Doctoral Thesis

Material flow analysis and economic evaluation as tools for system design in recycling of waste from electrical and electronic equipment
special focus on the recycling of personal computers

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Material Flow Analysis and economic evaluation as tools for system design in recycling of waste from electrical and electronic equipment. Special focus on the recycling of personal computers.

A dissertation submitted to the

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Cover photo:
‘Almost closed cycle’ on a printed circuit board of an electronic timer system.
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Summary

The vision of circular flow economy aims to influence the intensity of resources used by humans, firstly through the consumption of renewable resources wherever possible, and secondly by keeping non-renewable resources by means of recycling in the material cycle as long as possible.

The principle of circular flow can be applied to industrial processes as well as to individual consumption. Therefore, many governments in industrialized countries have incorporated the principle in their policies or in their legislation. In contrast, circular flow economy as a vision has yet to establish itself in developing countries or countries in economic transition. Even though some countries such as China have entered the consultative process to incorporate the principle of circular flow as a programmatic strategy, the implementation of the principle into practice is weak.

In the case of metals and many non-metallic elements and substances, this vision makes sense for two reasons: 1. environmentally damaging primary resource extraction would be reduced and 2. economic benefits would be gained as secondary resources from recycling are often cheaper than primary resources. Furthermore, recycling has many more effects: such as the reduced dependency of countries poor in natural resources on those rich in natural resources, and the educational benefits through awareness raising on the potential of waste as a resource.

This thesis promotes the introduction of the circular flow economy by means of applying material flow assessment and economic evaluation methods to the recycling of electrical and electronic waste (e-waste). Case studies were carried out in the City of Delhi, India and in Switzerland. In addition to this a case study was carried out with data relating to the whole of India. All studies examine the recycling of personal computers (PCs). The methods are applied to several existing recycling systems and are simultaneously developed further. Consequently, this thesis not only covers the investigation of particular e-waste recycling systems but also the development of assessment methodology.

1. In the first study, field data in the City of Delhi was collected in order to describe the prevailing recycling methods qualitatively, and to quantify the volumes of e-waste produced. In a simple material flow model both the reused number of PCs and the recycling volumes for each recycling practice were quantified for one single year.

The recycling system in Delhi shows some of the typical characteristics of unregulated e-waste systems in emerging economies. Recycling of almost all of the generated e-waste is carried out by informal businesses. These businesses are often individuals, families or micro enterprises. Although frequently earning their living at the very edge of legality or even by applying forbidden practices, they often provide disposal and recycling services to society. However the informality of the sector places huge demands on data collection.

One important result of the study is that the current recycling system generates value through the reuse of whole items, components of obsolete items, and through the material recovery of the waste stream. The largest amount of material volume goes to the material recovery processes which are responsible for the largest share of the monetary value gained. The reuse of items or components is an important process of the informal recycling system. Businesses active in this field react very quickly to changes in market demand. In contrast, the material recovery processes are driven by the demand for secondary resources.
2. The second study analyses the well established e-waste recycling system in Switzerland. Material flows and indirect economic indicators were investigated and the results were compared to some of the characteristics of a similar European system in Norway. Both systems have achieved stable financing methods which enable the operating bodies both to organise an efficient collection and transport system, and to create incentives for privately owned e-waste recycling enterprises. The operating bodies decided in favour of an advanced recycling fee as a financial mechanism. Since coming into being, they have been able to continuously lower the recycling costs per PC. Today, both systems are able to adjust the collected fees to the actual costs for environmentally sound e-waste treatment. But the systems differ in their policies of calculating the total costs of the system. This has a direct influence on the cost to the consumers.

3. The third study introduces a dynamic model which allows stocks of electronic equipments as well as a generation of waste volumes in the future to be calculated. The empirical data used is from India. The stock of equipment is calculated for several phases, from first until final use. This cascade use is extremely typical for the use of durable consumer goods in developing countries and is introduced theoretically. The recycling part of the model distinguishes between the distribution of waste volumes to the informal and formal recycling sectors. The material is distributed according to threshold values for copper and gold recycling, which are the financially most valuable material flows of PC recycling. For both metals the informal recycling sector applies special recovery methods. By doing this they lose considerable amounts of materials and simultaneously emit environmentally hazardous substances. Formal recycling businesses have much higher recycling costs but reach far higher material recovery rates and are able to control their emissions.

By calculating several scenarios the study has shown that formal recycling businesses are hardly capable of squeezing informal recyclers out of the market. Due to very low material recovery costs of the informal sector, the formal sector only becomes active under very favourable conditions or with the aid of external funding. Prospects for the formal sector may arise if tasks are distributed. If this were to occur, the informal sector could provide services in the collection of obsolete equipment.

The presented models help to gain an overview of recycling systems or to increase their system knowledge. They can be applied to analyse a specific region or a particular recycling system. The complexity of the models increases. This allows the models to answer both, general overview questions -such as the current waste generation of a certain region- or specific questions -such as how to set a specific recycling fee.

The study on hand provides a methodological contribution to the combined assessment of material and financial flows. Furthermore, the study has investigates existing e-waste recycling systems with modified methodological approaches. The main goal was to understand some of the specific systems characteristics.
Zusammenfassung

Das Konzept der Kreislaufwirtschaft zielt darauf ab, die Ressourcenintensität menschlichen Handelns so zu gestalten, dass eineseits vermehrt erneuerbare Ressourcen einzusetzen, andererseits nicht erneuerbare Ressourcen durch Recycling möglichst lange im Stoffkreislauf zu halten.


Die Fallstudien wurden in der Stadt Delhi, in der Schweiz und mit Daten für ganz Indien durchgeführt. Alle Studien fokussierten auf das Recycling von Personal-Computern (PC).

1. In der ersten Studie wurden Felddaten in der Stadt Delhi gesammelt, um einerseits die beobachteten Recyclingmethoden zu erfassen, und um andererseits die anfallenden Mengen von E-schrott zu quantifizieren. Dazu wurde ein einfaches Materialflussmodell entworfen, das die Mengen an wiederverwendeten PCs, als auch die Recyclingmengen für die beobachteten Recyclingpraktiken während eines Jahres abbildet.


4 Zusammenfassung


Die Systeme beider Länder betreiben Finanzierungsmodelle, die sowohl den Aufbau von effizienten Sammel- und Transportstrukturen ermöglichten, als auch Anreize für ein privatwirtschaftlich getragenes E-schrott-Reycling geschaffen haben. Die regulierenden Organisationen der Systeme haben sich für eine Finanzierung durch vorgezogene Entsorgungsgebühren entschieden. Über die Zeit ihres Bestehens haben beide Systeme kontinuierlich die Kosten für das Recycling von PCs verringern können. Sie unterscheiden sich aber in ihrer Strategie für die Kalkulation der Systemkosten, was wiederum Auswirkungen auf die Höhe der Gebühren für die Konsumenten hat.


Das Untemodell für das Recycling bildet die Verteilung der Abfallmengen auf einen formalen und einen nicht regulierten, informellen Sektor ab. Diese Verteilung geschieht anhand von Schwellenwerten, welche für die beiden finanziell interessantesten Materialströme, Kupfer und Gold, gesetzt wurden. Für diese Metalle wenden informelle Gewerbe besondere Rückgewinnungsmethoden an, akzeptieren dabei erhebliche Materialverluste und setzen gleichzeitig umweltgefährdende Emissionen frei. Formelle Gewerbe haben erheblich höhere Kosten aufzuwenden, erreichen aber auch höhere Rückgewinnungsraten und setzen nur kontrolliert Emissionen frei.


Goal of this thesis

The overall goal of the doctoral thesis is to introduce material flow assessment and an economic evaluation of material flows as an analytical tool. The novelty of this approach lies not only in its application to waste recycling from electrical and electronic equipment in Delhi, Switzerland and India, but in particular, in the modification of the analytical tools to investigate these systems on different levels. This is achieved by a combined assessment of mass and monetary flows, an evaluation of derived economic indicators of a recycling system as well as the institutional setting of it, and by including financial parameters of specific stakeholders. These methods have been applied for both developing countries and countries currently undergoing economic transition.

A circular-flow economy intends to close material cycles of human activities. This principle is applicable for both, the use of material and the generation of energy. Non-renewable resources are intended to be replaced by renewable ones. This is particularly relevant to the energy market where, slowly but surely, a shift from fossil fuels to renewable energy sources is occurring. The best option for non-renewable resources which can not be replaced is the recovery of such material of the same quality from waste products. That is, if the recycled material can be used for the same purpose as in the original product -and if losses are minimised- the goals of a circular-flow economy can be said to have been reached. Several developed countries have decided to implement the concept of circular-flow economy as a long term goal and have acknowledged this, either in their legislation or policies (Switzerland\(^1\), Japan\(^2\), Germany\(^3\)).

Economic incentives concerning specific materials or products have been known to lead to the implementation of efficient material use and reuse. Too often, however, decisions in favour of a particular policy have led to an open loop economy. For financial, organisational or other reasons, it is difficult to close loops or make a shift towards more sustainable alternatives. This is particularly so in the case of the energy sector, in which economies previously relying on cheap fossil fuels now have to struggle in their effort to find/ develop mechanisms for the shift to renewable energy resources. Today, closing material cycles creates economic benefits through material recovery and job creation. In addition to this, it prevents the occurrence of negative environmental impacts from lost materials and certain polluting substances.

But such concepts have not, as yet, become popular – be it in developing countries or those in economic transition. This is partly due to the lack of positive examples provided by other countries, as well as to the fact that a circular-flow economy brings with it certain costs. Some examples have shown that a concerted and intelligent institutional and legislative setting leads to the development of a comprehensive recycling culture. Too often, however, it becomes a catch-22 situation! Consumer behaviour concerning waste disposal fails to change without those incentives which lead to a raised awareness of the value of waste. No recycler is prepared to invest in recycling facilities as long as the quantity of the waste generated is unknown. Similarly, no manufacturer is prepared to be responsible for a product beyond the point of sale, unless they can rely on a trustworthy waste managing system, supporting legislation as well as marketing benefits. Unless the volume of particular waste streams and their environmental dangers are quantified, it is not possible to regulate the various individual categories of waste streams.

\(^1\) Eidgenössischen Kommission für Abfallwirtschaft et al. (1986)
\(^2\) Ministry of Environment (2000a)
\(^3\) Kreislaufwirtschaftsgesetz (1996)
6 Goal of this thesis

Waste recycling sectors in countries such as India or China are often dominated by informal economic structures which lack standardised accounting methods. Yet, although the waste load is not systematically monitored, the amount of future waste output can be defined by means of social consumption patterns. With the help of such patterns – both past and present – the proposed assessment design will enable future predictions concerning waste amounts and the size of waste-processing industries to be made.

Such methods can not only be applied to capital goods (such as buildings, ship vessels or industrial plants) but also to consumer durables (such as cars, furniture, printed products or consumer electronics). The origin of goods would predetermine the nature of the recycling process. Thus, industries might recycle themselves by means of reassembling processes, or specialised recycling industries might emerge through preceding collection and transport services. This thesis applies material flow assessment methods and economic evaluation of material flows to recycling processes for waste for electrical and electronic equipment (WEEE). The methods, however, can be applied to numerous other goods.

The following hypothesis can be formulated:

The combination of material flow assessment and economic evaluation:

I. Creates a comprehensive assessment of important technical and economic processes of the production, use, reuse and disposal of electrical and electronic equipment, including that of the informal sector.

II. Detects driving forces related to production, use and disposal of materials.

Allows for the formulation of recommendations concerning how to establish and design recycling systems which benefit from informal and formal recycling systems.

Comprehensive models will help to understand and evaluate present and future situations. Information on the material composition and the existing recycling practices will produce reliable information on the environmental threads of electronic-waste recycling systems, no matter whether formal or informal. Furthermore, the economic analysis of the material flows will give insight into the generation of value along the processes investigated.

Consequently, the development of formal models will improve the ability:

III. to better cope with bad data quality and uncertainties.

IV. to support scenario development and calculation.

The overall research questions that arise are thus:

How can the complex reality of a WEEE recycling system be depicted in a generic model?

(Question of how to depict material flows accurately)

How can the quantities and environmental impacts of the investigated WEEE recycling systems be measured?

(Question of how to quantify the material flows)

How can measures be identified which guarantee certain system developments?

(Question of how to steer the system in one direction)

How can models of different WEEE management and recycling systems be compared?
Structure of this thesis

The thesis is divided into two main sections:

Part 1: The chapter ‘methods used and proceedings’ places the thesis in particular scientific field and gives reasons for the particular research path chosen. This is followed by extended abstracts of the original publications and a general introduction of the topic WEEE. The general introduction gives an overview of the whole topic of e-waste, its recycling and its implication on a ‘global waste market’. At the end of part one, conclusions for the whole thesis are given.

Part 2: consist of the three original publications with the titles:

2. SWICO/S.EN.S, the Swiss WEEE recycling systems, and best practices form other European systems
3. Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies.
Methods used and proceedings

The starting point of the dissertation project was the belief that policies applied to the management and recycling of WEEE in Europe and other OECD countries have provided valuable information which can be of use to other countries. But the lessons learnt can not simply be transferred, especially to countries in economic transition, which often already have their own e-waste recycling systems. Such systems - which have emerged based on market mechanisms - are mostly unregulated and evolving rapidly. They do, however, face pressure, not only from national and international regulations, but also from negative publicity and international campaigns, as well as from the lack of confidence shown by original equipment manufactures and industry associations. Added to this comes the pressure created by the presence of environmental hazards which are currently reaching intolerable levels. So much so, that the Chinese authorities calculated environmental pollution as having caused costs equivalent to 3% of the GNP in 2004. The international cooperation and trade of producers and recyclers is growing, a fact which puts pressure on governmental bodies to make guidelines for such relationships. Some of the lessons learnt in OECD countries can be transferred and can facilitate the setting up of recycling systems, creating transparency for all stakeholders. To do this, however, a systemic understanding of e-waste recycling - including physical, economic and organisational parameters - has to be increased.

Scientific community and used methods

In this thesis three case studies are presented. The main methods used in the individual studies are: material flow assessment, expert interviews and literature research. The methods are used for the assessment of complex waste streams through model frameworks.

Model frameworks for integrated assessment

A comprehensive analysis of technological development can be based on model frameworks of integrated assessment. They can be differentiated into two groups: (i) frameworks driven by assessment models and (ii) frameworks driven by models of the underlying cause effect chains. Both groups provide indicators for environmental, economic and/or social impacts of technological change and can, thus, be used for a sustainability assessment (Rotmans 1998, Asselt van and Rijkens-Klomp 2002, Seppelt 2003).

Model frameworks driven by assessment models usually start by defining a set of goals and indicators to measure a system’s performance with respect to these goals. More recently, given indicator sets for sustainable development have been used. Some model frameworks define procedures to calculate aggregated indicator values and to generate an overall index (assessment models). To estimate indicator values for the assessed system (e.g. a recycling scheme), various sub-models are introduced (e.g. models to estimate CO2 emissions or factor income). In general, these sub-models are set up and work independently and their results are brought together in the overall assessment model. Thus, they do not provide a consistent model of the underlying cause effect relations (e.g. how CO2 emissions and factor income are interrelated). In consequence, this group of models is apt to evaluate given options, but fails when attempting to analyze systems with the purpose of better understanding how they work and where to intervene.

* Neue Zürcher Zeitung, 9./10. September 2006, "Hoher Preis für Chinas Umweltsünden"
Model frameworks which are driven by the underlying cause effect chains have the advantage of depicting a real world system based on system knowledge. They are mostly based on input output approaches such as Input-Output Analysis (IOA), Material and Substance Flow Analysis (MFA and SFA) or Life Cycle Analysis (LCA) (Heijungs 1997, Heijungs and Suh 2002). A large body of literature shows applications of economic IOA in this field. The core model in these studies is an input output model in monetary units. IOA was founded by Wassily Leontief in the 1930s. The method depicts how industries are interlinked and trade, and how these activities influence the demand of labour and capital within a national or regional economy. Many studies have extended the IOA by coefficient matrices to measure impacts on the environment (emissions or resource consumption) or on society (e.g. employment).

Most studies focus on selected indicators such as emissions of carbon dioxide, energy consumption or land use (Meyer 1998, Spangenberg 1999, Meyer 2000). These studies are in the majority built upon national input output tables. They are, therefore, tied to classification schemes of national accounting and exclude the informal economy (e.g. non-market oriented production of private households). In countries of economic transition or developing countries, the proportion of the gross national product created by the informal economy can reach substantial levels (Schneider and Enste 2003). Input output models of material flows in mass units (material flow assessment models) are a suitable means for depicting some of the services provided by the informal economy. They are usually built with a bottom up approach and researchers are free to choose an appropriate system definition -including the informal economy and ‘material stocks’ in private households if necessary. Yet, few material flow models include economic indicators. It is only in the last few years that attempts to extend material, substance and energy flow models have been developed in a way as to deliver values for the criteria of the economic assessment. Such approaches have been, from the perspective of environmental management, a combination of LCA and Life Cycle Costing (LCC) (Norris 2001, Senthil et al. 2003). The micro-economic view can be described by a combination of material flow analysis and economic IOA (Duchin 1992, Kytzia and Lichtensteiger 1998, Pesonen 1999, Kytzia and Faist 2002, Nathani 2003, Kytzia et al. 2004, Kytzia 2005).

Wrinsberg et al (2002) classified several quantitative methods according to the definition of the investigated system and the distinction of tools which purely describe the physical behaviour of the system or which include monetary information (Table 1). According to the source, Life Cycle Costing, Total Cost Accounting, Cost Benefit Analysis and monetary IOA are tools which are able to take into account both, physical and monetary information of a investigated system.

<table>
<thead>
<tr>
<th>Types of system definition</th>
<th>Tools with purely physical information</th>
<th>Tools with physical and monetary information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function-orientated</td>
<td>Life Cycle Assessement (LCA), Material Flow Accounting with hidden flows</td>
<td>Life Cycle Costing (LCC), Total Cost Accounting (TCA), Cost Benefit Analysis (CBA)</td>
</tr>
<tr>
<td>Region-orientated</td>
<td>Environmental IOA</td>
<td>Monetary IOA</td>
</tr>
</tbody>
</table>

Source: modified from (Wrinsberg et al. 2002)
 Whereas the first three tools mentioned above are function-orientated, the IOA focuses on the industry linkages of a specific region. LCC is a tool suitable for the total cost calculation of a product, including internal and external costs. TCA is a tool which looks much more at the long term cost development of a firm, including externalities. CBA is a widely applied tool which describes the costs and benefits of an investment or a policy in monetary units and states whether the overall sum is positive or negative.

**Material Flow Analysis**

Material Flow Analysis (MFA), sometimes called Material Flow Assessment or Material Flow Accounting, is a generic term for the analyses of matter flows, which are chemical elements, compounds, materials or commodities. The methods are based on the concept of material balancing representing the law of material conservation. MFA can be placed in the field of Industrial Ecology (Jelinski et al. 1992). It provides knowledge of a system which is currently under study, in line with the concept of industrial metabolism (Ayres 1989). Industrial Ecology is a young discipline, still in its ‘teenage years’, but has the potential to initiate and influence a technological change towards sustainable production patterns (Harper and Graedel 2004). Industrial Ecology is made up of a variety of methodological approaches and concepts. The methodological backbones of Industrial Ecology are MFA methods and economic Input-Output tables. MFA has been used to investigate pathways of materials through anthropogenic systems, providing a comprehensive picture of production, consumption and deposition in a studied region. These methods can be fully exploited when applying mathematical formulation and modelling as suggested by Baccini and Bader (1996).

In general, three different types of MFA can be distinguished:

(i) Substance Flow Analysis (SFA), which is primarily used to relate critical emissions of substances to processes, products and material inputs in the system;

(ii) Process-based MFA, which is primarily used to analyze specific questions on resource and waste management; and

(iii) Industry-based MFA, which is a tool to assess the environmental impact of economic development by analyzing the total material throughput of a system.

Another distinction of MFA models can be made by their driving forces. In most cases, material flow systems are driven by demand for goods either from consumers or producers (Kytzia 2006), and are therefore input driven.

In the case of consumer durables, process-based, dynamic, stock-driven MFA models have been applied (Redle 1999, Kleijn et al. 2000, Binder et al. 2001, Elshkaki et al. 2004, Müller et al. 2004, Elshkaki et al. 2005, Müller 2005, Wittmer 2006). In these MFA models, the demand for the service they provide is met by the goods in use. They show that consumer durables can have a retarding effect on emission control. For example, Kleijn et al. (2000) described an emission peak of chlorofluorocarbons (CFCs) some ten years after these substances were phased out by national regulations caused by emissions from refrigerators coming to the end of their life cycles. As the life span of durable goods is generally longer in developing/transition countries than it is in the industrialized world, this issue is of major importance. The corresponding material flow system can be seen to be driven by the in-use stock of goods. The development of this stock triggers both input and outputs of material flows. A stock-driven model; therefore, provides a better basis from which to depict possible pathways of future development.
Several studies promote an extension of MFA models through an economic dimension. A comprehensive study (Kytzia and Nathani 2003) focuses on process-based MFA models with integrated economic models, or economic modelling frameworks using MFA as sub-model. The study shows that the decision of whether an economic model or physical model should be used is more influenced by the preference of the researcher than by a standard set of criteria. The study promotes "developing a ‘common language’ in mathematical formulation as well as underlying theoretical concepts, eventually resulting in a toolbox of well defined models with clearly specified interfaces." (Kytzia and Nathani 2003).

