specific industry sectors. This hinders changing remanufacturing routes, which have to be (re)invented for each company. Some regulations seem to block this logical and more profitable route because sectoral policy considerations were dominant during their conception. An example is the EU RoHS (Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment) Directive which discourages the reuse of parts containing hazardous substances (lead for instance), even though these are not released during reuse. Achieving a better alignment with the goals of the WEEE Directive by the European Commission is desirable. A more positive incentive can be given through e.g. certification programs allowing certified companies less strict enforcement regimes. The government can contribute furthermore e.g. by setting long term recovery goals, as well as by softer instruments like eco-labelling.

5. Conclusions and outlook

This paper has discussed global e-waste streams and driving forces, such as EU-policy and resulting legislation/regulation, which will influence future developments. The findings include:

1. The volume of household WEEE streams, estimated for 2005 at 20 million tons globally, will continue to increase strongly if no additional measures are taken. Low growth rates in the EU and Japan will be rather the exception. Annual export/import flows between regions are estimated for 2005 at 3.8 million tons, creating serious environmental and health problems at the locations receiving these wastes.

2. Local disposal of WEEE, described as development stage 1, is still a major practice (12 million tons in 2005), but in certain regions of the world like North America a ‘local disposal’ policy may soon be followed by development stage 2, ‘export and dump’, which has also been practiced in the past by Japan and the EU. West Africa is a receiving region at risk in this respect.
3. Led by Japan and the EU, global low level recovery, development stage 3, mainly aiming at material recycling in Asia, is emerging.
4. Although global material recycling, as enforced by government regulations in international frameworks, is a more sustainable option than exporting and dumping, it is an open-loop system avoiding the more sustainable optimization that can be achieved within the original supply chain.
5. This analysis shows the importance and practicability of closed-loop high-level recovery options applied at regional scales (proposed as development stage 4). The challenge facing the business community, the Original Equipment Manufacturers, is to take the lead in taking further steps toward achieving truly sustainable solutions. The WARM approach, presented in this paper, illustrates the gains such an approach can provide at the individual company level.
6. Critical success factors have been identified to achieve high level recovery on a regional basis, giving a key role to industry. The business cases show that development stage 4 is achievable leading both to economic profits, and better eco-footprints. Several external forces, such as rising transport and material cost will probably favour stage 4 in the future. However, reaching this stage or even passing stage 3 is no trivial matter. Industry has to take the initiative but governments should facilitate by creating favourable conditions.
7. The government contribution may include long term recovery goals, standard setting, removal of inconsistencies in regulations, promotion and gratification of certification and eco-labelling.

This paper is a first modest step in showing the need and potential for high level recovery practices on a regional basis. For future research, it will be important to better quantify global WEEE streams using more accurate e-waste generation data. Furthermore it is needed to periodically update the overview of domestic and international e-waste flows and forecasts by including new policy decisions and private sector initiatives. This can show where and how fast developments from stages 1 till 4 are taking place. Such insights may help to indicate companies and governments which additional instruments and steps can be used to improve sustainable development on a local, regional and global level.

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Appendix I.

Estimation of actual WEEE streams generated by the EU, North America and Asia

Estimations for the year 2005

1. EU

1.1. Generated volume of WEEE

The EU JRC/IPTS report of Savage et al. (2006) states that electro-scrap is the fastest growing waste stream, growing at a rate of 3-5% per year. Each EU-15 citizen is thought to currently produce (2005) 17-20 kg of e-waste per year. Others have estimated a range of 14 – 20 kg per capita (Enviros, 2002) Some 90% of this waste is still land-filled, incinerated or recovered without any pre-treatment. The key aims of the EU legislation are to seriously reduce land-filling, improve take-back systems, improve product design and achieve targets for recovery (75-80%), reuse and recycling (50-75%) of different classes of WEEE. By the end of 2006, the member states of the EU were supposed to collect WEEE separately at a yearly rate of at least 4 kg/inhabitant. A more stringent target will be set later. Member states must inform the Commission on their results over 2005 and 2006 using a standard reporting format.

Detailed data show considerable differences between member states, of which Germany, UK, France and Italy are the largest WEEE producers and former Eastern European countries have much lower amounts of WEEE. The figure of 17-20 kg/inhabitant per year mentioned above may be too high, as the WEEE-Forum[7] calculates for the collected WEEE by the non-profit collective take-back systems of members of the forum for full operative collection systems 10 kg/inhabitant per year. This figure applies to 16 systems in 12 relatively small EU member states, however. Moreover, the collection systems do not achieve 100% recovery. A value of 15 kg/inhabitant/year for the total of 457 mln inhabitants of the EU is a reasonable preliminary approximation. Only after the reporting over 2005 and 2006 to the Commission is available, more accurate estimates can be made.

The present estimations result in a total estimated yearly supply of WEEE in the EU of:
457,.000,000 (inh.) x 0.015 tons(15 kg/inh.) = 7,005,000 tons WEEE in 2005;
of which roughly speaking:
50% is large household appliances (fridges and washing machines) (7.5 kg/inh.)
10% is small household appliances (vacuum cleaners, toasters) (1.5 kg/inh.)
20% is office and communication waste (computers, cell phones) (3.0 kg/inh.)
20% is entertainment electronics (radios, TVs, stereos) (3.0 kg/inh.)

[7] www.weee-forum.org

1.2. Amount recycled and land-filled in the region

Over the coming years, recycling and remanufacturing are going to be important obligations to EU members states, whereby high percentages of the total WEEE stream of 50% and more can be achieved, as demonstrated by leading countries in Europe such as Switzerland, Norway, UK, Belgium and the Netherlands. E-waste recycling in Switzerland amounted to 11 kg/capita in 2004 (Hischier et al., 2005). However, presently at least 15-20% of the WEEE streams is not collected and treated as prescribed due to free riders[8].

In the UK[9], 88% of large household appliances is recycled, 26% of office and communication waste is recycled and 4% of entertainment electronics. About 10 % of WEEE was shipped illegally to non-OECD countries.

Land-filling is still practiced but it is likely that an increasing number of the countries will prohibit land-filling in the future. A large part of the equipment will be shipped to other OECD countries for high-level recovery.

1.3. Amounts exported/imported

Countries are forced by the EU legislation to process generated WEEE as much as possible within the national borders or within the region/OECD. Switzerland for example is no longer issuing permits for the export of WEEE.

As long as data from the competent authorities (Basel Convention secretariat, European Commission, EEA) on WEEE import and export are lacking, a first rough estimation can be made of the amount of WEEE that the EU is probably exporting to Asia and other regions like Africa and Eastern Europe.

It can be assumed that free riders are still responsible for a volume of 10-20% illegal export of total WEEE to non-OECD countries, and that part of the computer, cell phone and TV equipment (say 30% of categories 3 and 4 of WEEE) is exported legally for reuse in developing countries. Thus, a total amount of 0.15 x 7,005,000 (free riders part) + 0.3 x (0.2+0.2) x 7,005,000 (tons cat 3+4 WEEE) = 1.9 mln tons of WEEE and related functioning (remanufactured) equipment is leaving the EU annually for non-OECD countries.

A control program of the Dutch VROM Inspectorate on illegal trans-boundary WEEE streams leaving the Netherlands, has shown that a total amount of 1000 tons of WEEE (mainly TVs and refrigerators) was illegally transported, of which 43% was destined for China/Hong Kong, 7% for other Asian countries (Malaysia, Pakistan, etc.), 28% for West Africa (Ghana, Nigeria etc.), 7% for Eastern Europe (Romania, Poland) and 10% for the Middle East and North Africa (Egypt, Jordan, Iran, Turkey). If this outcome is translated into an EU figure on the basis of population ratios, it would mean that 30,000

[8] Dutch Ministry of Housing, Spatial Planning and Environment, VROM Inspectorate, 2005, 2006

[9] www.wasteonline.org.uk

tons of these types of WEEE or roughly 10% is exported illegally. This corresponds reasonably well with our previous assumption of the contribution of free riders (10-20%).

Used TVs and PCs are often exported from the Netherlands to Eastern Europe, Africa and probably to India and China. Second-hand copiers are sold to Eastern Europe and Africa (VROM Inspectorate, 2005).

Excluding import quantities between member states of the EU, the total import of WEEE into the EU is not likely to be of quantitative significance.