An example of an MFA model combining physical and monetary information can be seen in the case study of wood flow in the Swiss mountain region of Appenzell/Ausserrhoden, which combined a MFA model with an agent analysis (Binder et al. 2003). The stakeholder interests, which Binder et al. included into the MFA model, were predominantly of an economic nature. The results of the studies showed that not the physical production of wood limits the utilization, but wood prices and the institutional power balance of key stakeholders.

**Material Flow Analysis for developing countries and countries in economic transition**

Some comprehensive studies have shown that Industrial Ecology methods can provide strategic planning information in developing countries: Erkman and Ramaswamy showed that MFA provides a valuable framework for introducing principles of Industrial Ecology to countries in transition. They present various case studies of resource flows caused by different industries in India (Erkman and Ramaswamy 2000). Chiu and Yong underline with their study the need and potential to introduce the principles of Industrial Ecology on a strategic level. They suggest implementing eco-industrial development in Asian developing countries in order to prevent many of the mistakes developed countries have experienced during their industrialization (Chiu and Yong 2004). Iles analyses some of the factors which shape the e-waste recycling chain across Asia. He takes e-waste as an example to show that, from an ‘environmental justice perspective’, the social and environmental impacts stemming from each stage of the life span of products have to be considered. He argues that

"In an era where not only neoliberal ideologies dominate the global economy, but consumers, governments, and companies are ill-informed because of the distances pervading the global production system, more is needed than simply a global ban on e-waste trade or boosted recycling efforts. Action needs to aim at the underlying causes of e-waste impacts, namely poverty, lack of industry accountability, and weak regulatory activism. Only then can policies and institutions effectively address e-wastes as transnational technology and material flows."(Iles 2004).

Kituyi shows that there is a need in developing countries to address the social, institutional and political preconditions as well as capacity building for life cycle thinking. He illustrates the process by outlining the LCA for a sustainable char coal production in Kenya, one of the most heavily deforested countries in Africa (Kituyi 2004a, b).

**Expert Interviews**

Expert interviews have been used extensively during this study. Following the structure of an expert interview, the main motive for interviewing the expert is to investigate his subject knowledge, rather than to find out details which would be of public interest (Mieg and Brunner 2001). Although the interviews should technically follow a manual, they were often held in an open form, to give the interviewed person the freedom to add important points which were not covered by the interview questions.

Experts are either:
• "Persons who somehow carry the responsibility for the layout, implementation, or monitoring of problem solving processes, or
• Persons who have a privileged access to information about groups of persons or decision processes" (Meuser and Nagel 1991).

The above-mentioned definitions of experts are applicable to all interviewees consulted in this study.

Literature study
The literature in this thesis was drawn from various sources. They are listed in decreasing order in their frequency of use:
• Publication in peer reviewed scientific journals
• Conference proceedings
• Books, reports
• Online resources
• Technical fact sheets, legal texts, acts

Proceedings
The author of this thesis approached the task in two ways: (i) examination and investigation of existing waste recycling systems, and (ii) theoretical development of assessment method

The common denominator of the thesis is the application of process-based MFA and an economic evaluation of material flows to WEEE recycling systems. Figure 1 summarises the different levels of analysis which also find their analogy in the three publications. Each individual study consisted of an empirical part, during which an existing e-waste recycling system was investigated, and a theoretical part, during which assessment methods were modified or newly developed.

Another common feature of the three studies is the use of a Personal Computer as a functional unit or tracer item through a chain of processes, comprising use, reuse, recycling and final disposal. Three publications have been produced, each taking a specific region as a focus for a case study within which the recycling sectors of PCs are assessed: The city of Delhi, Switzerland and India.
As the method focuses on system comprehension, rather than on environmental impact assessment, it is apt to reveal options for future development at an early stage of decision making. The MFA models follow an analysis of the economic flows—the focus being more on the decision making process than environmental impact assessment. There may be, amongst certain interest groups involved in the recycling of Information and Communication Technology (ICT) products, certain reservations concerning environmental impacts, but the underlying economies have shown in many ways that material values, rather than environmental impacts, have far greater influence on the decision making process for specific recycling systems.

The entire research period of this thesis was guided and influenced by the above mentioned iterative process. A textual representation of Figure 1 follows:

**Analysis of existing WEEE recycling systems**

**Paper I**

A process-based, static MFA model was applied in the first case study: Delhi. It was carried out in close cooperation with the Swiss Federal Laboratories for Materials Testing and Research (EMPA). EMPA launched the project 'knowledge partnership in e-waste recycling' with the aim of assessing and improving electronic waste recycling systems in different parts of the world. This was done by analysing existing recycling systems and by exchanging knowledge on recycling techniques and frameworks. Under the umbrella of the Advisory Services in Environmental Management (ASEM) several city assessments were conducted. ASEM is a joint program of the German Technical Cooperation (GTZ) and the Indian Ministry of Environment and Forests. The city assessments focused on:

- Identification of recycling processes applied in the informal sector
- Development and testing of a city assessment strategy for the WEEE recycling sector

Both tasks needed a framework to record and document the knowledge gained in this assessment and to structure the collected data systematically. The collected data only covers the flows in the city state Delhi in 2003.

**Development of assessment methods**

In most cases, material flow systems are driven by demand for goods, either by consumers or producers (Kytzia 2006). In the first and second paper, such an input/output driven model was applied. The knowledge of sales and recycling data, either for one single year or over a certain period of time, was used to investigate flows and stocks of a predefined MFA system. The MFA systems consist of a chain of processes which have been observed during field investigations. The applied models were used to estimate e.g. future WEEE loads or individual waste fractions.

In the first study a static process-based MFA model offered the most suitable method for depicting the material flows of the PC recycling industry, including reflow patterns for re-use and refurbishing. The model enabled the researcher to structure the gained field information in a systematic way. The whole range of applied recycling techniques and the quantified material flows were condensed into a MFA snapshot of one single year. This systematic overview subsequently allowed for the calculation of the monetary flows by multiplying the material flows with the material value per weight. This
study also included an evaluation of the monetary profits from the reuse, refurbishing or recycling industry.

Paper II

In the second study the Swiss and the Norwegian WEEE recycling systems are the objects of investigation. Both systems are operational, have achieved an almost 100% coverage of the WEEE waste stream and have built up financial reserves allowing profitable recycling without governmental interventions.

Obsolete PCs are collected under the SWICO system (Swiss Association for Information, Communication and Organisational Technology). They are dismantled and pre-processed by Swiss recycling firms which sell their products for final treatment or disposal, either in Switzerland or to other European counties. The Swiss recyclers are reimbursed for their disposal services by the SWICO system. SWICO charges consumers at the point of sales of a PC for the operational and recycling cost of the system. The analysis focused on the development of PC sales over a specific period of time, the resulting waste volumes, and the development of fees charged to the consumers.

Norway also charges consumer fees, but in contrast to the Swiss system, it reimburses recyclers according to the revenues gained from material recovery. As both the Swiss and Norwegian system are similar but reveal some differences in their financial structure, the comparison gives an interesting insight into how systems have evolved and how efficient they are.

The development of an existing recycling system was documented by applying the same methods as used in study one over a consecutive number of years. Depending on the life span of the equipment, the input of products of a specific year determines the waste generation of a later year. In contrast to the first study, an essential part of which was the exact quantification of each individual material flow, the second study put a greater focus on the institutional setting of those recycling systems which have been in operation over several years.

In order to analyse the financial structure of such a system, the development of consumer fees for recycling, the so called advanced recycling fee (ARF), was analysed. Ideally, this derived financial parameter reflects the real costs for recycling of a specific product, including the cost for collection, transport, recycling and the system's administrative costs. Assuming such an ideal situation, the system performance and efficiency was analysed. Furthermore, forecasts of the future system behaviour were made describing how much material needs to be processed and how fees should be adjusted.

During the second study, it became apparent that making an exact calculation of the cost of recycling WEEE, as well as of specific items of the waste flow, is a difficult task. Not only do recycling techniques evolve rapidly and have a tendency to become more cost efficient over time, but exact costs are often not disclosed by companies and can; therefore, not be assessed directly. But the investigation into how consumer charges have developed over-time revealed that a derived indicator (ARF) can be helpful in detecting some important system characteristics. This knowledge was used in the third paper, in which two metal flows were identified as system indicators.
Paper III

Paper three looks at the future development of PC saturation levels in India and the consequences for a recycling market. The model does not try to forecast future development of PC stocks. Rather, it introduces a tool which depicts a certain stock development observed in the past, and from this, predicts future scenarios for stock developments. For the India study, the suggested model with three stocks was condensed into one single stock. This was done in order to match available empirical data with the parameters required in the stock model. A commensurate number of conditions determine the PC life-span, which was crosschecked with literature data and expert knowledge. A more detailed analysis of the Indian PC stock could be made if more detailed stock data were available.

The same model analyses the recycling of PC leaving the consumer stock. The focus lies in the distinction between formal and informal recycling activities, depending on economic threshold values. These threshold values were introduced for two metals, gold and copper which are the main economic drivers for PC recycling and, thus, seen as system indicators.

In the case of formal and informal recycling, the study differentiates between crude recycling methods – as currently taking place in India – and state of the art recycling options – as currently available only in OECD countries. According to the particular threshold value reached, an obsolete PC may be given to either of the two sectors.

Paper three introduces a dynamic, stock-driven model to estimate the future development of PCs stocks and uses this information to derive the distribution of recycling volumes in two different sectors: the informal and formal recycling sector.

The model introduces a process chain of three consecutive stocks which represent the cascade use of PC from first users, second hand users and a third hand user or storage period. A given stock development determines the life-span of the individual items in the stock, as well as the variations of input and output flows.

How much material enters the recycling phase is determined by the in use stock and the life-span of PC. The model calculates the mass flows on two levels: the total PC mass balance and the mass balance for individual metals. Such an approach was chosen because recyclers base their decisions on economic factors – mostly the revenues they can gain from material recovery. The introduction of activity levels for formal and informal recycling – depending on the revenues recyclers can gain – allows for the inclusion of stakeholder information, in this case recyclers, into the MFA model. According to threshold levels the material flows become deviated to one or another process. Thus, the material content and value of two metals are the parameters which determine the activity of informal or formal recycling. This approach depicts some elements of the real world situation of the waste recycling sector in developing countries, which can not be described by an MFA model limited to the analysis of physical flows.

The whole study was lead by the investigation of existing waste recycling systems. In an iterative process the used method in one study was adjusted according to the requirements of the subsequent study. The physical MFA model proved to be the most elementary method of system investigation. The simplicity of the method supported a smooth running of the field work and clear communication of the scientific research in an intercultural surrounding. The extension for certain explicit economic parameters was done in cooperation with the Indian partners and required very little monetary information, namely only the price the informal and formal recycling sector pays for the waste material.
The chosen methodology is not the only one to be able to depict physical and monetary information. A monetary IOA or the combination of function-orientated methods, such as LCA and LCC, are certainly also strong tools to investigate physical and monetary flows. However, the requirements for economic data of an IOA or a LCC would have been beyond the scope of this thesis, particularly as detailed economic data in the informal sector is nonexistent. Generally, in the waste sector, monetary information is kept secret by various stakeholders, both in developing and industrialised countries, which makes the collection of monetary data even more difficult. An LCA of EEE including the evaluation of environmental impact as well as economic drivers is valuable information for decision-makers. But life cycle inventory data of developing countries or CET, which are needed to carry out the LCA, do not exist. Some first attempts to collect life cycle inventory data for China and Africa are currently being done, which leads us to hope that LCA will also become a tool in CET countries.
Extended abstracts of the individual studies

This section consists of extended abstracts of each paper. For each publication the case study including the system picture, the methods applied, the results as well as the conclusions and discussions are summarised.


Case study and research motivation

Paper I applies a qualitative system analysis of the PC recycling system in Delhi, India, and quantifies the material flows for 2003. One of the challenges lay in the task to assess a recycling system which is entirely carried out by the informal industry sector. Informality means that the businesses involved do not apply standard accounting methods, neither for materials nor for money. The businesses are in the majority not registered, and some even work illegally. In order to gain an overview of this sector’s activities as well as collect data to quantify the material flows involved, several field studies in Indian cities were planned.

One of these cities was the national capital territory of Delhi state, which spreads over an area of 1,485 km², and which also forms the physical system border of the model applied in this study. Delhi state is a very populated area and has one of the highest rates of PC per capita in the whole of India. It was, therefore, chosen for a first city assessment. An Indian consultancy was appointed to identify and describe WEEE recycling methods in general. They also collected data to quantify recycling volumes through questionnaires, participatory observations and transect walks.

Figure 2 Process chain of static MFA model Delhi in 2003
Methods

Based on the qualitative description of recycling processes and quantitative data from the city assessment, a first sketch of a static material flow assessment model was designed. It depicts the entire life cycle of the tracer PC, from production through sale and consumption - including reuse and refurbishment - to the material recovery in the mainly informal recycling industry. The definition tracer item, in this study called PC, includes a processing unit of a standard PC-terminal, a cathode ray tube (CRT) monitor, keyboard and mouse, and a printer and weighs on average 27.2 kilograms.

The field work included interviews with the relevant stakeholders, transect walks and literature study, which was followed by a software-supported MFA of the whole life cycle chain of the tracer item. Through these investigations the system knowledge was widened as well as missing data were collected. It enabled the researcher to draw a MFA recycling system for PCs in the city of Delhi. The model quantified the flows of materials and calculated the monetary values of material flows the year 2003.

The process chain is shown in Figure 2 depicts the input driven MFA used in this study. The material inputs in the system determine all flows and stocks of the entire system. By applying the ‘market supply method’ (also see page 52) two scenarios were calculated: the sales form 1998 (five year scenario) and 1996 (seven year scenario) equal the volumes of obsolete PC in 2003. As the field study allowed interpolation for certain flows, the researchers were enabled to test the plausibility of the model calculations. The total mass of the MFA model is balanced out, only the process ‘Consumer’ builds up a stock and is, therefore, a sink of PCs.

Results

The study revealed that the life-span of a personal computer has considerable influence upon the system, most notably in the following two aspects: (i) a prolonged life-span creates value by means of refurbishing and upgrading activities and (ii) it slows down the flow rate of the whole system. This is one of the simplest ways of preventing an uncontrolled increase in environmentally hazardous emissions by the recycling sector. Reuse and refurbishing industries create a considerable amount of material reflow. The field observation which confirmed by the study and accounted for 100-200 monitors and 300-350 PC-terminal refurbishments per day. The three largest volumes produced from the material recycling are in decreasing order glass, ferrous metals and plastics.

If the economic revenues are analysed, the gains from precious metal recycling outnumber all other processes. Gold and copper recycling together account for over 85% of the value from recovered materials. The value of both metals from recycling industries is more than double the revenues which are gained from reuse or refurbishment.

Discussion and conclusion

PC-terminal and monitor refurbishment offer attractive business opportunities. However, these activities are constantly under change as they react very accurately and quickly to the demands of second hand markets. The data which have been collected for the year 2003 can, therefore, not be used or extrapolated for other years. Only the market demand decides whether a product is offered or not. One can conclude that the refurbishment business sector is adjusting continuously in size of employees as well as applied techniques.
In contrast, businesses which execute material recovery from PCs can build on revenues which can be gained from producing secondary resources. As gold and copper offering the biggest share of revenues those metals can be seen as drivers for all recycling activities. Revenues of the business involved depend on the content material of interest in the waste stream, the applied recovery techniques and the prices of commodities. The material recovery sector is, therefore, not as susceptible to technical changes as the refurbishing sector, as long as it does not affect distinctively the material composition of the products.

Although the data base was not optimal, the combination of a systematic analysis of material flows and economic values, as well as the field assessment showed the potential to generate robust results. The model created allows the researcher to plan future assessments in a more focused way. The methods were used with modification in a second city assessment in Bangalore in 2005. The not yet published work depicts also with a static MFA model, several years of PC recycling. Another research step will be the development of a dynamic model. Such a dynamic model would make the integration of data possible to describe (i) the continuously changing material composition of EEEs and (ii) the different life-spans of EEEs including changes in consumer behaviour.

**Paper II: SWICO/S.EN.S, the Swiss WEEE recycling systems, and best practices form other European systems.**

**Case study and research motivation**

WEEE recycling is Europe is presently a very 'hot' issue. This is mainly due to two facts: Directives from the European Union have to be implemented in member state countries, and some European countries already have WEEE recycling systems which imply the existence of working recycling infrastructure.

The **EU Directive on waste electrical and electronic equipment (WEEE)**(EU 2002a), has been in force since August 2004 and will continue to dictate national implementation beyond the passed deadline of August 2005. This directive put pressure on the member states to create incentives for WEEE recycling within the national border. The second directive, **EU directive reduction of hazardous substances (RoHS)** (EU 2002b), was adopted and came into force in July 2006, focuses more on the production side. It forbids or restricts the use of certain substances in new EEE, both, whether produced in the EU or whether imported to one of the member states.

The second fact is that some European counties have built WEEE recycling systems prior to the Europe-wide legislation being passed. Consequently managerial knowledge of how to design WEEE systems and recycling capacities have been built up. This leads to situation in which these countries can offer their expertise and provide business solutions, but also at the same time have to be much more competitive than before.

Switzerland is one of those countries which has, since 1991, two WEEE management systems in place. They are voluntary systems but cover almost 100% of the waste stream. Norway is another country which has one WEEE management system operating since 1999. In Paper II PC sales data and recycling data taken from a consecutive number of years in Switzerland was analysed. The development of the fees charged to consumers has been traced over the same time period. The development of waste volumes and fees over time in Switzerland was compared to the tendencies of the Norwegian system.
Today, these systems can look back on a history and knowledge base how to set up WEEE recycling system and how to run it. But they are confronted with a great number of competitors, both management systems and recycling facilities, which start to operate under different, more advantageous situations than they did. This is due to record high metal prices, also resulting in much higher prices for secondary resources such as WEEE. It makes the WEEE recycling much more attractive to private enterprises than in 1991 or in 1999. Another condition which puts pressure on the competitiveness of WEEE systems is the sudden increase of material created by the legal obligation of the EU Directive on WEEE. This 'economies of scale' effect cuts down the cost for recyclers which start to operate today, compared to those which built up their facilities during a time without such strong legal backing.

The challenge of this study was to evaluate the cost effectiveness of two systems, both complying fully with the requirements of the directive and as well as with high environmental standards.

Methods

Paper II also applies the 'market supply method' over a consecutive number of years. The sales date of one year was used to calculate the volume of WEEE in a later year. To calculate the annual flows of PC waste from sales data, parameters such as increase of population, medium weight of a PC and medium life-span of a PC were kept stable. This was done over a time period of 37 years. Hence, the model is static input driven model which applies the same method to discrete time steps.

The study uses the desktop terminal of a PC as functional unit for the MFA without the consideration of monitors. The available date for this study was relatively good. The import and export data over 22 years were compared to producer sales data of PC in Switzerland, which were collected by a consultancy company through standard questionnaires. As Switzerland imports almost all PC, the comparison between sales data and net imports are adequate. To estimate the resulting volume of WEEE a medium life-span for a PC was assumed. The amount of expected WEEE equals the number of sales before a particular number of years, which is the medium life-span. In order to anticipate future volumes of PC wastes, the penetration rate of PC per capita in Switzerland was forecasted until 2020. In two scenarios the penetration rate was: first kept stable on the level of the year 2005 and secondly increased by 2% per year. The according annual sales of the two scenarios were calculated inversely.

As the recycling system allocates the costs for the recycling and management of WEEE according to own standards on the products, a system comparison is difficult. Often the systems collect fees upfront, also often called advanced recycling fee, and reimburse recyclers depending on their cost of recycling. Under some systems, the revenues recyclers can gain from material recovery are taken into account explicitly, whereas other systems apply other reimbursement methods. Despite these differences in cost models, expert interviews produced reliable information for the development of the costs over the investigated time period.

Figure 3 depicts the material and financial flows of the WEEE recycling system in Switzerland.
Results

The qualitative system analysis showed that the WEEE recycling system implementation was successful and achieved an almost complete coverage of 100% of the waste stream.

The quantitative system analysis allowed the detection of an almost saturated PC market in Switzerland in terms of PC per capita. Ex post one can conclude that the volumes of PC entering the recycling system will, in the coming years, still increase which is due the fact that the high saturation level was reached just recently. Also ex ante an increase in waste volumes at least until 2012 was revealed by the scenario calculation.

The cost for PC recycling has decreased due to a period of increasing financial reserves, increased efficiency in recycling, an increase of recycled volumes resulting in an 'economy of scale' effect. The financial mechanism as it is presently applied under the Swiss system runs the risks to be underfinanced in some time to come.

Despite applying different financing mechanisms, the Swiss and the Norwegian system shows a similar development of their fee charges to consumers.

Discussion and conclusion

During the setting up of the Swiss system, many pragmatic decisions had to be made, one of which resulted in the introduction of an advanced recycling fee on sales for each electronic item. The reimbursement for recyclers in set depending on the offers from recyclers. The Norwegian system applies the same fee to consumers but reimburses recyclers depending on several parameters: one of which are the revenues recyclers can gain from material recovery.

The choice for a certain financial mechanism is mainly a business decision. Previously the systems as well as the recyclers in Europe have been under less competition as the protection of national 'waste markets' was still alive. In the future, Europe-wide competition will most likely decrease the cost for consumers. This will be the case if WEEE management systems become more efficient or recyclers lower their demand on additional funding, e.g. through an ARF. This can happen if the metal prices stay at current high levels.

A closer look at economic entry levels for recycling is an aspect which has been elaborated during the next phase of this thesis.
Paper III: Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies.

Case study and research motivation

Emerging economies have a backlog demand for ICT equipment, as they need such infrastructure for their economic development. Due to economic growth, they are able to increase the personal computer penetration rate per capita rapidly. Such an increase of equipment will result in dramatically increasing waste volumes in the near future.

Presently, the waste processing and recycling from PCs is managed by informal recycling businesses, which carries high risks of environmental and occupational hazards and also loses valuable materials by applying inappropriate techniques. The impact will be multiplied if the whole waste volume will be absorbed by the informal recycling sector.

Formal recycling industries which comply with national environmental, occupational and working safety regulations have much higher costs for recycling. They must compete with the informal businesses for waste material.

The Indian recycling system seems to evolve rapidly as presently some developments indicate that formal recycling will either appear as a side activity of other business or be a result of upgrading informal activities. The former is a similar development as it has happened in developed countries where existing metals processing businesses embarked to offer WEEE recycling services, the latter is presently encouraged by organisation for development cooperation (such as the German Development Services GTZ). The sheer size of the Indian economy is also a reason why own Indian standards for WEEE recycling will be set and create their own market incentives and dynamics.

The challenge for this study was to develop a model which can depict some of the stakeholder decisions. As mainly economic factors drive the WEEE recycling in India, the focus was laid on the recovery of gold and copper.

Methods

The model presented in Paper III is a dynamic, process-based MFA model for PC recycling in India. This method was chosen for its ability to give a systematic overview of the system by describing and simulating the material flows of the whole system. It includes three sub-models of the processes: consumption, trade and metal recovery (Figure 3).

The sub-model describing consumption is a stock-driven model in which information of the PC stock as well as sales data of PCs in India were used for calibration. The consumption consists of a variable number of consumer stocks. They represent a consecutive chain of $n$ users which is characteristic for the use of ICT in countries in economic transition.

In the first step the raw data of the investigation was complied from PC/per capita data, and sales data over a consecutive number of years. The medium life span of PCs was then fitted to these data sources. In a second step, the development of the PC stock was estimated until 2050. A presumed stock development, along with the medium life span from step one, was taken to calculate the magnitude of the flows shown in Figure 3. Hence, the model can be described as a stock driven model.
Extended abstracts of the individual studies 25

The sub-models describing trade and metal recovery are closely linked. The first represents the trading pattern present in the Indian PC reuse, refurbishing and manufacturing sector, including the separation of material into recycling fractions. The second: metal recovery, focuses on the recovery of copper and gold in the informal and formal recycling sector. The two metals are the main economic drivers for PC recycling.

Recycling sectors, in this model the informal and formal sector, compete for waste material. To include this fact in the model, economic threshold values were introduced which, depending on the concentration of each metal and its world market price, determine the allocation to formal and informal recycling.

The sub models are not entirely independent. It was assumed that the recycling of the two metals within a specific sector may also determine how much of the other materials are recovered. Formal recycling reaches higher recycling rates, as some of the materials contained in PCs can be used as fuel or flux material. Consequently, the activity level of a certain process in metal recovery influences the total amount of the recycling flow in trade (Figure 3).

All parameters used in this model are time dependent. Many of them are kept constant but some selected ones have been varied over time, such as the stocks of PCs, the medium weight of a PC and the development of prices for gold and copper. The functional unit in this study is a PC desktop terminal without consideration of monitors.

Results

With the available data on PC/per capita and sales, only a single stock model was used for calculation.

The model produced three results, one for a base line, and two for scenarios: a price scenario and a threshold scenario. In the base line, it was assumed that the prices for gold and copper would not rise, but remain at a moderate value until 2050. The threshold values were set according to the recycler's payment for obsolete PCs. The PC weight and concentration of copper and gold was set according to measurements made by the authors. After calibration, it became clear that a PC medium life span of eight years fitted best to the stock and sales data. This medium life span also corresponds to reviewed literature data.

In the price scenario, it was assumed that copper and gold prices rise by 100% when compared to the copper and gold prices of the base line. In the threshold scenario, the entry level for formal recycling was lowered by 50% compared to the entry level of the base line.

Compared to the base line, the other two scenarios only show a slight increase of gold recycling in the formal sector. For copper, formal recycling only increases slightly in the threshold scenario, but it does not show any increase in the price scenario (always compared to the base line). In comparison to the base line, the total recycling volume under the price and threshold scenarios only increases slightly. This is due to the unchanged level of informal recycling which results in high copper and gold losses. The losses of gold and copper are higher than all the metals recovered through formal and informal recycling.
Discussion and conclusion

The model has shown that detailed information on the reuse volumes per time, on medium life span of reused products or on the amount of reused appliances from consumers is necessary if a model is to be calibrated with several consecutive numbers of stocks.

In all three scenarios, the calculation has shown that formal recycling will not become strong enough to squeeze informal recycling out of the market. An immediate leap from completely informal PC recycling to high standard material and energy recovery will fail, it being too expensive. Only under very favourable conditions or additional payments in the form of subsidies, might such a development be successful. Such strategies need further investigation. This means that policy makers and stakeholders should be considering other strategies which not only attempt to improve the recycling rates of the informal sector but also decrease negative environmental emissions. A means of doing this would be through informal recycler training programs, with a focus on environmental and occupational dangers and methods for increasing the efficiency of practices. Alternatively, informal activities might be partly integrated into formal recycling systems. This would result in a reduction of formal recycling costs, informal collectors being employed to collect the waste material. In the model, this would result in a reduction of the formal threshold value, which is currently under the base line high, due to high collection costs of the formal sector. To achieve such a change, informal recyclers would have to be paid better prices than those which they currently receive from the informal market. Indeed, such an improvement is long overdue, informal recyclers being highly efficient in their manner of collection. Further research on the feasibility of such an approach is needed.
General introduction

Usually, a country's economic development correlates with its increase in consumption of primary resources, either for production of materials or for energy generation. This is particularly the case in underdeveloped countries or those in economic transition (CET). The production and use of EEE epitomises this development, both in the use of materials and the consumption of energy. Challenges for the future lie in the urge to close material cycles through recycling obsolete EEE and to increase the energy efficiency of EEE during their use phase. This thesis focuses on the first: the system set up and management of waste recycling systems for WEEE.

Within a global economy, multinational manufactures produce goods for a global market. This means that their decision to produce or import to countries is in accordance with the pull of a country's demand. CET, such as those currently found in certain Eastern European counties as well as in China, India and Brazil, have shown a strong increase in their demand for EEE. But even though these countries have shown tremendous PC per capita growth rates between 1993 and 2000, the total number of PC per capita is still relatively low. In contrast, Switzerland, the USA and Sweden reach almost one computer per head of population (Schwarzer et al. 2005), a development which inevitably leads to an increased load of obsolete equipment.

WEEE is one of the fastest growing fractions in the municipal waste stream worldwide. The ICT industries are constantly adding to the panoply of EEE, both in terms of volume relevant material stock and in the raised level of material complexity. Many components of this waste stream contain hazardous substances, which should not be disposed of in landfill sites, incinerated in incineration plants but treated as hazardous substances. They also contain valuable materials like precious metals and copper, which are of considerable economic value for a national economy and should, therefore, be recovered.

The challenges faced by each country for coping with the management and recycling of WEEE are different, stemming from a variety of unique factors specific to the countries context. Nevertheless, the factors are interlinked in many ways and are a result of market interests of companies or whole economies, and development strategies with a specific goal. Two examples of very different objectives which both directly influence the need of the developing world to have a sound WEEE management are:

1. In 2005, Nicholas Negroponte officially announced the initiative 'One Laptop Per Child (OLPC)' at the World Economic Forum in Davos, Switzerland. Many agreements have since been made to support this initiative, including a partnership agreement with the United Nations Environmental Program (UNEP). According to its initiator, "It's an education project, not a laptop project" (OLPC 2006). It meets the interests of educational programs of least developed countries (LDCs) and their urgent need to invest in the education of the coming generation. This philanthropic initiative will increase the worldwide computer literacy and create a new market for the ICT industry. There can be no doubt that this will also increase the amount of WEEE which those countries have to handle.

2. A cold-blooded and inhumane view of how countries should deal with pollution was leaked in 1991 and published in 1992 in the Economist under the title "Let them eat pollution" (Economist 1992). Larry Summers, then Chief Economist of the World Bank and resigned in early 2006 as President of Harvard University, argued in a conversation not meant for the public's ears that: a) the countries with the lowest wages will show through instances of "increased morbidity and mortality" less economic loss than those with higher wages, since the costs to
be recouped from these losses would be minimal; b) the LDCs, specifically those in Africa, are seriously under-polluted and; thus, could stand to benefit from pollution trading schemes, having air and water to spare; and c) environment protection for "health and aesthetic reasons" is essentially a luxury of the rich, as mortality is such a problem in developing countries that the relatively minimal effects of increased pollution will pale in comparison to the problems these areas already face. This type of thinking has allowed black market e-waste recycling to thrive, even in the most remote corners of the world.

The initiative to supply each child with a laptop and the escaped memo sheds light on the range of interests when it comes to a more equal distribution of goods like education or bads like pollution. In the case of WEEE recycling, 15 years later after a leaked memo, some unpalatable predictions have come true: WEEE epitomizes the classic battle between North versus South, between OECD and LDCs or countries in economic transition. In the face of this, one can only hope that the 'One Laptop Per Child' initiative keeps up its high values and includes in the initiative consideration of how to deal with obsolete laptops.

**Waste of electrical or electronic equipment**

**Definitions and categories of WEEE**

Electronic waste or e-waste are generic terms encompassing various categories and condition of products which have ceased to be of any value to their owners. A universal definition for e-waste has not, as yet, been agreed upon. Table 2 gives a selection of definitions of e-waste. **Waste of electrical or electronic equipments** is a term which has been introduced by the **EU directive on waste electrical and electronic equipment by the European Council and Parliament**, (EU 2002a). In this thesis the term e-waste and WEEE is used synonymously as defined in the EU Directive on WEEE.

According to the definitions in the EU Directive, WEEE consists of ten different categories (EU 2002a) which are shown in Table 3. Electrical waste consists of household appliances like refrigerators, washing machines, dryers and kitchen utensils etc. Electronic waste, often also called e-waste, consists of discarded computers, televisions, etc.

**Table 2 Selected definitions of WEEE**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Definition</th>
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<tr>
<td>EU WEEE Directive (EU 2002a)</td>
<td>&quot;Electrical or electronic equipment which is waste... including all components, sub-assemblies and consumables, which are part of the product at the time of discarding.&quot; Directive 75/442/EEC, Article 1(a) defines &quot;waste&quot; as &quot;any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force.&quot;</td>
</tr>
<tr>
<td>Basel Action Network (Puckett et al 2002)</td>
<td>E-waste encompasses a broad and growing range of electronic devices ranging from large household devices such as refrigerators, air conditioners, cell phones, personal stereos, and consumer electronics to computers which have been discarded by their users.</td>
</tr>
<tr>
<td>Organisation for Economic Co-operation and Development (OECD 2001)</td>
<td>&quot;Any appliance using an electric power supply that has reached its end of-life.&quot;</td>
</tr>
<tr>
<td>Sinha (2004)</td>
<td>&quot;An electrically powered appliance that no longer satisfies the current owner for its original purpose.&quot;</td>
</tr>
<tr>
<td>StEP (2005)</td>
<td>E-waste refers to &quot;... the reverse supply chain which collects products no longer desired by a given consumer and refurbishes for other consumers, recycles, or otherwise processes wastes.&quot;</td>
</tr>
</tbody>
</table>

Table 3 Categories of e-waste according to the EU Directive on WEEE

<table>
<thead>
<tr>
<th>No</th>
<th>Category</th>
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<tbody>
<tr>
<td>1</td>
<td>Large household appliances</td>
</tr>
<tr>
<td>2</td>
<td>Small household appliances</td>
</tr>
<tr>
<td>3</td>
<td>IT and telecommunications equipment</td>
</tr>
<tr>
<td>4</td>
<td>Consumer equipment</td>
</tr>
<tr>
<td>5</td>
<td>Lighting equipment</td>
</tr>
<tr>
<td>6</td>
<td>Electrical and electronic tools (with the exception of large-scale stationary industrial tools)</td>
</tr>
<tr>
<td>7</td>
<td>Toys, leisure and sports equipment</td>
</tr>
<tr>
<td>8</td>
<td>Medical devices (with the exception of all implanted and infected products)</td>
</tr>
<tr>
<td>9</td>
<td>Monitoring and control instruments</td>
</tr>
<tr>
<td>10</td>
<td>Automatic dispensers</td>
</tr>
</tbody>
</table>

hi-fi systems, mobile telephones, digital cameras, video and game consoles etc. Categories three and four belong to electronic waste, all the others can be seen as belonging to electrical waste. Each group accounts roughly for 50% of the weight of the whole volume of WEEE.

Material composition of WEEE

In Europe, WEEE is the fastest growing type of refuse, accounting for 8% of all municipal waste (The Economist 2005). As material composition of WEEE is mainly metal dominated, difficulties arise for municipal waste treatments plants, such as waste incineration plants, which are not designed to treat such wastes. Some of the categories of WEEE contribute over proportionally to the total weight if we consider compared the actual number of items. This is logical as EEE differ considerably in their size and functionality. Figure 5 shows the weight fractions of WEEE per category from households and businesses for Western Europe in 2003.

A closer look at the two biggest categories one and three reveals that the composition of material in these categories differs considerably. According to (Crowe et al. 2003), the material composition of a refrigerator or freezer is dominated by iron, whereas televisions contain a lot of glass in cathode ray tubes. Refrigerators and freezers are 'Large household appliances', PCs and Televisions are part of the 'ICT' category (see Figure 6). The 'Electronic waste' from categories three and four contain relatively more electronic components than the other categories. These components are responsible for the precious metals and copper content in EEE.

![Diagram of material composition of WEEE in Western Europe (APME 2003)](image-url)
The EU Directive on WEEE sets two targets for each category. One for reuse/recycling, another for recovery. The first includes reuse of components and material recycling; the latter includes waste-to-energy recovery of combustible components. All rates are exclusively based on the amounts collected by weight. For category one, the recovery rate should be 80% and the reuse/recycling rate 75%. For category three, recovery should be 75% and reuse/recycling 65%. (For details also see Annexure A). These exclusively weight-based targets have put pressure on recyclers and are presently the cause of much heated discussion amongst experts. From a life cycle assessment approach they have also led to suboptimal recycling practices, a further point for improvement in the legislative framework. Why such an explicit focus on weight based recycling targets can lead to suboptimal recycling was investigated by Huisman (2003).

Figure 7 illustrates the weight composition of a cellular phone, versus the environmental weight. The environmental weight represents the environmental burden caused by the extraction of the same weight of materials from natural ores or other natural resources. For this life cycle approach Huisman's default choice for the environmental evaluation was the Eco-Indicator'99 (Goedkoop and Spriensma 2001), however, other evaluation sets were also implemented. While the physical weight of precious metal content of palladium and gold are minim, the environmental weight outweighs all other components. Therefore, from an environmental point of view, the recoveries of the precious metals from a mobile phone are the most relevant. But, if only recovered, the weight targets set by the EU Directive on WEEE are not met. The upcoming revision of the Directive; however, might bring about certain changes to these weight-based targets.
Recycling of WEEE

State of the art of WEEE recycling

The information of current best practices of WEEE recycling has been culled from various sources of information, including: recycler's conferences, personal visits to recycling factories and metal smelters, personal communication with experts and reviews of literature sources. The present demand for secondary resources naturally influences the presence of a particular recycling practice. Consequently, the economic feasibility of a certain practice is stated whenever it becomes apparent.

The 2004 material composition of the whole WEEE stream in Switzerland is shown in Figure 8. Over the last years, the metal fraction and plastic fraction have decreased in favour of an increase in the metal-plastic mixture fraction. The reason for this is the increase of mechanical recycling with big shredding facilities.

In the next paragraphs, some of the possible material or energy recovery practices of fractions will be presented and discussed. They are considered to be 'state of the art' environmentally sound recycling techniques for WEEE.

Metals

Complex metal refining plants combine the capabilities of a smelter, refinery, recycling plant or other specialized metal-recovery process into one integrated facility. Such integrated metal smelters are capable of recycling non-ferrous metals and precious metals, not only from ore-concentrates or metallic scrap but also from mixed metal concentrates, metal-plastic mixtures and compound material such as printed circuit boards. Many base metals can be recovered to over ninety percent, while precious metals can be recovered to an extent of 97%-98% (in Huisman 2003). Some integrated smelters and refineries have completely shifted from using ore-concentrates from mines to recyclable materials and industrial by-products. Over several smelting and refining steps the following metals can be recovered (example Umicore): precious metals (gold, silver and the platinum group metals palladium, platinum, rhodium, iridium, ruthenium); special metals (selenium, tellurium, indium), secondary metals (antimony, tin, arsenic, bismuth) and base metals (copper, lead, nickel). Depending on the process, certain individual metals cannot be recovered and as such, are transferred to slag. Such is the
case for aluminium and iron, which in copper smelters and integrated smelters are oxidised and lost, together with silica and other non-metallic elements, all of which end up as slag. This depleted inert slag can be sold as construction material. Another by-product is sulphuric acid from off-gas cleaning, which can also be sold as a product. At the kind of temperatures reached in a smelter, combustible residues in metal-plastic mixtures are only used as reducing agents (coke substitute) and as fuel (oil substitute). In order to comply with environmental regulations, integrated smelters must have extensive off-gas cleaning systems as well as special water purification plants which can deal efficiently with hazardous substances. The off gases are cooled and filtered with bag house filters, electro filters and scrubbers. Inorganic substances such as halogens or sulphur are transferred to the liquid phase. The waste water from the refining process, as well as all surface and sprinkling water used for dust prevention, is processed in a specialised waste water treatment plant which applies several stages of physical and chemical precipitation methods. A high percentage of the cleaned waste is reused internally. Substances of concern that cannot be recovered as metals (like cadmium and mercury) are isolated from the off gas stream and stored in a hazardous deposit site (Hagelüken and Kerckhoven 2005).

Voluminous metal parts –such as those from large household appliances which have been separated through magnetic separation or methods like ‘eddy current separation’– can be sold as scrap material. Such secondary resources are the feedstock for specialised smelters which can be considered as environmentally sound recycling practices.

**Plastics**

- **Recycling**

The reusability of plastic from EEE depends mainly on the sort of plastic used and the degree of purity of the sorted material after dismantling. In the main, Acrylonitrile Butadiene Styrene (ABS) and High Impact Poly-Styrene (HIPS) are used in EEE. More than 90% of the weight of fax machines, printers or photocopying machines belongs to these groups. These are also the plastics which are technically suitable and economically profitable for recycling. Recycled plastic alone does not meet the quality standard for plastics used in EEE. Thus, the separated and shredded material usually undergoes a down-cycling process during which virgin material is added. Recycled plastic is normally dyed black which means that specific colour specification of producers can not be met by recycled plastic (Arola 2006).

- **Gasification**

Shredder residues of plastics can be used for methanol production. The gasification process is a partial oxidation process, carried out with steam and oxygen at high temperatures and high pressure (1300-1600° Celsius and 25 bar). Traces of organic pollutants, such as POPs, dioxins, furans or PCB, are split as are all other organic components- into hydrogen gas, carbon monoxide, carbon dioxide and methane. This so-called synthesis gas can be used for methanol production. The remaining gas can be used for the generation of electricity and steam. Metals contained in the feedstock are transferred to the liquid slag which can be treated separately, or disposed of. This technique has been tested on a large scale at “Schwarze Pumpe” in Germany. (Buttker et al. 2005)

- **Combustion**

The biggest concerns arising form the combustion of plastics from EEE are the brominated flame retardants, traces of metals contained in the plastic fraction and chemical by-products produced during combustion. Brominated flame retardants (BFRs) are brominated organic substances that have an inhibitory effect on the ignition of com-
bustible organic materials. They are used as additives to plastics for EEE in order to comply with safety regulations. The BFRs Tetrabromobisphenol-A (TBBPA), Octabromodiphenyl ether (Octa-BDE), Decabromodiphenyl ether (Deca-BDE) and oligomeric brominated flame retardants are responsible for the bromine load in WEEE plastics, which does not exceed 2.6% of bromine per weight (Vehlow et al. 2003a). At a municipal incineration plant in Germany, a test for the co-combustion of plastic waste from WEEE was conducted. 25% of plastic from EEE was added to the ordinary municipal waste stream on a weight base. The plant had a grate combustion furnace equipped with boiler, fabric filter and two stages wet scrubbing system. The results of the study showed that bromine enhances the volatilisation of metals like potassium, zinc, cadmium, tin and antimony from the waste stream. These metals condense on the fly ashes and are discharged along with the filter ashes. Thus, the volatilisation of metals is of no environmental concern, as long as dust collection is performed. Bromine is mainly transferred into Hydrobromic acid (HBr), but it can recombine to elementary bromine (Br2) as soon as the level of sulphur-dioxide in the gas decreases. In order to prevent the formation of Br2 reducing agents are added at the second stage of the wet scrubbing system. It can be concluded that final deposition of WEEE plastics containing brominated flame retardants in modern household incinerators is environmentally sound (Vehlow et al. 2003b). Some studies even suggest that bromine recovery from waste incineration plants might be economically feasible. This would enhance the option for final deposition of plastics from EEE in municipal waste treatment plants (Tange and Drohmann 2003). Municipal waste incineration plants of Western European standards usually operate at approximately 900-1000°C Celsius. This is a high enough temperature to eliminate chemical by-products produced during combustion.