2. North America

2.1. Generated volume of WEEE

As no legal federal obligation exists in the USA to collect and reuse WEEE, there is less incentive to collect accurate data on the processing of these waste streams. Therefore, obtaining reliable data for the USA is even more difficult than for Europe. The analysis is based on information available in policy documents[10] and data from US EPA, such as a pilot study carried out in 2002 in Region 3 of EPA on the prevention of land-filling with WEEE by recycling[11] and a survey published in 2007 (EPA, 2007), as well as work done by Kahhat et al. (2008).
From these documents a rough estimation has been derived of the volumes of the four WEEE categories. These values have a relatively large uncertainty, which applies less to the total amount of discarded WEEE.

According to EPA, in 1997 more than 3.2 mln tons of e-waste ended up in US landfills. EPA estimated that 2 mln tons of used computers and TVs were discarded in 2000.
EPA estimated for 2003 that 2-5% of the municipal solid waste (approx. 236 mln tons annually) consisted of WEEE. This means a yearly WEEE supply of 4-10 mln tons. Until 2000, this amount was mainly dumped in land-fills.

In later documents[12], the following data are provided under the category “selected consumer electronics” in the municipal waste stream:

[10] The Voluntary National Electronics Policy Action Plan, 2005
[11] www.epa.gov/reg3wcmd/pdg/eCyclingExecutiveSummary.pdf.
[12] EPA: Municipal Solid Waste Generation, Recycling, and Disposal in the United States; Facts and Figures for 2003

Table I. US EPA estimates of selected consumer electronics in municipal waste steams.

Year	Generated 1000 tons	Recovery*	Discarded after materials recovery
2000	2.120	190	1.930
2001	2.260	210	2.050
2002	2.530	250	2.280
2003	2.790	290	2.500

*: does not include converting/fabrication of scrap

However, more recent data (EPA, 2007) estimate the generated waste quantities of home computers, monitors, TVs, printers and cell phones in 2005 at 1.9 mln tons, of which 18 % is recycled or exported and 80% land-filled or incinerated. Incineration involves only 3% of this fraction.
On the basis of these data it is estimated that in 2005, 2 mln tons of computers, TVs, monitors, etc. were generated.

Based on the information above, it is estimated that the total supply of WEEE in the USA amounted to at least 6.6 mln tons in 2005, or 22 kg/inh./year. For this estimation it is assumed, also looking at the more detailed EU data available, that computers and TVs comprise not more than about 30% of total WEEE in the USA. According to the Basel Action Network (2002), in 1998 WEEE waste generated in the USA amounted to 5-7 mln tons. Assuming a steady growth of that amount, our estimated figure for the USA of 22 kg/capita in 2005 may be too low.

The contribution of the four WEEE categories is roughly (yearly estimates):
60% is large household appliances (fridges, washing machines) (13.2 kg/inh.)
8% small household appliances (vacuum cleaners, toasters) (1.7 kg/inh)
16% office and communication waste (computers, cell phones) (3.5 kg/inh.)
16% entertainment electronics (radios, TVs, stereos) (3.5 kg/inh.)
.

2.2 Amount recycled and land-filled in the region

Until 2000 most of the WEEE, including some 50 million computers and TVs, was land-filled or incinerated in the USA. Only 11% of discarded computers were recycled in 1999. In 2003 this was not more than 12%. Land-filling is stabilizing in the USA, and the growing volumes are fuelling a search for other routes such as export. As said, about 80% of the national amounts of WEEE are estimated to be land-filled or incinerated, in recent years. This is the result of voluntary federal programs and the more strict legal requirements in states such as California. This value is likely to decrease slowly over the next decade. It is uncertain whether strong protests by NGOs in view of the negative environmental effects in developing countries as well as media attention, which is already arising, will cause this export to diminish in the future.