Glass
- Closed-loop CRT glass recycling

Glass culets from cathode-ray-tube recycling are mainly categorised according to their lead content. Whereas panel glass contains very little lead content (less than 3%), the amount in funnel glass is considerably more (30%-40%), as is the case in frit glass (65%-75%). The commercial techniques used to separate the glass categories of a CRT are well developed, these are: hot-wire or laser cutting, diamond sawing and thermal shock (ICER 2004). If separated into these categories, the culets are a tradable commodity and can be reused for the production of new CRTs (Cauchi 2006). Currently, the market share of CRT monitors and televisions is decreasing, whilst customer demand for flat screen panels and plasma screens – both of which are becoming cheaper – is on the increase. This indicates that the markets demand for reused CRT glass will either shrink or be shifted to counties where CRT monitors and TVs are still in demand. In the long term, the CRT market will become smaller, demanding other options for CRT glass recycling or deposition.

- Use of CRT panel glass as a raw material or additive

CRT panel glass can be used as additional raw material for the production of bricks and tiles. The additives create possibilities for decorative bricks and cladding tiles without constraining the physical properties of the products. When those products were tested for lead leaching, the maximum permitted values for drinking water were not exceeded (ICER 2004, Andreola et al. 2006). Panel glass can also be used as flux material in the brick and ceramic industry. Investigations in the UK have shown that large volumes can be absorbed by this sector but that's the costs are also higher, as the panel glass has to be finely ground into glass powder (ICER 2004, Shayan and Xu 2004).
Lead recovery from CRT glass

Flux materials are used in smelters to cleanse the molten metal of impurities. The impurities are transferred to a slag, whether refined from ore or secondary resources. Some specialised smelters can recover lead from CRT glass and produce inert slag which can be used as construction material or as road aggregate. But such smelters have to use flux materials such as sand. The silica from CRTs can replace sand and is transferred itself to the slag after the melting process. The slag produced has to be depleted to a level before it can be used as an additive. Otherwise, it has to be disposed of as hazardous waste. Out of the specialised smelters (e.g. for precious metals, zinc, lead or copper) it is mainly those dealing with copper who benefit substantially from adding CRTs to the smelting process. If copper coils from the yoke of CRTs are left attached to the CRT tubes, the financial gain for copper smelters increases. Primary lead smelters can also make use of CRT glass, but the high concentration of lead in the slag of those smelters prevents the slag being used in other application, resulting in an overall increase in the amount of slag produced. The higher the lead concentration in the feed material, the more attractive it is for lead smelters (ICER 2004).

Deposition of CRT glass

Hazardous waste landfills accept only CRT glass as waste if it fails the Toxicity Characteristic Leaching Procedure (TCLP) or other applied leaching methods. This alternative is extremely expensive for industries generating such waste.

Hazardous components and substances

PCB containing components

Polychlorinated biphenyls (PCBs) have been used in a wide range of 'open' applications such as sealants, lubricants and cutting oils. They are also apparent in 'closed' applications such as transformers, capacitors and electrical switching equipment, where PCB-containing oil serves as an insulant and coolant. The latter group accounts for the greatest tonnage of produced PCB (de Voogt and Brinkman 1989). PCBs range in appearance from colourless oily liquids, through to more viscous and increasingly darker liquids, and on to yellow and black resins -depending on the chlorine content. The substance group has been banned since 1977, after it became apparent that they accumulate in the environment (ATSDR 2000). Under the Stockholm Convention PCBs are listed as Persistent Organic Pollutants, the production of which will be phased out by 2025 (Stockholm Convention 2001).

In EEE, PCBs are mainly found in fluorescent strip lights for industrial and business premises, domestic appliances such as washing machines, spin dryers, mangles, cooker hoods, microwave ovens, freezers and dishwashers, audio/visual equipment and street and garden lights. The major waste stream containing small PCB filled capacitors is old fluorescent strip and street lighting (UNEP 1998, Welsh 2002).

The selection and deposition of PCB containing components is a difficult task for recycling companies. If larger PCB containing components are taken out of the WEEE stream, the best way to dispose of PCB is high temperature incineration. Another way to make use of the high calorific value of PCB-containing liquid is the incineration in cement kilns, which is also used quite widely to destroy PCBs (UNEP 1998).

Batteries

Batteries contained in WEEE are potentially hazardous and have to be removed. The environmental concern comes from the metals used particularly in nickel-cadmium, lithium, sealed lead acid, mercury oxide and silver oxide batteries. Some of the metals can be recovered in specialised battery recycling plants. Lithium batteries are generally pre-sorted and treated separately; however, they carry the danger of self incineration
if treated inappropriately. The remaining batteries are first pyrolysed with an off gas purification to prevent dioxin and furan emissions. Through vaporisation and condensation, Zink (at 1500° Celsius) and mercury (at 360° Celsius) can be recovered. Iron and manganese are transferred to an amalgam which can be sold. The depleted slag can be deposed of, while all other metals are collected in the waste water. Pollutants like cyanide, fluoride and heavy metals in the off gas are also transferred to the waste water, which is filtered and treated by means of precipitation methods (Batrec 2006). Zinc air, nickel metal hydride, carbon zinc and alkaline batteries are considered to be non-hazardous but can be treated in a similar way.

Ozone depleting substances (ODS)

ODS have been used as cooling liquids and foaming gas in fridges and freezers. These substances are chemically inert and reach the stratospheric ozone layer by diffusion, where they can deplete the stratospheric ozone layer. Since the 1985 Montreal Protocol (in force since 1989), the production of ODS is monitored. The international community agreed to phase out some of the substances with the highest ODS potential (UNEP 2006), such as chloro-fluoro-carbons (CFC) and several bromo-chloro-fluoro-carbons -or so called ‘Halons’. Partially halogenated hydrocarbons or ‘Hydrochloro-fluorocarbon’ (HCFC) are also; however, of concern. Halons have the highest ODS potentials found in cooling liquids. (See B for a detailed list of ODS). The cooling liquid of refrigerators and freezer, which accounts for approximately three grams (or less than 0.006% per weight), is; consequently, the most environmentally relevant substance in these appliances (Butler 2002).

According to (Zoe and Trevor 2005), six different stages have to be considered for environmentally sound disposal of ODS:
1. collection,
2. transport,
3. storage,
4. extraction of ODS,
5. material recycling and
6. disposal of collected ODS.

During stage 1-3, the careful handling of the appliances has to be ensured. In order to prevent leakage of ODS from broken compressors or cooling tubes, the appliances must be handled almost as carefully as functional fringes or freezers. During stage 4, the ODS from gas cylinders, the compressor and the insulation foams are collected. First, a hot-air blower is used to heat up the cooling liquid in the cylinders and compressors. A suction pump and an extractor hood are then used to extract the liquids without loss. After this, the insulation foams are removed and shredded in closed machinery. The ODS are then collected from the off air with an active carbon filter. In stage 5, the ODS-free remains of the appliances are treated in a similar way to other material fractions of WEEE. During stage 6, the collected ODS and the filter materials are disposed of in an incineration utility at 1100° Celsius, which breaks down the ODS into its basic chemical molecules. After treating the off gases and waste water from the incineration with special purification measurements, slag, water and off gas are then considered to be non-hazardous.

WEEE management in emerging economies

There are several reasons which have led to the rapidly increasing amount of WEEE in CET. Widmer et al (2005) refers to three specific problems:
• CET constitute the fastest growing markets for EEE.
General introduction

Growth in the Number of Personal Computers (PCs)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>China</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>700</td>
<td>500</td>
</tr>
<tr>
<td>India</td>
<td>600</td>
<td>400</td>
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<tr>
<td>Russia Fed.</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>Kenya</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Brazil</td>
<td>300</td>
<td>100</td>
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<tr>
<td>Australia</td>
<td>200</td>
<td>100</td>
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<tr>
<td>Cyprus</td>
<td>100</td>
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<tr>
<td>Korea Rep.</td>
<td>900</td>
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<tr>
<td>Norway</td>
<td>800</td>
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<tr>
<td>France</td>
<td>700</td>
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<tr>
<td>Canada</td>
<td>600</td>
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<tr>
<td>Japan</td>
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<tr>
<td>Thailand</td>
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<tr>
<td>Indonesia</td>
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<tr>
<td>Vietnam</td>
<td>200</td>
<td>100</td>
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<tr>
<td>Philippines</td>
<td>100</td>
<td>100</td>
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</table>

Figure 9 Top scoring countries of PC growth in number per capita (left in black, cumulated 1993–2000). By comparison the countries’ number of PCs per 1000 capita (right in grey for 2002) (Schwarzer et al. 2005)

- Although the per capita quantity per capita of WEEE is relatively small, in absolute terms, countries such as India or China already produce huge amounts of WEEE.
- Imports of EEE to CET countries—whether given as donations or mislabelled as such—account for a considerable additional amount of WEEE.

Increase of domestic demand and consumption of EEE

The economic development of CET depends on an improvement in their communication infrastructure. Consequently, the growth rates of information and communication technologies are used by the World Bank as a development indicator. CET show the fastest market growth for EEE and are, as yet, far from being saturated. From 1993 to 2000, the number of PC users in China increased by 1052%, while the average growth throughout the world was much lower: 181%. During the same period, India showed an increase of 604%. From 1996 to 2002, the number of mobile phone users in China increased to 200 million. (La Revue Durable 2005). This corresponds with the collected data from Schwarzer (2005) which notes a rapid increase of PC growth per capita in many Asian countries (Figure 9).

Domestic production of WEEE

Such an increase in consumption naturally leads to a growth in the amount of waste. Although the per capita waste production is still relatively small (estimated <1kg per capita and year), populous countries like China and India are already huge producers of electronic waste. Certain initial investigations have already quantified the material flow from WEEE in Asian countries (Terazono et al. 2004, Tong and Wang 2004). Many other studies mention WEEE as one important source of secondary metals, such as: (Graedel 2002, Graedel et al. 2002, Spataro et al. 2002, Spataro et al. 2003b, Vexler et al. 2004, Kapur 2006, Tong and Lifset 2006). These studies do not; however, quantify the specific flows per country.
The material flows of WEEE offer business opportunities. Often the lack of national regulation and/or lax enforcement of existing laws promote the growth of semi-formal or informal recycling economies. An entire new economic sector evolves around trading, repairing obsolete EEE and regaining materials from redundant electronic devices. Many of the recycling practises applied are those involving intensive manual labour work. Not all of those practices pose occupational or environmental hazards but often provide a living for the urban and rural poor. Some of the applied crude methods employed, however, put humans and the local environment under severe risk. WEEE recycling -with little to no control and using extremely risky techniques- is a grim reality in some of the densely populated regions of developing or transition countries. Most of the participants in this sector are not aware of the risks or better practices and simply have no access to investment capital for financing even minor improvements. The challenge lies in upgrading this situation to prevent polluting emissions and occupational hazards without taking away the income from the local population.

Imports

The WEEE quantity of domestically generated e-waste in developing and transition countries is topped by the flow of imports from industrialized countries and -to a certain extent- is beneficial for both parties. Some industrialised countries find it suitable to force the developing world countries to continue their role as the OECD dumping ground. Such countries support the exportation of used EEE to the developing world, and accept that clandestine appliances which no longer function are included in those exports. Other countries may well set no barrier on the official export of WEEE to countries which offer cheaper recycling and deposition options, to the extent that they are even prepared to take on board the occurrence of massive environmental hazards. Developing countries, as recipient countries of waste, support the import for similar reasons. In the case of China, Li states three primary economic motives for the inflow of WEEE (Li et al. 2006): Firstly, the costs for recycling and environmental management in China, when compared internationally, are extremely low. This is mainly due to lax regulation enforcement. Secondly, the low labour costs make intensive selective labour recycling profitable. Lastly, fast economic growth creates a large demand for low cost secondary resources. WEEE is a perfect example of such a resource. Terazono quantified the material flow of four different waste categories (ferrous, copper, aluminium and plastic waste) between Japan and China and other south-east Asian countries (Terazono et al. 2004). The illegal imports of WEEE between countries, mislabelled as donations or as used EEE, are either hidden in the official statistics quoted in these studies, or not accounted for at all.

Figure 10 gives a glimpse of the suspected flows of WEEE between Asian countries and of imports from OECD countries. (Note that the thickness of the arrows is not proportional to the actual traffic of WEEE.)

Reuse of electrical and electronic equipment

Whenever international conferences are held, the reuse of electronic equipment is a controversial topic, particularly when several stakeholders from different countries are present. It is common sense to reuse those items which still function in countries where a sufficient number of equipment is lacking. In many countries, reuse is a general policy priority for the waste sector. E.g. '3R -Reduce, Reuse, Recycle Initiative' in Japan (Ministry of Environment 2000), or the priority of reuse before recycling in the EU Directive on WEEE (EU 2002a). But reuse often involves the trading of used appliances and is therefore criticised. The reasons behind such criticism include the lack of an appropriate recycling system in the recipient countries. The reused EEE may rapidly break down or become obsolete for other reasons after being imported, requiring an appropriate recycling or disposal system in the country. The trading of reused items is
also potentially problematic when reuse is in conflict with the sales interests of original equipment manufactures -in particular when producers are willing to cooperate or offer their assistance to build up national WEEE recycling systems.

To clarify the semantics and to shed some light on the observed practices in the field of reuse, the definitions from the EU Directive and the distinction between refurbish and remanufacture is given as follows:

**Excursus:**

'Reuse' means any operation by which WEEE or components thereof are used for the same purpose for which they were conceived, including the continued use of the equipment or components thereof which are returned to collection points, distributors, recyclers or manufacturers.

'Recycling' means the reprocessing in a production process of the waste materials for the original purpose or for other purposes, but excluding energy recovery which means the use of combustible waste as a means of generating energy through direct incineration with or without other waste but with recovery of the heat.

'Recovery' means ... the use of materials principally as a fuel or other means to generate energy, ... the recycling/reclamation of metal sand or metal compounds without endangering human health and without the use of processes or methods likely to harm the environment.

'Disposal' means ... deposit into or onto land (e.g. landfill, etc.),... specially engineered landfill (e.g. placement into lined discrete cells which are capped and isolated from one another and the environment, etc.),... incineration on land or incineration at sea.

Source: EU Directive on WEEE (EU 2003a)

'Refurbish' and 'Remanufacture', both reuse processes, have not been specified under the EU Directive on WEEE. Nevertheless, the concepts appear frequently in CET and are; thus, defined as follows:

'Refurbish' means in the context of WEEE recycling in CET, the reuse of appliances after minor technical improvements or replacements of minor dysfunctional components. This can consist of: simple cleaning or the replacement of minor parts for es-
General introduction

Theoretical reasons; a mere functional test and/or fine tuning of technical settings; or an upgrade of ICT products with newer software.

'Remanufacture' means in the context of WEEE recycling in CET, the reuse of appliances after major technical operations. This includes the total dismantling of a product into its components. These can be either used as individual replacements in other products or form the core of a new product, which is recombined by using original manufactured components. Such processes have been described for the recycling of cathode ray tubes from televisions and PC monitors in India (Jain and Sareen 2006). The technical preconditions for the remanufacturing of liquid crystal panels have been outlined by Ladányi (Ladányi and Miklós 2006).

Considerable differences exist between industrialised countries and CET concerning the institutions involved in reuse. In Western Europe, such activities are typically performed by charities or non-profit organisations. Income is often generated by additional government support programmes, rather than via the sale of refurbished products (Enviros 2002, Knigge 2006). In countries like India or China only the market decides which reuse, refurbishing or remanufacturing operation is profitable and which not.

Informal economy

Cross describes the informal sector as a sector which

"economic activity ... takes place outside the formal norms of economic transactions established by the state and formal business practices but which is not clearly illegal in itself. ... It includes the production and exchange of legal goods and services that involves the lack of appropriate business permits, violation of zoning codes, failure to report tax liability, non-compliance with labor regulations governing contracts and work conditions, and/or the lack of legal guarantees in relations with suppliers and clients." (Cross 1998).

Schneider deviates slightly from these definitions, grouping informal economic activities into legal (self sufficient economy) and illegal (shadow economy) activities (Table 4). Legal activities which execute market transactions stand, according to his definition, for the informal sector. He subdivides the illegal sector into an irregular sector which produces illegally, but has legal output (goods or services), and a criminal sector which has illegal outputs (drugs or forgeries).

Schneider also compares the size of the informal economy between different continents and different groups of countries in the early 1990s. It shows that Africa has the largest shadow economy with 44% of the gross national product (GNP), followed by Latin America with 39%, and Asia with 35%. The OECD countries lie at the bottom end of the scale with 12%. In 1998, India was below the Asian average, with 22% GNP generated by the informal economy, employing 50% of the labour force or 22% of the population (Schneider and Enste 2003).

Table 4 Sectors of informal economy

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Household sector</th>
<th>Informal sector</th>
<th>Irregular sector</th>
<th>Criminal sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production and Distribution</td>
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<td>legal</td>
<td>illegal</td>
<td>Illegal</td>
</tr>
<tr>
<td>Market transactions</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Output (goods/services)</td>
<td>legal</td>
<td>legal</td>
<td>legal</td>
<td>Illegal</td>
</tr>
<tr>
<td>NIAC conventions</td>
<td>Self-sufficient economy (legal)</td>
<td>Shadow economy (illegal)</td>
<td></td>
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</tbody>
</table>

NIAC (National Income Account Convention), (Source: Schneider and Enste 2003),
A literature survey on the use of the term informal economy in developed and LDC revealed that a majority of studies applied variations of three criteria: the economic, political and social criteria. These are subdivided into sub-criteria (Table 5). The most frequently used in this study are in bold letters (Gerxhani 2004).

According to Schneider, generally, recycling activities in CET are carried out by enterprises which belong to the informal and irregular sector (are shown in grey in Table 4). In this study, the informal recycling activities occur across both fields, as the recycling chain includes some informal recycling steps which are legal as well as some irregular steps which are theoretically illegal and forbidden. But all recycling activities produce legal outputs and execute market transactions. In this study, both informal and irregular recycling activities will be referred to as informal recycling.

Environmental hazards and toxicity of WEEE

The environmental impacts from WEEE recycling, particularly in informal business sectors which are not controlled by official bodies, can originate from three sources:

(I) Direct leaching of environmentally hazardous substances from WEEE while being dismantled or pre-processed.

(II) Indirect impacts from toxic substances which are generated by crude methods employed for recycling, incineration or final deposition. A main source seems to be incomplete combustion and chemical reactions occurring in complex mixed wastes.

(III) Impacts from discharging chemical agents used for recycling processes.

WEEE contains more than 1000 different substances, and many of them are toxic - including lead, mercury, arsenic, cadmium, selenium, hexavalent chromium, and flame retardants. As studies in Switzerland have shown, the content of bromine, copper, chromium and nickel in separately collected WEEE is 120% to 500% higher than in the ordinary Swiss municipal waste. Similarly, the present amount in the municipal solid waste stream of antimony, zinc and cadmium is exceeded by 60% to 90% in WEEE (Morf 2004). If considered that the amount of WEEE from all the above mentioned elements going into the municipal waste stream, one realises that this alters the material complexity of the whole waste stream considerably. This is of utmost importance, if soil contamination, leaching to groundwater or emissions to air is to be prevented.
As shown earlier, the applied technologies for WEEE recycling have to be very specific if occupational hazards or negative impacts on the environment are to be prevented. This can be seen in the disposal of ODS from cooling appliances, or the treatment of printed circuit boards containing precious metals and PCB bearing capacitors.

The following selection of studies report on crude methods applied in the informal recycling sector in India and China. Annexure A gives an overview of the observed informal recycling activities in India and China taken from Brigden et al (2005):

- roasting of printed circuit boards over burners for component separation or for solder recovery (Leung 2004, Brigden et al. 2005).
- toner sweeping, plastic chipping and melting, burning wires to recover copper, heating and acid leaching of printed circuit boards (Leung et al. 2006).
- gold recovery from printed circuit boards with (i) cyanide salt leaching or (ii) nitric acid and mercury amalgamation (Keller 2006).
- manual dismantling of cathode ray tubes and open burning of plastics (Puckett et al. 2005, Jain and Sareen 2006)

The toxicological effects of heavy metals are well known. The effects on organism of some trace metals are not entirely understood. The most prominent metals of concern in EEE are given in Table 6.

**Organic pollutants**

Organic pollutants can be contained in WEEE or released while recycling is happening. The toxicological effects of those substances are less well documented but are an intensive field of scientific study. The pollutants are also named Persistent Organic Pollutants (POPs) and are characterized by four properties:

- high toxicity for living beings,
- persistence in the environment,
- bio-accumulation in lipids and the
- ability to be transported over long distances and across international boundaries by means of atmospheric, aquatic or biological media.

The oral intake of POPs via the food chain accounts for more than 90% of exposure (Leung et al. 2006). The recyclers themselves are most prone to oral intake, water from nearby lakes being used as drinking or bathing water. Pollution of the water bodies accumulates in fish which are often used as a food resource. While performing crude recycling practices, POPs may also be inhaled directly or absorbed via dermal assimilation. In the annexure E the list of twelve POPs regulated under the Stockholm convention is given. The most relevant in the case of WEEE are PCBs, dioxins and furans.

**Brominated flame retardants**

Tetrabromobisphenol-A (TBBPA) is the most relevant BFR in terms of production and consumption. It is frequently used in conjunction with antimony trioxide, which raises the inhibitory effect of ignition, and as an additive in ABS or HIPS. Highly brominated Diphenyl ether (Octa- and Deca-), less brominated Diphenyl ether (Tetra-, Penta-, and Hexa-) are also used as additives in plastics. A study carried out by the Swiss Ministry of the Environment summarised the main environmental concerns arising from BFRs. The direct toxicity of BFR to humans is very low but its bioaccumulation in the food
chain and storage in fatty tissues poses serious problems - little being known about how these substances are metabolised over long periods. The degradation in environmental compartments is slow. UV radiation splits BFRs with higher molecular weight into smaller molecules. BFR carries the risk of dioxin and furan emission if not burned at high enough temperatures and under controlled conditions. The reason why the toxicological effects and the degradation processes of BFR are not entirely understood is due to their complexity and the chemical properties of the molecules created when partly broken down (Morf et al. 2003).

Table 6 Metals present in EEE and their danger to humans (alphabetical order).

<table>
<thead>
<tr>
<th>Metal</th>
<th>Presence in EEE</th>
<th>Properties (environmental and technical)</th>
<th>Main intake</th>
<th>Toxicological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimony (Sb)</td>
<td>• Semiconductors • Alloying element • Antimony trioxide as additive to BFR • Solders</td>
<td>• Biotransformation to methyl antimony • Bioaccumulation • Catalytic effect on dioxin and furan formation</td>
<td>• Dust • Fumes</td>
<td>• Inhibition of enzyme • Antimony trioxide classified as carcinogen</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>• Semiconductors • Alloying element • Doping agent in transistors</td>
<td>• Bioaccumulation • Formation of several compounds such as inorganic arsenites, methyl arsenic and others • absorption and retention in the body</td>
<td>• Fumes • Fly ash • Water</td>
<td>• Genome interaction of methyl arsenic • Inhibition of enzyme • Increased risks of cancers in bladder, kidney, skin, liver, lung, and colon</td>
</tr>
<tr>
<td>Barium (Ba)</td>
<td>• Front panel of CRTs</td>
<td></td>
<td></td>
<td>• Brain swelling • Muscle weakness • Heart, liver, spleen damage</td>
</tr>
<tr>
<td>Beryllium (Be)</td>
<td>• Alloying metal with copper • Mechanical parts, springs, connectors • Relays</td>
<td>• Light and strong metal, very brittle</td>
<td>• Dust • Fumes • Skin contact</td>
<td>• Sensitization through constant exposure even in small amounts • Berylliosis • Emphysema and fibrosis of the lungs • Classified as carcinogen</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>• Batteries • Switches • Fluorescent materials • Old screens • Solders • Stabilizers in plastics • CRTs</td>
<td>• Bioaccumulation in plants and animals • Natural concentration very low</td>
<td>• Mainly via food chain • Dusts • Fumes</td>
<td>• Dysfunction of kidneys • High blood pressure • Lung damage and lung cancer • Bone defects • Lung emphysema</td>
</tr>
<tr>
<td>Hexavalent Chromium, Chromium VI</td>
<td>• Decorative surface • pigments containing dry chromate • coatings containing chromate • stainless steel</td>
<td></td>
<td></td>
<td>• Inhibition of nose, throat, and lungs • Potential lung carcinogen • Permanent eye damage due to direct eye contact with chromic acid or chromate dusts • Dermatitis and skin ulcers due to prolonged skin contact • Sensitization to chromium • Kidney damage (Department of Labor 2005)</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>• Omnipresent in EEE</td>
<td>• Hardenier for steel • Anticorrosive</td>
<td>• Dust • Fumes • Skin contact</td>
<td></td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>• Solders • Radiation shield in CRTs</td>
<td>• Bioaccumulation • Pb can pass the placental barrier • Natural concentration very low</td>
<td>• Dusts • Fumes • Food chain • Soil (children)</td>
<td>• Damage of central and peripheral nervous system • Damage to brain, kidneys • Foetal are highly susceptible to CH$_3$Hg$^+$ • CH$_3$Hg$^+$ connects to the DNA and can cause reproductive diseases</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>• Ubiquitous metal • Fluorescent lights • Electrical switches • Sealed relays • Batteries • Flat Screen backlights</td>
<td>• Highly volatile • Liquid at room temperature • Biotransformation of methyl mercury (CH$_3$Hg$^+$) • Bioaccumulation of CH$_3$Hg$^+$ • CH$_3$Hg$^+$ can pass the placental barrier • Used in gold recovery process (Keller 2006)</td>
<td>• Inhalation of Hg vapour • Water • Food chain, mainly fish</td>
<td>• Damage of central nervous system • Damage to brain, kidneys • Foetal are highly susceptible to CH$_3$Hg$^+$ • CH$_3$Hg$^+$ connects to the DNA and can cause reproductive diseases</td>
</tr>
</tbody>
</table>

If not stated otherwise, all information is taken from (Agarwal et al. 2003, Brigden et al. 2005, Yu 2005).

**Polychlorinated biphenyls (PCBs)**

In EEE, PCBs have been widely used in 'closed' applications, such as transformers, capacitors and electrical switching equipment. Today, capacitors are often PCB free. Nevertheless, PCB can still be found in the waste stream and is released if the components are damaged mechanically. The toxicological effects are: suppression of the immune system, liver damage, tumour growth, neurotoxicological effects and damage to the
male and female reproductive system (Safe 1993). If burned at low temperature, PCB containing capacitors can cause emissions of dioxins and furans.

**Dioxins and Furans**

Halogenes are present in many substances of complex mixed wastes. Polyvinyl chloride (PVC) - a plastic used for cable insulation- and flame retardant plastic parts or BFRs can be a source of chlorine and bromine in WEEE. If such wastes are incinerated at low temperatures, Polychlorinated dibenzo-dioxins (PCDD) and Polychlorinated dibenzo-furans (PCDF) can be emitted. If incineration is carried out under carefully controlled conditions, e.g. in a municipal waste incineration plant meeting Western European standards, no significant dioxin and furan emissions occur (OECD 1994). These substances are highly toxic and have become famous as 'Seveso toxics'. When cables and printed circuit boards are burned in the open, the temperatures reached range between 200° and 600° Celsius (Steiner 2004). According to several models, the formation of dioxin and furans occurs between 200° and 800° Celsius (Mätzing 2000). These crude recycling methods are, thus, likely to cause dioxin and furan emission. Several other studies have reported and analyzed the release of these toxins during WEEE recycling (Brigden et al. 2005, Hicks et al. 2005). Open burning of computer casings and circuit boards can produce toxic fumes and ashes. As dioxins and furans are very susceptible to particles in air, humans nearby can inhale the substances easily (Leung et al. 2006). If the soil and waste bodies are contaminated with dioxins and furans, the toxins can be assimilated via the food chain.

**Value of WEEE**

The values of material contained in WEEE can vary considerably. Waste from electronic product per kilogram has a higher value than waste from electrical products. This is due to the higher percentage of electronic components. The value of the precious metals (gold, silver and the platinum group metals) and some of the base metals (copper, nickel, lead) contained in WEEE, exceed the value of ferrous metals. The first two are contained in electronic components, such as printed circuit boards, gold-plated pins, ceramic condensers and processors, cables, motors and magnetic coils. Iron is mainly present in mechanical parts or metal casings. The value of glass or plastic contained in EEE is nothing compared to that of the precious metals and copper. Table 7 shows estimates for the material value of a Personal Computer.

<table>
<thead>
<tr>
<th>Material</th>
<th>%</th>
<th>Gram / PC</th>
<th>US$/kg</th>
<th>Maximal expected revenues (US cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics and fiber</td>
<td>6.8</td>
<td>838</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Plastics</td>
<td>13.0</td>
<td>1602</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Iron</td>
<td>66.2</td>
<td>8156</td>
<td>0.05</td>
<td>41</td>
</tr>
<tr>
<td>Aluminium</td>
<td>6.6</td>
<td>813</td>
<td>1.87</td>
<td>152</td>
</tr>
<tr>
<td>Copper</td>
<td>6.6</td>
<td>801</td>
<td>3.58</td>
<td>287</td>
</tr>
<tr>
<td>Lead</td>
<td>0.2</td>
<td>25</td>
<td>0.99</td>
<td>2</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.1</td>
<td>12</td>
<td>1.48</td>
<td>2</td>
</tr>
<tr>
<td>Tin</td>
<td>0.3</td>
<td>37</td>
<td>6.21</td>
<td>23</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.1</td>
<td>12</td>
<td>14.88</td>
<td>18</td>
</tr>
<tr>
<td>other metals</td>
<td>0.2</td>
<td>25</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

ppm US$/gram

Gold 24 0.30 14.30 423
Silver 107 1.32 0.24 31
Palladium 9 0.11 6.47 72

100.0 12320

5 Non ferrous metal prices: http://www.lme.co.uk (26th of October 2005), ferrous metal prices: http://www.meps.co.uk (11th of January 2006)
In PCs, the concentration of copper and gold do not account for more than 7% of the total weight (SWICO 2002, Schischke and Kohlmeyer 2005). However, these metals have the highest economic value recyclers can theoretically gain if materials are recovered. The maximum expected revenues from recycling are calculated with the actual material concentration per PC multiplied with the world market prices for metals.

In industrialised countries, the stock of copper per capita accumulated in the anthroposphere exceeds the estimated stocks of copper per capita contained in ores (Wittmer 2006). For developing countries, the in-use copper stock per capita is often far lower but recent economic developments, such as in China, show that the demand for raw material in CET will continue to rise. India's degree of copper use is due to increase until 2050. The current consumption of 300,000 tons copper per year will increase more than 30 fold in the next 100 years. Housing, power and transport sectors will be the major driving forces behind copper consumption. Currently, recovered copper as a secondary resource originated from WEEE recycling (Kapur 2006). An increasing scarcity of materials anticipated by certain prominent publications (Meadows, H. 1972, Meadows H. et al. 2005) has also been reported in the case of certain rare metals predominantly used in EEE: the Tantalum craze due to the high demand of this metal in mobile phones capacitors (Bond and Braeckman 2001); Indium, a metal which is essentially used for liquid crystal displays being as transparent as oxide and which is already recovered from obsolete items in Japan; and light diodes containing gallium, whose price development rocketed in 2006. This clearly indicates that metal recovery from wastes will become increasingly important. Whether material recovery is profitable or not depends on actual commodity prices. These are set for many metals according to market demand and supply. Most of the metals can be recovered and reused almost indefinitely. Thus, the supply of metals is a trade off between raw material production from ore and metal recovery from secondary resources. The more scarce ores become or the more technically difficult it is to mine them the more economically feasible the recovery of metals from the waste stream will become. The developments between 1985 and 2006 of gold, silver and copper prices are depicted in Figure 11. For the same period

Figure 12 shows the indexed price development of ferrous crude products as well as for non ferrous metals in Germany (year 2000=100). The values of 2006 are the average from January until August. As can be seen, the overall picture is not consistent. Each metal price development has its own dynamic due to a particular set of circumstances.
In the case of gold, the circumstances may be due to the fact that over 80% of worldwide gold production is used for jewellery, while only 12% goes to industrial application and electronics. In contrast, 25% of worldwide copper production is used for EEE, 14% for industrial machinery, 11% for transport equipment, 10% for consumer products and 40% for the construction sector. The demand of copper is, therefore, mainly driven by technology rather than by investment for savings or luxury articles (Feneau 2002). But the tendency over the last five to six years has been an increasingly upward one. In the case of copper, an increasing scarcity of the metal is one of the reasons behind the development of recovery from WEEE into a profitable business.

The metal fraction is not the only economically feasible recycling activity. Glass and plastic can also be recycled. If disposal costs are taken into account, the recycling of CRT glass becomes an economically profitable business (Jorgensen 2004) as well as the recycling of plastic from WEEE, which is blended with virgin material and used as a lower quality material (Arola 2006).

Legislative aspects of WEEE management

Directives from the European Council and Parliament

Since the European Union release of the EU directive on waste electrical and electronic equipment by the European Council and Parliament, (EU 2002a) many European states have launched initiatives for the recycling of EEE. The directive obliges EU member states to install a recycling system for EEE with the objectives to (i) reduce the quantity of WEEE that goes to landfills, (ii) increase the recovery, re-use and recycling WEEE and (iii) to mandate an extended producer responsibility for the whole life span of EEE. The directive has been in force since August 2004 and will continue to dictate national implementation beyond the passed deadline of August 2005. A second directive from the EU, the EU directive reduction of hazardous substances (RoHS) (EU 2002b) was adopted and is due to be enforced by July 2006. The directive bans the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) in EEE and stipulates the substitution of hazardous containing components by safe or safer materials where technically and economically feasible. This includes the imports of EEE from outside the EU.

Basel Convention and Basel Ban

To deal with the unsustainable and unjust effects of hazardous waste trades, the international treaty Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (1989a) was created in 1989 and has been in force since 1992. The Convention puts an onus on exporting countries to ensure that hazardous wastes are managed in an environmentally sound manner in the country of import. Apart from Afghanistan, Haiti, and the United States of America, all 164 signatory countries have ratified the convention. To abolish trade of hazardous waste between developed countries and developing countries, the Basel Convention in 1994 agreed to adopt a total ban, the so called Ban Amendment. This act would also forbid trade of hazardous wastes for the sake of environmentally sound recycling in another country. However, the Ban Amendment has not yet entered into force. This is due to occur upon ratification by at least three-fourths of the Parties who accepted the amendment. Up to July 2006, only 62 parties have ratified the amendment.
The legal interpretations of the convention are difficult. E.g. pre-processed WEEE from which hazardous substances have been removed does not fall under the Basel convention. (See Annexure D for Basel Convention details.)

**Stockholm Convention**

The Stockholm Convention held in 2001 which came into force on May 17, 2004, is an international legally binding treaty restricting or banning the use, production, import and export of twelve of the world's "most dangerous chemicals." (2001b). Many of them are chemical products such as pesticides, which are produced intentionally for sale. Others are industrial chemicals which are used in hundreds of applications, or certain chemical by-product substances, which are produced unintentionally. The Convention also makes provisions for the possibility of additional POPs. The relevant substances contained in EEE are PCBs, dioxins and furans. (See Annexure D for details.)

**Rotterdam Convention**

The *Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade* was adopted in 1998 and came into force in 2004. The international legally binding treaty is designed to promote shared responsibility and cooperative efforts among parties in the international trade of certain hazardous chemicals. It focuses mainly on information exchange between parties for the trade of hazardous chemicals and pesticides (1998).

**Indian Legislation**

Even though India has signed and ratified the Basel Convention, there is no specific legislation regulating the import and export of WEEE. Until 2006 no specific regulation dealt with the collection and treatment of WEEE in India. There are, however, several existing environmental legislations which are of importance and useful in the context of WEEE; -Table 8 gives an overview:

<table>
<thead>
<tr>
<th>Law or Regulation</th>
<th>Major Content</th>
<th>Status /date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment (Protection) Act (1986) (Amendment 1991)</td>
<td>An umbrella legislation that empowers the central government to take measures to protect and improve environmental quality, control and reduce pollution from all sources.</td>
<td>Effective from November 19, 1986</td>
</tr>
<tr>
<td>Municipal Solid Wastes (Management and Handling) Rules, (2000b)</td>
<td>Provides compliance criteria to municipalities for the collection, segregation, storage, transportation and disposal of municipal solid wastes.</td>
<td>Effective from September 25, 2000</td>
</tr>
<tr>
<td>Batteries (Management and Handling) Rules, (2001a)</td>
<td>Confers responsibility for the safe disposal &amp; recycling of used lead acid batteries on the manufacturers/ assemblers/ importers.</td>
<td>Effective from May 16, 2001</td>
</tr>
</tbody>
</table>

Source: (Sinha-Khetriwal et al. 2006)
Policy aspects of WEEE management

Extended Producer Responsibility (EPR)

The management of WEEE is subject to EPR policies. The complexities of the products means that original equipment manufacturers are almost forced to be involved in the appropriate management of obsolete equipment. EPR was defined by the OECD in 2001 as an environmental policy through which the producer’s responsibility for a product is extended to the post-consumer stage of a product’s life-cycle. It also tries to close material cycles by means of recycling and to support the designing of environmentally compatible products. The responsibility for a product’s whole life-cycle can be of a physical and/or financial nature, depending on the product. The policy should ensure that the physical and/or financial burden of such responsibility is incorporated into the cost of the product. This leaves the consumer to choose whether to pay for such a product or not. It also relieves local government authorities and the general tax payers from paying collectively for costs which arise from a specific product. Consequently, EPR policies can be seen as being compatible with the ‘Polluter-pays Principle’ (OECD 2001). Over the last couple of years, governments, especially European ones, have favoured EPR-based waste management systems for WEEE over their traditional counterparts (see also Annexure F for OECD definition of EPR).

Different instruments and measures have since been developed, four of which were suggested by the OECD: take-back requirements, economic instruments, standards and other industry-based measures as illustrated in Table 9.

Application of EPR policies to WEEE recycling

Both EU Directives, on WEEE and RoHS, have applied EPR principles for EEE design and WEEE treatment. Many European countries have gone about applying these principles in different manners. Certain countries had already launched their own legislation before the EU Directive on WEEE came into force (e.g. Norway, The Netherlands, Sweden and Belgium). In other countries, the producers or producer organisations started a WEEE recycling system before the national legislation was even adopted (e.g. Switzerland). Presently, two different groups of compliance models have evolved: the collective system and the clearing house system.

<table>
<thead>
<tr>
<th>Type of EPR Approach</th>
<th>Characteristic</th>
<th>Example of application to products or waste streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-back requirements</td>
<td>Mandatory or voluntary take-back</td>
<td>Cars, tyres, batteries, EEE, packaging, used oil and oil filters, containers</td>
</tr>
<tr>
<td></td>
<td>schemes</td>
<td></td>
</tr>
<tr>
<td>Economic instruments</td>
<td>Deposit-refund schemes</td>
<td>Beverages containers, fluorescent light bulbs, tyres</td>
</tr>
<tr>
<td></td>
<td>Advance recycling fees</td>
<td>EEE, batteries, PET bottles</td>
</tr>
<tr>
<td></td>
<td>Fees on disposal</td>
<td>Hazardous substances</td>
</tr>
<tr>
<td></td>
<td>Material taxes/Subsidies</td>
<td>recycled paper products, recycled aluminum products</td>
</tr>
<tr>
<td>Standards</td>
<td>Minimum recycling requirements</td>
<td>paper, glass and plastic products</td>
</tr>
<tr>
<td></td>
<td>Prohibitions of certain hazardous</td>
<td>EEE, building material</td>
</tr>
<tr>
<td></td>
<td>materials/products</td>
<td></td>
</tr>
<tr>
<td>Other industry-based measures</td>
<td>Leasing</td>
<td>Cars, photocopy machines</td>
</tr>
<tr>
<td></td>
<td>Servicing</td>
<td></td>
</tr>
</tbody>
</table>

Source: modified from (OECD 2001)
Under the collective system, the collection, recycling, and financing of all or some selected WEEE categories within a national boundary is organised by one single organisation. Some countries with a collective system have more than one organisation, although they do not compete in their coverage of WEEE categories. Whilst the legal status of the organisations differs from country to country, they are generally non-governmental non-profit companies, set up and owned by one or more trade associations. Switzerland and Norway, both non-EU members, have collective systems which were established long before the EU Directive on WEEE came into force.

Under the clearing house system a national framework allows several parties to provide services. These can be producers, recyclers, transporters, or waste organisations. The regulating body obliges producers to register themselves in a national register. The clearing house co-ordinates the allocation of WEEE and is responsible for the monitoring system. They also check whether producers comply with their obligation to recycle WEEE according to their market share of sold products. One of the reasons behind the decision to opt for such a system was the desire to hinder monopolist structures from establishing themselves within the collective system. Such structures are prevented from taking hold under the clearing house system, due to the fact that legislators approve the licensing of schemes and can withdraw these or impose fines if such monopolist structures appear (Savage et al. 2006). Most countries allow a visible fee for the collection, transport, and recycling. This fee is brought to the attention of customers when buying a new product. The WEEE Directive currently permits the implementation of such fees for large household appliances. This policy is due to run for the next eight to ten years—that is up to 2012/2014. In many countries this has led to systems which levy charges at the point of purchase.