2.3 Amounts exported/imported

Contrary to the situation in the EU, the USA has no political objections to exporting to non-OECD countries, which has resulted in a growing export of the total supply of either still functioning equipment or equipment that will be dismantled, incinerated and land-filled in developing countries. For the EU a total export portion of approximately 25% of total WEEE was estimated.
On the basis of an interview with a trader in 2002 (Exported Harm, The High-Tech Trashing of Asia), the Basel Action Network and Silicon Valley Toxics Coalition (SVTC) estimated that 80% of what is labeled as recycled computers and TVs is exported from the USA to Asia, of which 90% is estimated to go to China. In 2005, the export of category 3 and 4 e-waste from the USA may therefore have been around 16%, due to the large remaining role of land-filling, but this value may rise to similar or higher levels as for the EU after 2010.
For the category 1 WEEE stream, possibly higher export levels occur in view of the higher metal content which is in great demand in China.
On the basis of these considerations, the total amount of US e-waste exported is estimated at 0.2 (average of 20% is exported) x 6.6 (mln tons of total WEEE supply) = 1.3 mln tons per year. This value is somewhat lower than the export of WEEE from the EU.
No figures have yet been found on the import of WEEE, but it is not likely that such amounts are of substantial significance compared to the export figures.
Data for Canada have not been included. Roughly speaking, including Canada would increase the figures by 10 %.

3. Asia

3.1 Generated volume of WEEE

The situation in Asia is diverse. Japan, with an even higher ICT expenditure per inhabitant than the USA[13] (US$ 3,256 in Japan and US $ 2,924 in the USA in 2001), contrasts with Malaysia (US$ 262), Thailand (US$ 76), China (US$ 53) and India (US$ 19). However, China and India belong to the countries with the fastest PC growth in the world and are dump sites for e-waste residues.
Against this background most attention will be given to China and India. The legal situation in Japan is to a large extent comparable to the situation in the EU (Kahhat et al. 2008; Widmer et al., 2005).

Japan

[13] World Bank, World Development Indicators Online

On the basis of its population and by using ICT expenditure as reference point, the total WEEE production in Japan can be estimated through a comparison with the USA. This amount can be estimated as follows:

3256/2924 (ICT expenditure ratio Japan/USA) x 127/298 (population ratio Japan/USA) x 6.6 mln tons (WEEE production USA) = 3.1 mln tons or 24 kg/inh./year.

Japan has enforced obligations on retailers to collect and transfer discarded EEE from consumers, as well as a compulsory system since 2001 of recycling personal computers, including recycling fees. To estimate the contribution of the four WEEE categories in Japan, the average values of those developed for the EU and the USA are applied (yearly averages):

55% is large household appliances (fridges, washing machines) (13.2 kg/inh.)
9% small household appliances (vacuum cleaners, toasters) (2.2 kg/inh.)
18% office and communication waste (computers, cell phones) (4.3 kg/inh.)
18% entertainment electronics (radios, TVs, stereos) (4.3 kg/inh.)

It is likely that most of it stays in Japan (Schwarzer et al., 2005) with the remainder exported to China and India, as only a small fraction ends up in e.g. Lagos, Nigeria. According to an article in National Geographic News[14], 45% of the WEEE coming into Lagos originates from the USA, 45% from the EU and 10% from Japan.

China

A similar formula as used for WEEE production in Japan can be used to approximate WEEE production in China. This results in:

53/1924 (ICT expenditure ratio China/USA) x 1314/298 (population ratio China/USA) x 6.6 mln tons = 0.53 mln tons WEEE per year. However, Yang et al. (2007) have made a more detailed study of waste production in China and estimate total WEEE generation for 2003 at a much higher amount of 1.76 mln tons and for 2005 already at 3.1 mln tons, values that do not include imports. The rapid increase is the combined effect of increasing sales numbers and decreasing medium lifetimes. In 2003, about half of this WEEE is caused by obsolete TV sets.

For 2005 the following WEEE production data can be calculated using data from Yang et al. (2007):

large household appliances (fridges, washing machines, aircos) (2.0 kg/inh.)
small household appliances (vacuum cleaners, toasters) (estimation) (0.2 kg/inh.)
office and communication waste (computers) (0.3 kg/inh.)
entertainment electronics (TVs) (0.8 kg/inh.)

India

For India the WEEE approximation results in the following amount: 19/1924 x 1095/298 x 6.6 mln tons = 0.24 mln tons per year.