In the transposition of the EU Directive on WEEE within Europe member state countries into national law, three tendencies can be detected. (I) Many of the countries which already had a WEEE recycling system before the EU directive came into force opted for a collective system (8 out of 24). (II) The installation of a clearing house mechanism was favoured in those countries with no pre-directive WEEE systems (16 out of 24). (III) Most of the countries allow a visible fee until 2012, this being the deadline given by the EU Directive (19 out of 25). (See Annexure G for details).

Savage et al. found another interesting tendency across Europe. Most of the larger economies opted for clearing house systems. Such systems seem to allow more competition and, thus, encourage lower costs. These systems are "designed to meet the minimum levels of collection and recycling in the most cost-effective manner, ... it creates therefore a 'financial stretch'". In contrast, smaller countries opted for the simpler collective system, smaller markets not being as competitive as their larger counterparts. Such systems "have invariably exceeded the collection and recovery targets" [and have thus provided] “an 'environmental stretch’ building a stronger recycling ethos” (Savage et al. 2006). It should be mentioned that a useful comparison between the countries which have opted for the clearing house systems against those using the collective system cannot, as yet, be made, the former group having considerably less experience than the latter.

Producer Responsible Organisations in Europe

To understand the organisational development of WEEE recycling systems one needs to take a closer look at the organisations themselves. Producer Responsible Organisations (PROs) are a cooperative industry effort to share the responsibility of WEEE recycling between the members. Generally, they are responsible for environmentally sound WEEE recycling and have the managerial authority to collect, distribute and transport
WEEE, as well as to control and monitor recyclers. Belgium, The Netherlands, Norway, Sweden and Switzerland have collective systems with PROs. They are the regulating bodies for WEEE recycling and have a virtual monopoly within the national borders (Table 10). In the case of Belgium, the PRO is a non-profit company which was founded by producers and importers and is subdivided into different sectors according to the various EEE categories. The sectors have are closely linked to industry associations. In the Netherlands two PROs are active, both of which are foundations in which the members of the board of directors come from producer associations. The Norwegian PRO is an independent non-profit company with close bonds to industry associations. In Sweden, it is a service oriented company owned by 20 industrial organisations. In Switzerland, two PROs are present; one an independent foundation, the second a branch of an industry association (S.EN.S 2005, EL-Kresten 2006, Elretur 2006, ICT milieu 2006, NVMP 2006, SWICO 2006).

These systems have proved to be effective when it comes to the recycling targets of 4 kg per capita and year, set by the EU Directive on WEEE. Numbers are given for 2002 (Savage et al. 2006) and 2004 (SWICO 2002, S.EN.S 2005, Loken 2006, Recupel 2006).

Types of fees and cost models

Recyclers can gain profits from the sales of the recovered material and from the sales of materials which can be used for energy generation. Profits from the former depend on the commodity prices of secondary resources; profits for the later, from those of the regional energy market and the national regulation for waste incineration. If the profits from these materials do not cover the costs for recycling, often fees are introduced to cover those gaps. This is particularly so if the waste material needs special treatment due to the presence of toxic substances or its complexity (e.g. WEEE, cars, batteries). Another reason for charging fees may arise from the low material value of wastes (e.g. municipal waste in general, polyethylene containers). The fee can be collected at two points: at the time of sale or of disposal.

Advanced recycling fee or pre-recycling fee

Advanced recycling fee (ARF) is collected at the point of sale with the purchasing price. The fee can either be inbuilt into the price or explicitly stated as a visible fee. The ARF collected should ideally cover the additional cost of recycling a product, after profits from material recovery or energy generation have been subtracted. Today, the ARF on EEE is used to pay for the recycling of all products, those upon which no levy was raised and those which were levied. Such an apportionment procedure or rent like system was, strictly speaking, not intended by legislators. For the so called 'historical waste'
"from products put on the market before 13 August 2005, the financing of the costs of management shall be provided for by producers. Member States may, as an alternative, provide that users other than private households also be made, partly or totally, responsible for this financing." (EU 2002a).

The advantage of ARF is that, from a psychological point of view, consumers are far more willing to pay a small fee for a new product than to pay one for a useless product at the moment of disposal. One of the greatest disadvantages of ARF is that it does not promote environment friendly design of new products. This is because ARF collected at the point of sale of new products pays for the recycling of previously manufactured products. New products which are designed with environmentally friendly materials, or for dismantling, are not rewarded, because the same fee is collected on these as it is on ordinary products.

As the pre-recycling fee is collected at the point of disposal, it has the advantage of being able to charge exactly the amount which is required for environmentally sound recycling. Such a system is applied to historical consumer equipment waste in Japan (Mitsubishi E.C. 2005). The pre-recycling fee runs the risk of promoting illegal dumping of obsolete EEE in order to avoid the fee. As pre-recycling fees should increase with the toxicity of the contained substances, appliances with a high damage potential - such as refrigerators- may end up being disposed of in an uncontrolled manner.

Visible fee or inbuilt fee

The advantage of a visible fee is that (i) it makes the system for the purchaser transparent; (ii) it creates awareness that the products contain harmful substances and (iii) it prevents extra charges from being levied by unscrupulous collectors or recyclers. The visible fee is problematic if the actual price for the consumer becomes hidden behind too many additional fees (an example of which can be seen in the price of flights which often exclude airport taxes and service fees). This cannot happen with an inbuilt fee, as the purchaser pays the price which includes the fee for disposal. According to the EPR principle, the inbuilt fee...

"...creates the setting for a market to emerge that truly reflects the environmental impacts of the product, and which consumers could make their decision accordingly." (OECD 2001)

Cost models

The EU Directive on WEEE and its national transpositions oblige WEEE systems to cover all EEE categories and to ensure for the recycling of whole appliances. This prevents ‘cherry picking’ of the profitable appliances or single components which contain profitable materials. The revenue/costs relation for the recycling or disposing of non-valuables or hazardous substances is normally a smaller one. Recyclers have to either pay for or invest in special treatment processes for the right to deposit in hazardous landfills. The difficulty for the PROs lies in setting the right fees for the various products or product categories. This involves considering:

- How the differing material composition between products or product categories should be taken into account. Should levies from some products pay for others or should each be product levied according to their actual necessary costs for recycling?
- How to deal with historical waste from products upon which no recycling fee was levied. In an apportionment procedure, the fees of today pay for the products which were sold yesterday. Such systems run the risk of being underfinanced when sales numbers or obsolescence rates change.
Who is responsible for the products which are no longer produced by their original producers, or whose producers can no longer be identified - the so called 'orphan products' or 'grey market products'? Shared responsibility increases costs for all, thus penalising - rather than promoting - the innovation of environmentally friendly design. On the other hand, separate pre-recycling fees for orphan products, such as recycling stickers or vouchers, are confusing for consumers and encourage illegal dumping.

How one can equitably allocate the costs for collection and transport to the product mix?

Many individual financing structures for WEEE recycling have evolved across Europe. Some countries have applied different cost models for individual categories. The cost models themselves, as well as the fees on products, are constantly under revision. Across Europe the recycling systems become less costly. This is due to: (i) an increased level of processed volumes (economy of scale effect), (ii) a convergence of previously over financed systems towards fees which represent the actual costs of recycling, and (iii) increasing competition between recycling facilities.

Magalini describes four different cost models (Table 11). The models differ in their direct financial burden for producers or consumers and in their financing mechanism for new products and historical WEEE. Under the EPR policy, the consumer pays in all models for the costs of recycling ('Polluter-pays principle'), as the cost should ideally be inbuilt into the price of the product. But the direct financial burden for consumers is the fact that they have to pay fees which are used for system implementation and management. This burden increases the closer one gets to the 'Advanced recycling fee' model. In this model, the consumer pays recycling fees which cover all costs for WEEE recycling. The fees are, therefore, not the product specific costs for recycling, but a solidarity shared payment. The most commonly applied models in the 20 EU member states are the 'Compliance cost' model and the 'Reimbursed compliance cost' model (Magalini and Huisman 2006). Japan has implemented a 'Compliance cost & Visible fee' model for large household appliances and consumer equipment. The models 'Advanced recycling fee' and 'Reimbursed compliance cost' do not create incentives for improving the design of new products, as the producers are fully reimbursed or do not pay any fees into the recycling system. Producers are not encouraged to implement design for environment into the design of their products. Therefore, these two models do not strictly comply with the EPR principles (see also annexure F).

### Table 11: Cost model across the EU for WEEE recycling

<table>
<thead>
<tr>
<th>Cost model</th>
<th>Producer responsibility</th>
<th>Consumer responsibility</th>
<th>WEEE split in new and historical</th>
<th>In accordance with EPR principles</th>
<th>Burden for consumer</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Compliance cost'</td>
<td>Pays compliance cost for all WEEE (according to share of sales)</td>
<td>Pays no visible fees into the system</td>
<td>not required</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>'Compliance cost &amp; Visible fee'</td>
<td>Pays compliance costs for new sold products</td>
<td>Pays visible fee to finance 'historical WEEE' treatment</td>
<td>required</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>'Reimbursed compliance cost'</td>
<td>Pays compliance costs which is later fully reimbursed</td>
<td>Pays visible fee on new products which is used for all WEEE</td>
<td>not required</td>
<td>Not fully</td>
<td></td>
</tr>
<tr>
<td>'Advanced recycling fee'</td>
<td>Pays no fees into the system</td>
<td>Pays ARF on new products which is used for the current management of WEEE</td>
<td>not required</td>
<td>Not fully</td>
<td></td>
</tr>
</tbody>
</table>

Source: modified according to Magalini and Huisman 2006
Assessment of WEEE streams

For effective cost calculation, WEEE management and recycling systems need to know how the volumes of WEEE will develop in the future. To depict or estimate quantities of WEEE, numerous methods have been applied. But many of them are modified static input output models. Lohse basically distinguishes between two models: the 'consumption and use method' and the 'market supply method'. Both methods assume a medium life-span for EEE and calculate the yearly output of WEEE with the additional data (Lohse et al. 1998).

Studies on pervasive computing anticipate that ICT appliances of the future will be more integrated in buildings, transport systems and everyday objects than they are today (Hilty et al. 2004a). Hence, "traditional" PCs are expected to be replaced by other integrated appliances. Sales data in both developed countries and developing countries already show that desktop computers are being replaced by laptops, possibly the first step towards pervasive computing. Fast increase in numbers of sales is counteracted by the tendencies of miniaturisation and integration. (Hilty et al. 2004b) This rebound effect will be particularly strong in CET counties as they have a backlog demand for ICT. The assessments presented below, use functional units itself, or the mass of functional units for calculations. Hence, assuming a 100% rebound effect of miniaturisation, models which use a product type as functional unit, such as data input and output equipment, or the weight of such units, are able to depict the future development of generated waste from these appliances.

The calculation results of the different methods concerning the produced mass of WEEE vary considerably. Apart from the methodological differences of the methods applied, they differ in their coverage of single appliances, single categories of appliances or the whole range of EEE. The studies also differ in their focus on private and/or corporate WEEE, the assumed saturation rates, and other parameters. All these differences have to be taken into account when comparing results.

'Cumsumption and use method'

The 'consumption and use method' assumes a basket of EEE-commodities per household. For each product, an assumed weight is multiplied by the total number of households. By dividing this amount by the life-span, the expected annual WEEE potential is received. This method was applied to estimate the potential of WEEE generation in The Netherlands (Bureau B&G 1993).

\[
\text{WEEE generation per year} = \frac{m_n \cdot hh \cdot r_n}{ls_n}
\]

with:
- \(m_n\) medium weight per appliance n
- \(hh\) number of household
- \(r_n\) saturation rate with appliance n per household
- \(ls_n\) medium life-span of appliance n

'Market supply method'

The 'market supply method' uses data on production and sales. By extrapolating the assumed life-span backwards in time, the WEEE potential is estimated from historical production and sales figures. In some studies this calculation was corrected by imports.
and exports data. The WEEE potential on weight basis is calculated by multiplying the number of appliances in each product group by their average weights.

For saturated markets where only product replacement occurs, the medium life-span of a product becomes irrelevant. If the 'market supply method' is applied to such situations, the numbers of obsolete appliances equals the numbers of sales minus the number of reused items.

The 'market supply method' and modified versions of it have been widely applied (ZVEI 1993, Streicher-Porte et al. 2005, Jain and Sareen 2006, Streicher-Porte 2006) and others.

\[
\text{WEEE generation } (t) = N_s(t) - N_s(t - \text{Is})
\]

\[
N_s(t) = N_{sp}(t) + N_{im}(t) - N_{es}(t)
\]

with

- \( N_s(t) \): National sales of EEE of certain category in year \( t \)
- \( N_{sp}(t) \): medium life-span of new product
- \( N_{im}(t) \): National production EEE of certain category in year \( t \)
- \( N_{es}(t) \): Imports of EEE of certain category in year \( t \)
- \( N_{es}(t) \): Exports of EEE of certain category in year \( t \)

'Time step method'

In addition to the 'market supply method', the European Environmental Agency also applied the 'time step method'. The Agency applied both methods for calculating the material flow of five different EEE categories in the former 15 EU countries. In the 'time step method' the amount of WEEE generation is calculated based on private and industrial stocks of two consecutive years and sales data. This method only applies in the case of a steady state with similar material composition of old and new products. In such a state each obsolete item becomes replaced by a similar new one.

\[
\text{WEEE generation } (t) = [stock(t-1) - stock(t)] + \text{sales}(t)
\]

'Carnegie Mellon method'

Matthew extended the 'market supply method', assuming a typical lifetime data for recycling and storage phases of EEE appliances. This so called 'Carnegie Mellon method' was applied to estimate the generated waste amount from PCs in the USA. According to this study, about 150 million PCs would be land filled in 2005 (Matthews et al. 1997). He introduced a cascade of processes consisting of 1. use of new products, 2. reuse of used products and 3. storage of used products. This resulted in three stocks which determine the WEEE generation during a specific year. The transfer parameters from one stock to another were kept constant. The same method was applied again in 2003, though with slightly altered parameters.
Figure 13 shows the cascade flow of the 2003 study, illustrating the percentages in each stock from the original input (Matthews and Matthews 2003). Most notably, between 1997 and 2003 study, the lifetime estimates of new products and the percentage of PCs going to ‘landfill’ and ‘recycling’ varied. This resulted in the medium life-span of a PC being decreased from ten to nine years. This cascade model is ideal for the extensive examination of individual products, although one does need more specific data on consumer behaviour (such as life-spans) and country specific data (such as recycling percentages). This method has also been applied to estimate future volumes of generated WEEE in different kinds of appliances—e.g. televisions, washing machines, air conditioners, refrigerators and PCs in the Philippines (Peralta and Fontanos 2006).

Figure 13 Pathway of a PC from purchase to end of life (data taken from Matthews et al 2003)
Discussion and Conclusions

The overall research question will be discussed in light of the results from the three case studies. Special focus will be laid on the conclusions which can be drawn from the development of assessment methods and from the analysis of existing waste recycling systems.

How can the complex reality of a WEEE recycling system be depicted in a generic model?

Electrical and electronic products are complex in their functionality as well as in their material composition. After being used for their original purposes, they enter the waste stream, outdated in their technical features but unchanged in their material complexity. Quantitative methods which use products as functional units and trace the decomposition of such products step by step lend themselves well to the assessment of environmental or economic impacts of recycling. These methods are mainly MFA, SFA, IOA and LCA or modified versions of these. The studies have shown that MFA models which differ in their level of complexity can produce valuable information for specific aspects of WEEE recycling systems. Static MFA models tend to deepen system knowledge, provide an overview of certain regions, allow access to certain recycling techniques and their material flows, or depict material flows from a certain product range. Dynamic MFA models, on the other hand, tend to forecast the magnitude of future waste generation or to estimate derived variables, such as monetary values, from the waste flows.

A generic MFA model can be applied, for the purpose of detecting the main distribution of materials, monitoring material flows, or identifying material losses or material sinks within a predefined system border. Generic models help to structure data e.g. from monitoring or compliance schemes of WEEE management and recycling systems which already exist in Europe and Japan. Such a field of research has been touched upon in the second case study. The disadvantage of a generic model is that once applied to a specific tracer item or functional unit, intersecting elements of a WEEE management system are difficult to accurately allocate. This occurs if the recycling fee of one WEEE category is used for cross-subvention of other categories (an example of which can be seen in the Dutch WEEE management system).

In order to investigate specific system characteristics, such as stakeholder interests or the influence of metal prices of strategic metals, more specific models are required. In addition to this, from a system management point of view, specific models which describe the underlying cause-effect chains of existing WEEE recycling systems are of greater interest than a generic model. Such an approach is justified by the results of the first case study, which revealed the considerable degree to which the recycling methods vary in CET countries and how much the recycling volume is influenced by the retarding effects from reuse and refurbishment. Analysing WEEE recycling systems in CET countries can, therefore, be said to require more specific models. The third case study goes a step further by introducing threshold values of formal and informal WEEE recycling. This is due to the fact that individual conditions of a recycling sector, the threshold from which recycling becomes profitable, is included in the MFA model. Once again, then, the context of recycling in developing or CET countries reveals the need to design specific models, rather than a generic one.
How can the quantities of the investigated electronic waste recycling systems be measured?

The quantification of waste recycling systems stands and falls with the quality of the data provided. MFA models are the most suitable and obvious methods for quantifying the WEEE stream. They directly assess the physical material flows and apply accounting methods and the mass conservation law; thus, allowing for a comprehensive analysis.

The material composition and the specific life-span of EEE vary considerably, both between various categories as well as between specific products within one single category. In addition to this, the technological changes which certain products undergo from one generation to the next bring about changes in the materials used. Thus, although products such as cathode ray tube monitors and flat screens may be used for the same purpose, their composition is quite different. Finally, the amount of new products added to the panoply of EEE increases continually, especially in the case of ICT equipment. The above mentioned degree of variation, poses difficulties for MFA WEEE recycling models. Those of a more abstract nature, despite being easy to apply, lose in their degree of accuracy whilst those of a more accurate nature tend to be more complicated when applied.

The studies have shown that input-driven or stock-driven MFA models of functional units are suitable for the description of the consumption of EEE products. Monitoring the units of sales and imports is relatively easy as the data is collected by the original equipment manufactures, governmental bodies or private consultant agencies. Data for stock-driven models is more difficult to obtain. But it depicts the time shift of consumer goods more accurately than input-driven models.

Study one and two applied input-driven models. In the first study they were used to help structure the results gained during field studies and to provide an initial impression of the quantities of materials involved. The second study used them to investigate saturated PC markets in Switzerland. This fact diminishes some of the dynamics, as in a saturated market products becoming obsolete are simply replaced. The model investigated PC units but did not focus on the material composition per PC. A second main focus of study two concerned itself with economic factor, which were analysed also on the base of PC units, independently from the mass flows. As long as these preconditions, -saturated markets and calculation of fees per unit-, are fulfilled, input-driven static MFA models are applicable.

In contrast, study three applied a dynamic, stock-driven MFA model, it being the ICT consumption of a fast developing economy that was investigated. The decision in favour of such a model was taken due to the following reasons:

1. The use of PCs is driven by the demand for the services they provide, rather than by the supply of the physical product itself. Many of the services can only be accessed by individuals if a certain level of PC saturation in the society is secured. Therefore, the number of PC per capita is a good indicator of a country's state of economic development (e.g. also used from the World Bank as a world development indicator). The model which deals with future developments has the advantage of including the numbers of PC per capita directly in the model.

2. For durable consumer goods of a medium and long life span, it is consumer behaviour which mainly determines whether a product should be replaced or purchased. In the case of PCs, this mostly depends on how up to date the PCs are. It is not the physical structure of a PC which determines this life-span, but rather, the consumer's demand for newer software, faster processors, larger memories or new functions which
also require new hardware. To assess such systems one can monitor the inputs and estimate the life spans, that is to say, apply an input driven model. Nevertheless, a stock-driven model allows for the direct control of both the stocks and the medium life-span of the goods, and thus, represents the actual driving forces of durable goods better than modulation of inputs do.

The studies also revealed that in addition to the input and stock information, an output control is necessary. Trends have shown that some metals, such as copper and gold, decrease in their weight percentage used in PCs, whereas others, such as iron, are constant or on the increase. These major tendencies in the material composition of EEE were recognised in study three –thus, justifying the decision to use a dynamic MFA model in which all parameters are time dependent. The model allowed an accurate calculation of costs and revenues that recyclers can expect from PC recycling. With adjustments, such a model also allows for the controlling and monitoring of toxic substance treatment and the costs involved. Ongoing discussions about the revision of the EU Directive on WEEE suggest that both output and input control of WEEE management systems would be desirable. (Huisman 2003, Magalini and Huisman 2006).

Models which are designed for monitoring and controlling have to be of a different nature than scientific MFA models. The first and third studies include specific processes as system understanding and stakeholder involvement are of interest. The second study takes a closer look at institutional setting. Specific information on treatment processes or economic benchmarking was therefore not necessary. While designing specific models, processes have to be simplified and pulled together. Models which describe the changing environment of WEEE recycling must keep track of technological, economic and institutional parameters.

How can measures be identified which guarantee certain system developments?