[14] news.nationalgeographic.com/news/2005/11/1108_051108_electronic_waste_2.html

In the eWaste Guide[15], a value of 0.15 mln tons generated is given for India for 2002. As in China, however, fast growth may, result in nearly a doubling in three years' time. Nearly 90% of this WEEE comes from large household appliances (42.1%), information and communication technology equipment (33.9%), and consumer electronics (13.7%). Top cities in WEEE generation are Mumbai, Delhi, Bangalore and Chennai. Total e-waste generated for 2005 is 0.22 kg/capita, considerably less than the 3.3 kg/capita calculated for China. To get some idea we can compare the estimated number of scrap PCs in India in 2005 calculated by Streicher-Porte et al. (2005) to be 500,000 units. In China the corresponding number was 9.8 mln units, which is nearly 20 times higher. This confirms the estimated large difference in WEEE generation between these two countries.

3.2 Amounts recycled and land-filled in the region

All WEEE produced in China and India probably is processed domestically.
The recycling system is highly unorganized and mainly takes place in the informal economy. In cities like Beijing there are large second-hand markets. After sorting and dismantling e-waste, it is sent from Beijing to Southeast China (Yang et al., 2007), mainly to the provinces Guang Dong and Zhe Jiang, where the actual refining and metal recovery operations take place[16].

3.3 Amounts exported/imported

Japan

Most exported WEEE from Japan ends up in China and India because of geographical and cost considerations. As Japan is a nation of islands it will have a higher incentive than the USA to avoid land-filling. Therefore it is assumed that land-filling will be practiced at a level between that of the USA and of the EU, and that a comparable level of export as found for the EU will be realized, such as 20-25 %. However, data supporting this assumption have not yet been found. On the basis of an assumed export value of 20% of the WEEE supply generated, export from Japan to non-OECD countries may be as much as 0.2 x 3.1 mln tons = 0.62 mln tons**,** about half of the quantity exported by the USA. It may be assumed that about 60% goes to China, 30% to India and 10% to Africa. Import will not be an important factor.

China

For China, export is as yet of no significance. Figures for the total amount of WEEE imported are difficult to obtain. Importing e-waste is formally prohibited[17], but enforcement is still weak. However, Chinese requirements have been upgraded recently and transports not meeting standards are returned regularly. An approximation of the total import in China may tentatively be derived from the earlier estimations. To produce this figure, estimations have to be made of the total amounts imported from the USA and the EU in addition to the import from Japan. As China has been very active in attracting

[15] www.e-waste.in/weee_basics
[16] www.e-waste.ch/case_study_china
[17] Regulation on Waste Imports for Environmental Protection and Management (Interim), SEPA, 1996

WEEE as a source of raw materials and economic growth - and until recently neglecting serious environmental concerns - it will have higher imports from Europe and the USA than India. This active approach is reflected in China's offices in major global seaports such as Rotterdam. In this phase it is assumed that 70% of USA WEEE export ends up in China[18], 20% in India and 10% in Africa Export to Africa is likely to increase in the coming years as requirements are becoming more stringent in Asia. For the EU it is assumed that 20% of WEEE export ends up in West Africa and 20 % in Eastern Europe and North Africa. The remainder 60% probably goes to Asia, of which 65% may go to China and 35% to India, neglecting, for the time being, export to smaller other Asian countries.

The following amounts result for import into China:

Imported from EU	0.6 x 0.65 x 1.9 mln tons	= 0.74 mln tons
Imported from USA	0.7 x 1.3 mln tons	= 0.91 mln tons
Imported from Japan	0.6 x 0.62 mln tons	= 0.37 mln tons
		_____________
Total estimated import China		2.02 mln tons

According to Greenpeace China[19], a concentration of e-waste dismantling sites can be found throughout the Guiyi area since 1995. In 2002 it was estimated that 100,000 workers were employed in this area in the e-waste sector, causing very serious pollution problems. According to the Xinhua News (2005), 30,000 – 40,000 workers are involved in WEEE treatment in Guiyi, treating over 1 mln tons of WEEE annually. As this reflects only part of the reuse activity in China, the above estimate of 2.02 mln tons of imported WEEE is in line with this source. E-waste in this area is reported to be mainly of American origin, while to a lesser degree e-waste came from Japan, South Korea and Europe. These indications are not too different from the estimates given above.

India

Like China, India has formally prohibited the import of e-waste but is not very strict about enforcing this policy. About 50% of the computers sold in India are products from the second-hand market. The market for e-waste is less concentrated than in China and spread across many different places, each handling a different aspect of recycling. All work is done with bare hands and by women and children.[20]

On the same basis as developed for China, the total amount imported in India can be estimated as follows:

Import from EU	0.6 x 0.35 x 1.9mln tons	= 0.40 mln tons
Import from USA	0.2 x 1.3 mln tons	= 0.26 mln tons
Import from Japan	0.3 x 0.62 mln tons	= 0.19 mln tons
		_____________

[18] Xinhua News, 2005,http://news.xinhuanet.com/fortune/2005-09/03/content_3437772.htm (in Chinese)

[19] BAN report, Exporting Harm, 2002, p. 15

[20] eWaste Guide: www.e-waste.in/weee_basics

Total import India	0.85 mln tons

West Africa:

Finally, an estimation for West Africa based on the previous assumptions produces the following figures for 2005:

Import from EU	0.2 x 1.9 mln tons	= 0.38 mln tons
Import from USA	0.1 x 1.3 mln tons	= 0.13 mln tons
Import from Japan	0.1 x 0.62mln tons	= 0.06 mln tons
Total estimated import West-Africa		0.57 mln tons

Estimations for the year 2010

Estimations for WEEE processing and recovery for the year 2010 are based on a number of assumptions, which are presented below.

EU-25

Based on sources such as Huisman et al. (2007), it is assumed that e-waste generation increases by 5% each year. In consequence, the total amount generated will increase from 7 mln tons in 2005 to 8.94 mln tons in 2010.

It is furthermore assumed that as a result of stricter legislation and better enforcement, illegal export will diminish from 15% to 10%, resulting in a quantity of 0.89 mln tons in 2010.

Due to regional EPR programs, legal export will diminish from 30% to 20%, resulting in (2.2x(0.2+0.2)x8.92 = 0.72 mln tons in 2010. The total export from EU to non-OECD countries will come to 1.61 mln tons.

Recycling will consequently increase to 66% of the waste stream, resulting in 5.9 mln tons in 2010.

USA:

Based on values for 2003-2005 from EPA (2007), e-waste generation of categories 3 and 4 increases by 5% per year:

The total amount generated will then increase from 6.6 mln tons to 8.4 mln tons.

It is assumed that recovery will increase from about 15% to 25% in 2010 due tot programs at State level, resulting in 2.1 mln tons. However, 80% is exported (1.68 mln tons), resulting in 2.1-1.68 = 0.42 mln tons recycled.

Exports of recovered materials after recycling are estimated at 1.7 mln tons. It is not yet known what will happen with the accumulating amount of stored devices, which will in the future either be dumped or exported for a good price. The latter is the most likely scenario as market forces are the main driver for actions in the USA. Therefore an extra export flow can be expected to emerge at the cost of land-

filling, storage and incineration, with a magnitude of approximately 10% of the potential land-filling/incineration flow.
This will result in 8.4-1.7-0.42=6.3x 10%= 0.63 mln tons extra export. Total export will on the basis of these assumptions amount to 0.63+1.7=2.3 mln tons in 2010.

Japan

Assuming similar growth figures as for the EU and the USA, WEEE generation will increase by 5% annually, resulting in an increase from 3,1 to 3,96 mln tons.(Yoshida et al, 2007).

Assuming a growth of collected e-waste from 60-80% (in South Korea 70% recollection was achieved in 2006 (Kahhat et al., 2008)), of which 10% goes to landfills/incinerators, this results in a recycled amount of 0.7x3.96=2.77 mln tons.
In 2005, 20 % of e-waste generated was exported. It is likely that this amount will slowly diminish. A value of 15% is applied, resulting in an export flow of 0.59 mln tons.

China

Yang et al. (2007) have estimated growth figures for e-waste generation in China until 2010. Their projections show a stabilization of the supply of obsolete refrigerators and washing machines but a steady growth of PCs and aircos. The result is a projected e-waste growth from 3.1 to 5.7 mln tons in 2010.
Assuming a similar distribution of export flows from OECD countries as used in 2005, the following contributions to import can be estimated:

From USA	2.3 x 0.7 = 1.61 mln tons
From EU	1.6 x 0.39= 0.62
From Japan	0.59x0.61=0.36
Total import	2.59 mln tons.