Today, management knowledge of how to organise an efficient WEEE recycling system is in demand. One look at the present chaos in European Union member states as they attempt to implement such systems gives an impression of the choices and decision making problems faced by countries when involved in such a process. European WEEE recycling systems have shown that the size of the economy to which it belongs seems to have an influence on the system setting. Larger economies favour a more competitive system in which several WEEE 'service providers' may exist whereas smaller economies tend to prefer collective systems, concentrating the managerial competence in one organisation. Fee collections of WEEE recycling systems also vary between advanced-recycling and pre-recycling fees, as well as visible and inbuilt fees.

The second study evaluates two systems within smaller European economies (Switzerland and Norway), both of which have chosen collective systems. It shows that during the setting up and implementation of systems, many pragmatic decisions have to be made. In the case of both countries, one such decision resulted in the decision to set up a specific fee structure. These fees provide financial resources for the system, enabling it to cover a large range of products and maintain a high recycling rate, whilst still complying with environmental standards. Business models also had to be chosen, such as the coupling of reimbursements for recycling to sales prices or to profits from material recovery. In the case of the Swiss system, the assessment of material flows and recycling fees over more than ten years showed that the system runs the risk of being underfinanced before reaching a steady state. Today, both the Swiss and Norwegian systems endeavour to carefully monitor the material composition of WEEE flow and include an economic evaluation of this into their future planning of arising costs and fees to be collected.
The preference for this specific system in smaller economies is an indication that it might be difficult to implement collective WEEE recycling systems in larger economies such as India or China. Indeed, the current presence of informal recycling alongside certain initial formal activities in India shows that two WEEE recycling systems already co-exist. The sheer size of the Indian and Chinese economies suggests that several systems might be more suitable for the regulating of the WEEE waste stream. The results of the second paper show that a system which collects pre-recycling or advanced recycling fees, is able to organise the collection and transport of WEEE and can, through additional funding, create incentives for recyclers to make environmentally sound recycling economically feasible. These are some of the typical features of the collective systems in existence today. To economically optimise the system performances, an economic evaluation of material flows and supervision of the actual costs is required.

The key questions: which business model and how to finance it, are of greatest importance for fast system implementation. Systems or companies which leave out the question of how to finance the services they provide, run the risk of crashing - a mistake which, although obvious, has frequently been made.

WEEE recycling creates profits by means of valuable material recovery, but also incurs costs by the sound disposal of non-valuable or hazardous components - be they real or costs which are not internalised and paid for by society. Recyclers are part of a bigger economy which in turn sets certain frameworks for the recyclers themselves. These frameworks can be legislative obligations, the cost of the production factors labour and capital, technical knowledge, economy of scale effects, subsidies for a particular recycling practice, voluntary corporate responsibility programs and other factors. Thus, it is hardly surprising that WEEE recyclers as an industry sector make up an extremely inhomogeneous group. This can be particularly observed in CET countries, in which social strata vary strongly and entrepreneurship of individuals creates income from small scale WEEE recycling. Therefore, scientific investigation of the key driving forces is helpful, if the system's understanding is to be deepened. In the case of WEEE it is well known that metals play an important role for profitable recycling. This proved to be the case in the first study. Nevertheless, additional studies which take into account specific regional features should be considered during system planning. Collection systems for WEEE are currently one of the big issues in India and China. It may be that valuable information on how to efficiently collect WEEE could be gained from social studies, e.g. who is responsible for waste disposal of private households. Information gained from other socio-economic studies might provide options on how to include the informal economy into a formal recycling industry. An example of this can be seen in the small scale Indian milk production firm, which delivers milk to multinational dairy companies.

Stakeholder interests are highly influential on system design. Such interests are often financial benchmarks which define the level at which a stakeholder expects positive revenues to be achieved. Representing these interests in a model requires a more complex approach as more detailed data is required. But too often reliable data on material flows and losses and economic indicators is not available or can not be collected systematically. Such information is particularly difficult to obtain in the informal recycling sector but can also prove difficult to obtain in formal industries in which processing techniques and recovery levels are often confidential. To avoid or bypass such knowledge gaps, the third study introduced a tool which channelled the recycling flows according to mass-flow and economic values. The advantage of a combination of MFA and an economic evaluation model is that the physical flows and economic factors which influence the individual decision of recyclers are connected. This more "agent based approach" acknowledges that there is competition between recyclers, and shares
of the whole recycling volume are distributed to recycling sectors according to their economic efficiency. Thus, the combination of methods is particularly suitable when assessing formal and informal industries. The study differentiates between two options for metal recovery of PCs. For a more accurate depiction of a specific regional situation, it would be necessary to include other parameters in a future study – such as collection or transport.

To limit the MFA models to a specific tracer item or functional unit is of great advantage, as data mining becomes more focused and data on material composition is more accurate than it is for a range of products. The number of stakeholders is also reduced if one looks at only one product and not at the whole EEE sector. But this limitation has its disadvantages, key parameters of the model changing considerably within EEs. This can have substantial influence on the modelling results. In addition to this the change of the tracer item itself challenges the research. Particular in ICT markets, products change rapidly and an increase in sales units is expected.

It is expected that the sales of ICT appliances will continue to increase strongly in CET counties. At the same time, ICT appliances will undergo considerable change in design and size. For example, sales data in developed countries and India already show that desktop computers are being replaced by laptops. On top of this, ICT will pervade everyday life to a far greater extent than it does today. Indeed, we may reach a state in which traditional PCs no longer exist as functional units, but as integrated parts of buildings, transport systems and everyday objects. Considering both developments, - increase in sales and effects of miniaturisation–, models which use functional units are in danger of becoming inaccurate the longer they attempt to predict the future.

How can models of different WEEE management and recycling systems be compared?

Different scopes have to be considered when WEEE management and recycling systems are compared. These are:

- Product scope (types of products covered under the system)
- Process scope (applied processes, business network)
- Stakeholder scope (relevant stakeholders, institutional settings, legal requirements)
- Financial aspects (business and financing models applied, type of fee)
- Controlling and enforcement (licensing and monitoring)

If one wishes to compare WEEE management and recycling system, it is of great importance to take the product coverage into account. This is due to the variety of EEE material composition, life-span and their need for specialised treatment. Consequently, the handling of EEE requires very specific knowledge for collection, transport and recycling. The studies were simplified, insofar as only PC recycling was considered, the upshot of which being that it did not allow for a full system comparison.

The process scope of a WEEE management and recycling system influences the level of material and/or energy recovery as well as the system’s performance. To make a valuable analysis, only systems or system elements which reach the same level of recycling should be compared. A system which only performs collection, dismantling and pre-processing always does better in its environmental performance than one which has to deal with full material, substances or energy recovery.
As shown in paper three particular stakeholders can influence the direction of material flows, such as WEEE being treated within the formal or informal sector. The legal requirements can be seen as part of the stakeholder scope, as some systems are enforced by law (e.g. such as in EU countries under the EU directive on WEEE), or in others which are self organising (e.g. in India and Switzerland). If systems are to be compared, the resulting institutional setting and stakeholder’s involvement have to be described.

The financial scope looks at the business model and the applied financial mechanism. Systems can also be self organising in their financial structure, as is the case in India in which the free economy determines the prices of recycling, or in the case of Europe, Japan and some US states, where the decision for a particular financial mechanism dictates recycling costs. In the latter case, the type of collected fees and the use of these have to be considered before any valuable system comparison can be made.

The controlling and enforcement aspects only apply to formal WEEE management and recycling systems which have identifiable bodies for these tasks. The power balance and the formation of recycling monopolies are under fierce discussion at the moment. To shed some light on the licensing and monitoring procedures of systems, such as those currently emerging in Europe, the individual standards of monitoring and controlling bodies as well as the enforcement mechanisms within each country have to be considered.

The performance or sustainability of WEEE management and recycling systems are best measured on three different levels: environmental efficiency, economic efficiency and social acceptability. It is, however, hard to define one “best practice” for WEEE recycling or reuse schemes, the situation between industrialized and developing countries differing considerably. For example, how should a “best practice” weigh up the damage of pollution against the profits of income generation, or the benefits of a prolonged life-span against environmental costs of growing consumption? Despite such difficulties, the definition of “best practices” remains important, national regulations for waste exports relying on it and mutual learning between countries or regions benefiting from it. Nevertheless, results which favour certain recycling systems (such as that used in Switzerland) do not prove that such systems would be suitable for India or China.

Environmental and material efficiency

Best practices for the environmental aspects of WEEE management and recycling are relatively easy to determine and are in the majority defined by technical processes. These have not been investigated in detail in this study, but are of utmost importance if systems are to be compared. MFA studies are particularly suitable for depicting the material efficacy of recycling processes as well as emissions to the environment involved.

Economic efficiency

The economic efficiency of WEEE management and recycling is difficult to assess and is linked with a third level: that of social acceptability. Comparisons of economic efficiency between systems in different countries very much depend on how WEEE recycling is organised and the prevailing recycling practices:

The second study revealed that the institutional setting of a WEEE recycling system is of importance if the financial efficiency is to be measured. It also showed that knowledge of material compositions in the waste stream can help to optimise the overall cost for recycling and create transparency, particular if systems charge additional fees for
recycling. To optimise systems such as those in Switzerland or Norway, little consideration of social issues is necessary.

The third study revealed that if recycling practices differ considerably, a more detailed analysis has to be made if valuable conclusions are to be reached. Not only can the material efficiency vary, but also the necessary investment for applying and running certain techniques. This has direct consequences on the competitiveness of recyclers. In addition to the above, the social dimension is affected by different techniques, some practices requiring more employees than others.

Social acceptability

For countries which do not yet rely on highly mechanised dismantling and recycling, a recycling system may profit from existing informal activities. The challenge to improve the environmental and financial efficiency, whilst still taking the social dimension into account, lies in finding an intelligent balance between acceptable and unacceptable informal recycling activities. Acceptable activities are those which adjust to the market and labour conditions of such countries and apply techniques which do not produce hazardous emissions. Irregular activities are those which apply crude recycling methods, pollute the environment and pose risks for people involved in recycling. Decision makers will be challenged in the future to consider possibilities for supporting acceptable recycling activities as well as pre-processing steps by those within the informal economy.

On a macro level of comparison, the historical development of the WEEE management and recycling systems, and country or regional specific characteristics have to be considered.

These are for example:

- the level of saturation of EEE products per capita in the country or region (e.g. almost one PC per person in Switzerland and little more than one PC per 100 persons in India)
- the size of the economy (e.g. India or Switzerland)
- the macro economic situation during system set up and implementation (e.g. the Swiss system was set up at a time with low metal prices and great concerns of the emissions of ODS from EEE).

It is necessary to be accurate while comparing WEEE management and recycling systems. The second study takes this into account when comparing the Swiss and the Norwegian system.

The greatest challenges for WEEE management and recycling systems in countries like India or China are:

(i) rapid implementation, as the environmental impact, the economic losses and the impacts on health from WEEE recycling are rising fast

(ii) to be flexible enough to grow according to economic development. Currently, urban centres are definitely the hot spots for the implementation of WEEE management and recycling systems, soon, however, system managers will have to consider how to collect, transport and recycle WEEE from more remote areas.
One can conclude that there is no single answer to the question of how to introduce and organise WEEE management recycling systems. Systems have to be designed in accordance with consumer behaviour, the existing recycling structure and the particularities and idiosyncrasies of a specific region or country. One can also conclude that the best available technologies for WEEE recycling vary depending on the specific recipients. There will always be a trade-off between the environmental, economical and social efficiency of a WEEE management system. Some systems favour the one dimension at the expense of another. However, such variety mainly lies in the way material is handled before entering the final material or energy recovery –that is during collection, transport and pre-processing of WEEE. The economic or environmental efficiency of final material or energy recovery is mostly determined by technical factors and increases with the volume of processed material. Hence, one can identify an increase in possibilities concerning how to introduce and organise WEEE management recycling systems. Technical and environmental parameters are practically fixed, whereas the economic and social dimension can vary and depends on the targets which want to be achieved.

It can be hoped that future studies will assist in the finding of various ways through which WEEE recycling in CET countries can be turned into businesses which allow those involved in collection, transport and waste processing to upgrade their profession whilst still optimising environmental and economical efficiency of material and energy recovery from WEEE.

This challenges research to design specific models to depict the complex reality of WEEE recycling, and predict the future development of waste generation. In the case of the former, this study provides specific insight into both WEEE systems in the developed and developing world. In the case of the latter, whilst not presuming to make specific estimates for future figures, it does alert stakeholders to their responsibilities.

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Abstract
The management and recycling of waste electrical and electronic equipment WEEE was assessed in the city of Delhi, India. In order to do this, the personal computer was defined as the tracer for which a model was designed. The model depicts the entire life cycle of the tracer, from production through sale and consumption - including reuse and refurbishment -, to the material recovery in the mainly informal recycling industry. The field work included interviews with the relevant stakeholders, transect walks and literature study, which was followed by a software-supported material flow analysis (MFA) of the whole life cycle chain of the tracer item. In addition to the MFA, several economic aspects of the recycling system were investigated. The study revealed that the life span of a personal computer has considerable influence upon the system, most notably in the following two aspects: (i) a prolonged life span creates value by means of refurbishing and upgrading activities and (ii) it slows down the flow rate of the whole system. This is one of the simplest ways of preventing an uncontrolled increase in environmentally hazardous emissions by the recycling sector. The material recovery of the system is mainly driven by the precious metal content of personal computers. A first estimate showed that precious metal recovery contributes to over 80% of the personal computer materials’ market value, despite the small quantity of them found in computers.

Keywords: Material Flow Analysis, Informal Sector, E-waste Recycling, WEEE, Developing Countries, Countries in Economic Transition, Personal Computer, Upgrading and Refurbishing
1. Introduction

Situation and problem description

Electronic waste, e-waste or waste electronic and electrical equipment (WEEE) can be considered a danger to humans and the environment. The directive from the European Union on the restriction of the use of certain hazardous substances in electrical and electronic equipment intends to contribute to the protection of human health and the environmentally sound recovery and disposal of waste electrical and electronic equipment by means of these restrictions. “Member States shall ensure that, from 1 July 2006, new electrical and electronic equipment put on the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE).” (2002a).

E-waste is a generic term embracing various types of electronic equipment. According to the definitions in the directive of the Parliament and European Union Council on waste electrical and electronic equipment, WEEE can be subdivided into the ten different categories listed in Table 1. The categories “IT and telecommunications equipment” and “consumer equipment” constitute e-waste (2002b).

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<table>
<thead>
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<tr>
<td>1</td>
<td>Large household appliances</td>
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<td>2</td>
<td>Small household appliances</td>
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<td>3</td>
<td>IT and telecommunications equipment</td>
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<td>4</td>
<td>Consumer equipment</td>
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<td>5</td>
<td>Lighting equipment</td>
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<tr>
<td>6</td>
<td>Electrical and electronic tools (with the exception of large-scale stationary industrial tools)</td>
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<tr>
<td>7</td>
<td>Toys, leisure and sports equipment</td>
</tr>
<tr>
<td>8</td>
<td>Medical devices (with the exception of all implanted and infected products)</td>
</tr>
<tr>
<td>9</td>
<td>Monitoring and control instruments</td>
</tr>
<tr>
<td>10</td>
<td>Automatic dispensers</td>
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</table>

Table 1: WEEE categories according to the EU directive on WEEE

In the former 15 European Union member countries (EU15) the amount of WEEE produced varied between 3.3-3.6 kg per capita for the period 1990-1999 and has been projected as 3.9-4.3 kg per capita for the period 2000-2010 (EEA, 2003). According to this study (which assessed only five appliances: refrigerators, personal computers, televisions, photocopiers and small household appliances), this amount covers only 25% of the whole WEEE stream of the EU15. Hence, these numbers correspond to other estimates of total WEEE amounts, which range between 14 kg (Key note, 2003) to 20 kg per capita (estimated by AEA, cited in Enviros, 2002). The amount of WEEE generated constitutes one of the fastest growing waste fractions, accounting for 8% of all municipal waste (The Economist, 2005).

Although the per capita waste production in populous countries like China and India is still relatively small (estimated <1kg per capita and year), these countries are already huge producers of WEEE. These countries tend to also have the fastest growing markets for electrical and electronic equipment (EEE), ones that are far from saturation. From 1993 to 2000, the number of PC users in China increased 1052% whilst the average growth throughout the world was much lower at 181%. During the same period, India showed an increase of 604%. From 1996 to 2002, the number of mobile phone users in China rose to 200 million (La Revue Durable, 2005).
Due to these developments, countries like India face a fast increasing load of WEEE originating both inland and through illegal imports. For emerging economies these material flows offer a business opportunity. The backlog demand of EEE in developing countries as well as the lack of national regulation and/or lax enforcement of existing laws, promotes the growth of a semi-formal or informal economy. An entire new economic sector revolves around trading, repairing and regaining materials from redundant electronic devices. It provides a living for the urban and rural poor, but causes severe risks for humans and the local environment. For some of the densely populated regions poorly controlled WEEE recycling with extremely risky techniques is a grim reality. Most of the participants in this sector are not aware of the risks, do not know of better practices or simply have no access to investment capital to finance profitable improvements.

Environmental impact assessment and material flow studies for information technologies

Environmental impacts of information technologies have been assessed on various scales. A first group of studies discussed and evaluated how Information and Communication Technologies (ICT) change national economies and societies. These studies covered indirect as well as direct effects of the services provided by ICT industries on the natural environment (Allenby, 2004) and discussed the rebound effect of the ongoing change (Binswanger, 2001). Gleiber et al. (2005) investigated the direct and indirect impacts of Information Technology (IT) including the consumption of resources and energy during the production and use of ICT products.

A second group of studies evaluated the effect of changing entire systems for providing certain services. Hischier and Reichert (2003) compared the environmental impacts related to reading a printed newspaper to the impacts related to reading an online version and related to watching news on television. Matthew et al. (2002) analyzed different systems of distributing consumer goods.

The third group of studies investigated the life cycle of individual electronic products or components of EEE (e.g. Anders, 2004; Alonso, 2003; Vehlow, 2003). Hilty et al. assessed the future impacts of pervasive computing on health and the environment (Hilty et al., 2003). A major finding was that, due to continually increasing innovation cycles and material throughputs, electronic products are increasingly being thrown away which in principle could still be considered functionally sound.

The last category of studies however, focuses on the end of the life cycles of electronic products and the management of electronic waste on national or international scales. ICT equipment is representative of other EEE. This research supported the development of strategies to manage and recycle WEEE. A comprehensive report of the material flow of 17 EU countries and the EU15 (countries having been EU members longer) has been executed by the European Environmental Agency (EEA, 2003). An assessment methodology was developed in order to estimate the quantities of WEEE generated during the period from 1990-1999. By applying different algorithms for the life span of appliances future WEEE streams were extrapolated for the period 2000-2010. From this data the emissions of dangerous substances was estimated. AEA Technology Environment compiled a comprehensive and detailed report on the medium composition of WEEE and hazardous waste (Ogilvie, 2004). The report on a WEEE demonstration project carried out in 1999 and 2000 in the US state of Minnesota (Minnesota Office of Environmental Assistance, 2001) stated that voluntary partnerships for the col-
lection of EEE and product responsibility shared between the private and public sectors create opportunities to prevent the disposal of WEEE in municipal waste.

The Technology and Society Laboratory at the Federal Institute for Materials Testing and Research (www.empa.ch/tsl) is currently conducting a study of the situation of WEEE recycling in three selected regions in developing countries. The overall project aim is to reduce hazards without reducing the attractiveness of the WEEE recycling business. This implementation-oriented project has been scientifically complemented by two master theses both dealing with the pilot region in India: Sinha (2004) compared the recycling of e-waste in Switzerland as one of the very few countries with long-term experience in managing e-waste with India, which handles huge amounts of imported e-waste, but is continually experiencing problems. Steiner (2004) focused on a spatial risk assessment of the burning of copper cables, which is an important process in WEEE recycling.

Toxics Link, a non governmental organization (NGO) active on the supervision of harmful and hazardous substances in India, has published several reports on the matter of WEEE recycling in Delhi and Chennai including an estimate of material flow, a toxicological overview as well as an analysis of the economics of WEEE processing (Toxics Link, 2003/2004).

Many assessments focus on the environmental and economic evaluation of industrial processes or the activities of sectors of an industry. This paper in contrast focuses on the assessment of the informal sector of the recycling industry in Delhi. The goal of this study is to identify key drivers within the WEEE managing system. Which factors influence (i) the establishment of an informal industry and (ii) maintain such a highly inefficient system? The challenge that would really improve this situation is to prevent pollution without taking away the income from the local population.

2. Methods

The method applied to support the material and substance flow management in the waste and especially the e-waste sector of third world countries is the Material Flow Analysis (MFA). Material Flow Analysis is a generic term for analyses of matter flows (chemical elements, compounds, materials or commodities) which are based on material balancing representing the law of material conservation. In general, three different types of MFA have been presented in recent literature: (i) Substance Flow Analysis (SFA), which is primarily used to relate critical emissions of substances to processes, products and material inputs in the system (Baccini and Brunner, 1991; Baccini, 1996 und Bader, 1996; Voet, 1996; Graedel, 2002; Spatari, 2003; Vexler, 2004); (ii) Process-based Material Flow Analysis, which is primarily used to analyze specific questions of resource and waste management (Baccini, 1996 und Bader, 1996; Bringezu, 2000a) and (iii) Industry-based MFA, which is a tool to assess the environmental impact of economic development by analyzing the total material throughput of a system (Adriaanse et al, 1997; Bringezu, 2000b; Matthews et al., 2000; Daniels and More, 2002; Daniels, 2002).