Recycling will slowly move from the informal to the formal market in China, the pace of which depends on the type of government priority given to this sector. It is not unlikely that recycling will increase from 30 to 50% in this period.
This would lead to a total amount recycled of 0.5 x (5.7 + 2.6)= 4.2 mln tons.

India

It may be assumed that e-waste growth in India will be similar to that in China. PC sales data indicate that this sector follows a similar path in both countries. This means that the total quantity of e-waste generated will be at least 0.66 mln tons.
Assuming a similar distribution of export flows from OECD countries as for 2005, the following contributions to import can be estimated:

From USA	2.3 x 0.2 = 0.46 mln tons
From EU	1.6 x 0.21= 0.34
From Japan	0.59x0.29=0.17

Total import 0.97 mln tons.

Recovery will gradually increase in India but probably not as fast as in China. It is assumed that recycling will increase from 30 to 40% in this period.

This would lead to a total amount recovered of 0.4 x (0.7 + 1.0)= 0.68 mln tons.

West Africa

Assuming a similar distribution of export flows from OECD countries as for 2005, the following contributions to import can be estimated:

From USA 2.3 x 0.1 = 0.23 mln tons

From EU 1.6 x 0.2 = 0.32

From Japan 0.59x0.1 = 0.06

Total import 0.61 mln tons.

Recycling will slowly improve in West Africa but probably not as fast as in China. It is assumed that recycling will increase from 30 to 35% in this period.

This would lead to a total amount recycled of 0.35 x 0.61= 0.21 mln tons.

The following table provides a summary of the data discussed.

Table I.1. Global WEEE production, disposal, recovery and import/export estimates[21] (2010)

Country/region	Annual household production in mln tons	Landfilling, storage and incineration in mln tons	Domestic recovery in mln tons[22]	Annual export in mln tons	Annual import in mln tons
USA	8.4	5.7	0.42	2.3	-
EU-25	8.9	1.4	5.9[23]	1.6	-
Japan	4.0	0.6	2.8	0.59	-
China	5.7	4.1	4.2	-	2.6
India	0.66	0.95	0.68	-	0.97
West Africa	0.07	0.47	0.21	-	0.61

[21] From the recovered stream, part is disposed within the country/region (see estimate), part is exported to the developing world (see estimate), and the remainder is reused directly or through different types of processing like refurbishment and remanufacturing.

[22] It is assumed that 30% of the waste generated and imported is recycled in China, India and West Africa.

[23] It is assumed that 66% of the waste generated is recycled in the EU-25.

Appendix II. WARM approach: a simple tool for decision making

To help equipment manufacturers, in particular SME's, identify the profitable options that high-level recovery offers, a method has been developed which we call the 'WARM[24] approach'. This approach was developed in an applied research program involving a series of pilot projects, studies and many interviews. It involved manufacturers of quite different types of equipment as well as businesses offering services in remanufacturing and refurbishment. The focus was on SME's or smaller units of larger consortia. Nevertheless, much use was made of the experience of larger companies, such as Océ and Flextronics. These firms were quite eager to share their knowledge in this field. In total some 15 manufacturers were involved in practical pilot studies, and some 25 who already practice remanufacturing were used as reference, or as 'critical' respondents in interviews and workshops. The 15 firms mentioned included manufacturers of medical and healthcare equipment (Focal Instruments, Moving People), beverage dispensers (Coffee3), air separation equipment (Norton Filters), and office equipment (a Flextronics production and research location).

The WARM approach aims to assess the profitable high-level recovery options that exist, as well as the possible constraints and efficient solutions to deal with those constraints. These solutions can be of a technical but also commercial or logistical nature. The objective is a method particularly suited to smaller equipment manufacturers, implying a simple and time-efficient approach. That approach is therefore, step-by-step:

1. a quick analysis with few but highly relevant questions: could it be interesting at all;
2. an in-depth analysis of parts and costs available for reuse, using with a fast and structured model:
3. a checklist of specific actions to be taken to implement reuse in a low-cost and efficient manner.

Figure II-1 shows the framework as we present it to the manufacturer. The first step is fairly qualitative, bringing into view the possible complexity and the problems in the various areas of the whole framework that need to be addressed. It is based on the 'subjectively perceived extent' of options and problems in the three main areas of the operations that have to be adapted, as perceived by people within the company (though critically reviewed by the consultant). This is performed rapidly, in just a few hours. The result is a diagram as shown in Figure II-2. A score of over 50 indicates a positive view of the possibilities, below 50 indicates a less attractive situation. This step also makes the company aware of the actual possibilities that reuse offers in their case. Since it costs so little time, the threshold to 'discuss it just once' is low. Even if the score is below 50, some companies continue to consider the options, possibly returning to it later. Problems are often solved simply, just by introducing an innovative procedure alone or minor adaptations to the design. In the second step, the critical factors determining the feasibility of reuse are identified for all parts and modules. This concerns:

- technical aspects, expected wear and remaining lifetime
- testing method and guarantees that have to be given
- costs for refurbishment and remanufacturing against remaining value, using 'activity based costing'
- market options
- specific company priorities and ambitions.

[24] WARM is an acronym for Waste And Recovery Management.

Based on these results, the parts and modules to be reused are selected. In some of the cases of our research program we observed that up to 90% of parts could be are reused . Nevertheless, for practical reasons companies were advised to start with a limited number of high-value parts such as electrical motors, the main frames of the equipment and so on. Refurbishment is not very complicated and redesign is not directly required, meaning that one can start with the parts in their present form.

The next step is the implementation, for which much knowledge is already available, such as for reverse logistics and testing methodology. In the Netherlands, a platform has been set up to make such knowledge easily available to companies considering introducing closed-loop reuse.

Figure II-1. WARM framework

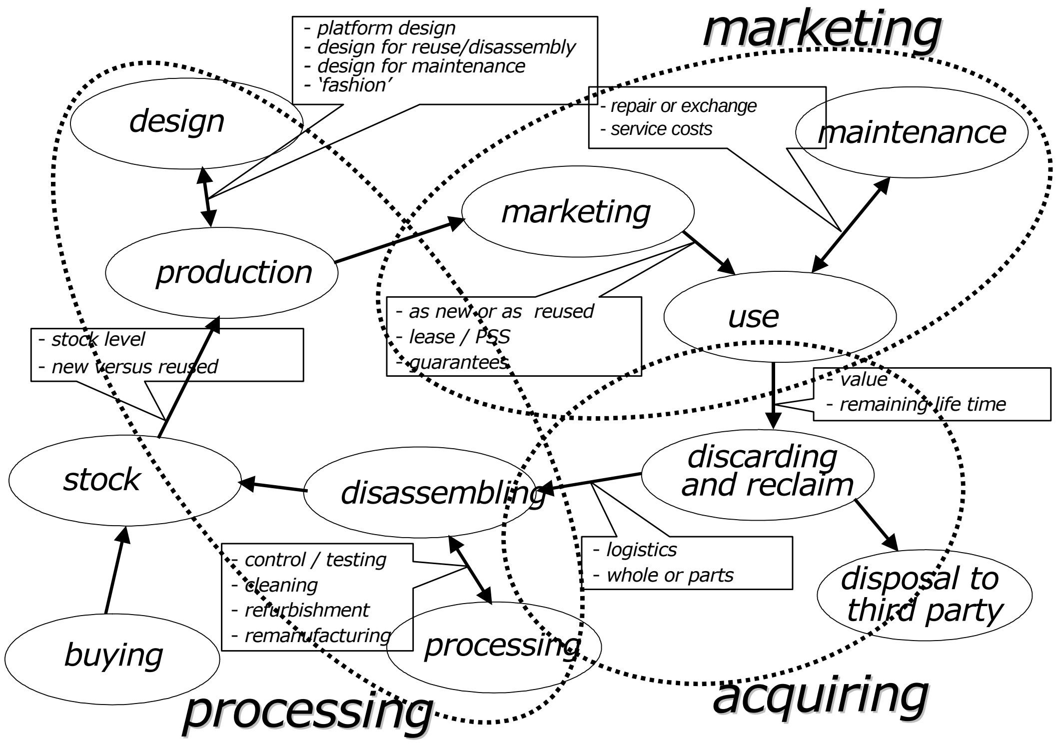

Figure II-2. A simple diagram to show constraints or opportunities for reuse