In this study, a process-based Material Flow Analysis is applied. This choice of method is motivated by its ability to link material flows (resources as well as waste) to consumer needs, economic structures or technological development (Müller, 1998, Kohler et al., 1999, Redle, 1999, Faist, 2000, Hendriks et al., 2000, Faist et al., 2001, Hug and Baccini, 2002). Process-based MFA studies deliver indicator values for a system's characteristics (e.g. recycling rates), performance (e.g. resource efficiency, rates of resource depletion) and impacts (e.g. range of available resource deposits or landfill
capacities). As the method focuses on system comprehension rather than on environmental impact assessment, it is apt to reveal options for future development at an early stage of decision making.

This method taps to its full potential by applying a mathematical formulation and modelling as suggested by Baccini and Bader (1996). In the last 10 years this mathematical MFA has been applied in numerous studies in different fields: Zeltner et al. (1999), Real (1998), Binder et al. (2001), Sörme (2003), Hedbradt (2003), van der Voet et al. (2000), Hug et al. (2004), Bader et al. (2003), Bader et al. (2005), Müller et al. (2004), Johnstone (2001), Kohler et al. (1999), Schmid et al. (2004 a, b), Kwongponsagoon et al. (2005) and others and ongoing works respectively.

Furthermore, process-based MFA can be used as starting point for a joint evaluation of physical and economic characteristics of industrial systems (Kytzia et al., 2004; Kytzia and Nathani, 2004). The corresponding method, called Economically Extended MFA (EE-MFA), builds upon the similarities between process-based MFA and (economic) Input Output Analysis (IOA). If applied to analyse industrial systems, both methods describe flows of commodities between the various producing and consuming sectors within an economy over a stated period of time (Leontief, 1966; Miller and Blair, 1985, and Duchin, 1998). If each flow in a process based MFA is multiplied with its market price, the result can be interpreted as a kind of IOA, neglecting some conventions normally used in input output economics but following its basic principles. For example: the surplus gained by the sales of refurbished electrical items minus the payment for second hand or broken items and intermediates, is the value added created by the refurbishment industry. From point of view of input output economics, however, the process based MFA can be interpreted as a physical input output model and incorporated in a Leontief price model (Duchin, 1992). For example: the physical input output coefficients can be used to relate the product prices (e.g. for refurbished computers) to the prices of value added (e.g. wages per hour).

In this study a first outline was drawn suggesting how such a method could be applied to an informal recycling sector such as the one in Delhi, the capital of India. The national capital territory is spread over an area of 1 485 km2, which also forms the physical system border of the model applied in this study. The city of Delhi borders in the west on the state of Haryana, in the east on Uttar Pradesh. Solid waste management and recycling are organized by an informal industrial sector. Approximately 85 000 people are estimated to work in this sector, a lot of whom are immigrants from other Indian states such as West Bengal, Bihar or Uttar Pradesh, and neighbouring countries such as Bangladesh (Datta, 1997 in Agarwal, 2005 and Agarwal, 2005).

For this study the tracer item chosen was the personal computer (PC). A tracer item in this context stands for an electrical or electronic item which is surveyed along its whole life span, from the cradle to the grave. The definition of one tracer item PC represents all sorts of PCs. As the study focuses on the investigation of the years 1996–2003, a PC from that generation includes a processing unit of a standard PC terminal, a cathode ray tube (CRT) monitor, keyboard and mouse, and a printer and weighs on average 27.2 kilograms (Table 2). MCC (1996) calculated the average weight of a PC as 60 lbs, which correlates with the above mentioned number. Reliable statistics of sales data, measurable recycling practices and the high dynamics in the information technology sector were reasons for the decision to use the PC as a tracer.
Table 2: Fractions and medium weight of a personal computer (Atlantic Consulting and IPU, 1998; IRGSSA, 2004).

The assessment strategy followed a certain order: first players and stakeholders of the WEEE recycling stream were identified including importers, producers/manufacturers, consumers, traders, (individual households and the business sector), repair shops, dissemblers, scrap dealers and dismantlers. After establishing a rough system model, we decided on the assessment methodology. With transect walks and semi-structured interviews the different recycling processes were identified and described in detail, including photo documentation. Secondly, semi-structured interviews were carried out subsequently with the relevant stakeholders mentioned above. As some of the recyclers operate illegally, the assessment team had to interview them often in a totally casual manner and compile the information thereafter. Thirdly the assessment included the calculation of published and unpublished data from producers and manufacturers' associations.

To estimate quantities of PCs in Delhi a simplified calculation was used, as explained in the following two steps.

1. The MAIT (Manufacturers' Association of Information Technology India 2004) published data which give an overview of PC market penetration over the period 1996–2004 for all of India and for Delhi (Table 3).

2. We assumed obsolescence time by applying a very simple model and calculated the resulting quantities for scrap PCs: PCs shipped to the market (sales in Table 3) entirely and suddenly drop out, for instance, after 5 or 7 years. Hence, the number of obsolete PCs in 2003 equals the sales in 1998 (5 years earlier) and 1996 respectively (7 years earlier). The obsolescence time is subsequently fixed to match the number of actually found scrap PCs (comparison of Tables 3 and 4). This obsolescence time is valid if it stays in a window of the actual life spans indicated by the age of current scrap PCs (somewhere between 5 – 9 years).
3. Results

A field survey was conducted in order to confirm these data as well as to derive quantified regional data of the city of Delhi. At the same time an iterative process with participants from Indian non-governmental organizations, and Swiss and Indian research institutes produced a model. The survey results are presented first, followed by the model calculations and the economic aspects of the material flow analysis.

Field survey

Traditionally Delhi has recycled large quantities of imported waste streams. This is also true for e-waste. Truckloads of scrap PCs arrive from all over India. Although the origin of this e-waste was not tracked, we distinguish between local e-waste (generated in Delhi) and imported e-waste (generated in India and abroad), (Table 4).

### Scrap PCs in Delhi (2003)

<table>
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<tr>
<th>Description</th>
<th>Obsolete after years</th>
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<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td>local PCs</td>
<td>250 000</td>
</tr>
<tr>
<td>imported PCs</td>
<td>133 000</td>
</tr>
<tr>
<td>grand total</td>
<td>383 000</td>
</tr>
<tr>
<td>total Number of PCs dismantled/day</td>
<td>1 277</td>
</tr>
<tr>
<td>scrap mark up (ratio imported/local)</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>89%</td>
</tr>
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</table>

Table 4: Total number of scrap PCs entering Delhi's dismantling/recycling market. Imported PCs may arrive from abroad or from other Indian cities. Field surveys showed that 2 truckloads of scrap PCs arrive in Delhi on 300 days in a year. Considering a truck having a capacity of 6t, the total weight of scrap PCs imported into Delhi's dismantling market is 3 600 t/a. If an average PC weight of 27kg is assumed, this results in some 133 000 units imported per year. The scrap mark up indicates the ratio of imported scrap PCs to local scrap PCs. For an assumed obsolescence time of 7 years, for instance, the quantity of locally produced PC scrap is almost doubled by imports (+89%) (Source: MAIT 2004 and Empa Survey 2004).

In order to confirm these quantities, the CRT (cathode ray tube / monitor) was identified as a tracer item mainly because in the e-waste recycling chain in Delhi all scrap CRTs are processed in a small number of informal enterprises. There it is possible to count the units processed daily. It was thus possible to estimate the annual total obsolete PCs (assuming one monitor per PC) and to confirm an obsolescence time of approximately seven years (Table 5).

Mainly two stakeholders were identified to be involved in CRT handling:

- monitor dismantlers (very small informal enterprises, often in private households)
- CRT re-gunners (re-gunning = replacing the electron gun). These are small informal enterprises with several semi skilled workers and with some rather sophisticated equipment such as vacuum pumps to evacuate the re-gunned CRTs. The total number of re-gunning enterprises identified and operating in Delhi is 7. Their average daily output is 45-50 re-gunned CRTs totalling 320-350 re-gunned CRTs/day in Delhi.

### Description units/day

<table>
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<tr>
<th>Description</th>
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<tr>
<td>CRTs operational/day</td>
<td>47</td>
</tr>
<tr>
<td>CRTs being re-gunned (320 – 350 units/day)</td>
<td>350</td>
</tr>
<tr>
<td>CRTs rejected for re-gunning/day</td>
<td>544</td>
</tr>
<tr>
<td>Total number of monitors/day</td>
<td>941</td>
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</tbody>
</table>

Table 5: Summary of the assessment of CRT recycling units in Delhi. The number of re-gunned units was assumed to be at the upper limit of the range. The resulting total number of monitors is approx. 941 per day, which corresponds well with an obsolescence time of 7 years, which would produce 943 scrap PCs per day (refer to Table 3).
Development of PC scrap in Delhi

![Graph showing the trend of growth rate of PC sales in the Delhi market and the resulting scrap PC projection using the procedures described above: the time series of PC sales is shifted 7 years into the future and scaled up with a factor 1.89 (mark up of 89% according to Table 3).]

Taking the timelines of Steps 1 and 2 we constructed the confirmed obsolescence time of CRT recycling/day and the scrap mark up factor from imported and locally produced PC scrap, yielding a timeline for obsolete PCs (Figure 1).

**Model description**

During a workshop in 2004, various stakeholders established a material flow model. Representatives from Toxics Link (2005) and Saahas (2005), two Indian based NGOs, which have conducted surveys in the field of WEEE recycling, and the authors participated in this discourse. The resulting model (Figures 2, 3 and 4) shows a chain of processes through which the tracer item PC was followed. The material flow was calculated for the year 2003.

The system can be split into two sections: pre- and post-recycling processes. Figure 2 describes the material flow in kilograms per day of the pre-recycling processes. Figures 3 and 4 show the post-recycling processes. The process "Recycling" links the two sections of the system and at the same time symbolises a "point of no return". After entering the "Recycling" process, no items, components or material ever return directly to the pre-recycling processes. The material recovered during the post-recycling processes may enter factories of manufacturers or producers later, but in this study the material leaves the system simply for further use.

The boxes indicate processes, whereas the arrows show material flows for the scenarios five and seven years' life span of a personal computer. The live spans have been calculated in order to estimate the potential output. The life span of a personal computer is one of the crucial values needed to calculate future loads of waste. Darby (2005) outlined the consumer behaviour of WEEE disposal in the UK and IRGSSA (2004) described a sophisticated chain of reuse and refurbishing of personal computers in Delhi. The life spans of five and seven years as scenarios were chosen according to the estimations of these studies.
Material Flow Analysis

After the life span of a personal computer has expired, the tracer item enters the “Repair” process. The process chain is characterised by a forward supply chain including the cascade of the tracer good PC through the process chain. The daily input into the “Producer” process accounts for 3 712 PCs for the five year scenario, and 2 609 PCs for the seven year scenario. 441 PCs are imported daily into the system. This number is a rough estimate of the daily load brought into Delhi from the country or abroad. This import stream feeds into the “Repair” process, which sorts the functioning from the broken items. 5% of the items produced are rejected and go directly into the “Recycling” process.

Figure 2: Material Flow of the pre-recycling processes of the tracer item personal computer within the system border Delhi in kilogram/day. Balance calculated for the year 2003. The stock of the process consumer is according to Table 3: 2 350 000 PCs (or 86 330 000 kg) plus “sales” minus “obsolete”, (rounded off at three and four digits).
The second characteristic is a reverse supply chain, which is of particular interest in counties such as India. The field assessment of this study revealed the existence of a vital refurbishing and upgrading industry, dealing exclusively with used personal computers. The back-log demand of different social strata in developing countries for PCs has fostered an informal industry, which specialises on the refurbishment und upgrade of used items. The numbers of the flow from the "Repair" to "Traders" processes shown in Figure 2 include the upgrading of PCs with faster processors, increase in hard disc memory or other replacements of whole components. One example is the re-gunning of CRT tubes. This refurbishment includes several manufacturing processes as described above. The output is CRTs which are manufactured to produce unbranded PC monitors and re-enter the market through traders. With a medium weight of 12 kg per monitor the numbers shown in Figure 2 account for 325 (7 years) and 398 (5 years) re-gunned CRTs per day. The field data of the discovered daily re-gunning rates are slightly lower (300-350) than these calculated data (Table 5). The reuse of components (flow from "Reuse" to "Traders") depicts the recycling of components - such as IC processing chips, memory cards, capacitors or other individual components - which enter the market by being sold after having their functionality checked.

The post recycling processes showed in Figures 3 and 4 list the fractions of WEEE which have to be separated from the waste steam according to the EU directive on WEEE. The fractions have been calculated according the literature sources. Whereas the Minnesota report on recycling practices for used electronics (Minnesota Office of Environmental Assistance, 2001) provided information on the total fractions of plastics in PCs, Toxics Link (2004) provided information from the Handy & Harman Electronic Materials Group on the total material composition of PCs. Richter et al (1997) measured the content of components in and the medium material composition of printed wiring boards (PWB). The IRGSSA (2004) report calculated the medium weight of a PC monitor and the share of that comprised by cathode ray tube glass. The Indian specific recycling processes discovered during the field survey are indicated.

The manner in which the Indian recycling system deals with these fractions is illustrated in the following graph. By comparing the EU requirements to the existing recycling processes in Delhi, it may be noted that the Indian recycling system already complies with a regulative instrument such as that of the directive. The reason for and goal of this comparison is to draw attention to the general lack of clear guidelines for the management of WEEE and the presumption that some practices of informal industries in developing countries already conform to legal requirements. For example, the recycling of plastics in India separates all sorts of different plastics, produces plastic pellets and feeds them into the plastic industry. These markets are particularly dependent on the current price of plastic pellets or raw materials for the plastic producing industry. Nevertheless a sound system of recycling plastics was observed during the field survey of this study.

The largest material flow for the tracer item PC occurs within the CRT recycling and produces CRT glass (5 984/4 680 kg/day), (amounts for the five/seven year scenario are given in brackets, note from the editors). Current glass recycling in India does not consider the hazardous substances contained in CRTs' coating. The glass from CRTs is fed into a secondary glass market. Glass containing heavy metals and other contaminations enable the melting of glass at a lower temperature and is therefore welcomed by second-rate glass manufacturers.
Figure 3 and 4: Material flow of the post recycling processes of the tracer item personal computer within the system border Delhi in kilograms/day. Balance calculated for the year 2003.
Plastics constitute the third largest flow (3 456/2 752 kg/day). This amount in addition to the amount of burned plastic in the system adds up to the total amount of plastic in a PC. Halogenated plastics are of particular environmental and human toxicological concern; examples of them include: PCBs (polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)), substances with similar properties such as polybrominated biphenyls (PBB), polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol a (TBBP-A). PCBs are very persistent in the environment since they are very resistant to biodegradation. In addition, they are fat soluble, and tend to accumulate in organisms, with those highest in the food chain being most affected. Heating and burning of materials containing PBBs, PBDEs and other brominated flame retardants can produce polybrominated dibenzo-p-dioxins and dibenzofurans, which have similar toxicological effects similar to those of chlorinated dioxins (WHO, 1998). Halogenated plastics are flame retardant and abundantly used in electronic consumer products. The process of plastic recycling has to be assessed in a more detailed manner in order to estimate environmental impacts; nevertheless the fate of the plastics after they leave the system has to be included if the overall burden is to be properly evaluated.

The metal fractions of the recycling process are iron (4 957/3 960 kg/day), aluminium (2 280/1 820 kg/day), copper (1 255/1 000 kg/day) and precious metals (19.54/15.6 kg/day). These fractions are probably recycled in smelters, as they either form a large flow or contain valuable materials. The non ferrous metals are a mixed flow of a whole range of metals. In the order of prominence this flow contains lead, zinc, tin, nickel and others. This flow needs further examination, as the study revealed no information of the future fate and behaviour of these metals.

Economic aspects of the MFA

The economic analysis of the recycling system revealed the following information: The monetary flows of the pre-recycling processes are much greater than those from the post-recycling. This is hardly surprising, as a functional PC has a value far greater than the value of its material, no matter whether new or second hand. The "upgrade" flow from "Repair" to "Traders" results in a considerable monetary flow. These monetary flows have to be handled with caution, as they only refer to the surplus obtained from sales of refurbished or upgraded PCs or CRT monitors. Costs for additional components, wages, packing and transport costs have not been included in this calculation. In order to calculate the value added to the recycling system through upgrading and refurbishing, the exact input of all intermediate costs have to be considered. For this, a more detailed economic data inquiry is necessary.

The extent to which revenue can be gained by upgrading PCs depends upon several factors. The age of a computer, its brand, processor and general condition are just of the many factors which influence the second hand market in India. The value of a used computer also depends on the cost of new computers, which currently range from 15 000 to 20 000 Indian Rupees (INR) for a PC of 2.4 GB. The rough cost of second hand computers (up to 2-3 years old) ranges from approximately 2 000 to 3 000 INR for a monitor, 6 000 to 9 000 for a control unit (CPU) and 2 000 to 3 000 for a printer (authors' own investigations). The overall revenue generated by the process "Repair" (by means of refurbishing and upgrading monitors and PCs) ranges from 40 000 to 80 000 US dollars (USD) per day for the five year scenario, and from 30 000 to 70 000 USD for the seven year scenario (Table 6). The scenarios have been calculated for moni-

---

6 Calculated on the 08th of April 2005 with international exchange rates
tors and PCs, as the field study only provides an estimate for the daily rate of refurbished CRTs. One can suppose that for each CRT refurbished one monitor will re-enter the market. The calculation of the refurbished or upgraded PCs was carried out accordingly. Employment created through refurbishing and upgrading has yet to be analysed in full.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>INR/ refurbished or upgraded items (min. and max.)</th>
<th>$/item</th>
<th>$/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>6000</td>
<td>137</td>
<td>54595</td>
</tr>
<tr>
<td>5 year</td>
<td>9000</td>
<td>206</td>
<td>81893</td>
</tr>
<tr>
<td>7 years</td>
<td>6000</td>
<td>137</td>
<td>44582</td>
</tr>
<tr>
<td>7 years</td>
<td>9000</td>
<td>206</td>
<td>66872</td>
</tr>
<tr>
<td>PCs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>10000</td>
<td>229</td>
<td>40466</td>
</tr>
<tr>
<td>5 year</td>
<td>15000</td>
<td>343</td>
<td>60700</td>
</tr>
<tr>
<td>7 year</td>
<td>10000</td>
<td>229</td>
<td>33150</td>
</tr>
<tr>
<td>7 year</td>
<td>15000</td>
<td>343</td>
<td>49726</td>
</tr>
</tbody>
</table>

Table 6: Economic evaluation of the refurbishing or upgrading processes

The largest material flows of the post recycling system do not correlate with the monetary flows. The greatest monetary value of the material recycling is created by the precious metal content of personal computers. If one assumes that half the precious metal flow constitutes gold and the other half silver, these material recoveries would generate 134 063/107 031 USD for gold and 2 230/1 781 USD for silver per day. The value of gold would account for more than 80% of all the material recovered during the recycling processes (Table 7). Profits from sales of non ferrous metals have not been included in this calculation.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Recovered Material</th>
<th>$/kilogram</th>
<th>$/day</th>
<th>%</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>9.77</td>
<td>13721.93</td>
<td>134063</td>
<td>81.97</td>
<td></td>
</tr>
<tr>
<td>7 year</td>
<td>7.8</td>
<td>13721.93</td>
<td>107031</td>
<td>86.07</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>9.77</td>
<td>228.27</td>
<td>2230</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td>7 year</td>
<td>7.8</td>
<td>228.27</td>
<td>1781</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>2280</td>
<td>1.95</td>
<td>4444</td>
<td>2.72</td>
<td></td>
</tr>
<tr>
<td>7 year</td>
<td>1820</td>
<td>1.95</td>
<td>3547</td>
<td>2.82</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>1255</td>
<td>3.39</td>
<td>7070</td>
<td>4.32</td>
<td></td>
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<tr>
<td>7 year</td>
<td>1000</td>
<td>3.39</td>
<td>5624</td>
<td>4.47</td>
<td></td>
</tr>
<tr>
<td>Scrap</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>4957</td>
<td>0.10</td>
<td>496</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>7 year</td>
<td>3906</td>
<td>0.10</td>
<td>396</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Plastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>3456</td>
<td>1</td>
<td>3456</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td>7 year</td>
<td>2753</td>
<td>1</td>
<td>2752</td>
<td>2.19</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 year</td>
<td>5894</td>
<td>1</td>
<td>5894</td>
<td>3.60</td>
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</tr>
<tr>
<td>7 year</td>
<td>4680</td>
<td>1</td>
<td>4680</td>
<td>3.72</td>
<td></td>
</tr>
<tr>
<td>Sum of 5 year scenario</td>
<td>163547</td>
<td>100</td>
<td></td>
<td></td>
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<tr>
<td>Sum of 7 year scenario</td>
<td>125811</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Economic evaluation of the material recovery of the recycling processes

7 Calculated on the 30th of March 2005 with international trading prices
4. Discussion and conclusions

The refurbishment and upgrading of PCs and monitors constitute one of the key drivers of the pre-recycling processes. However the calculation of the monetary flow is only based on the market value of the upgraded or refurbished items. This scheme comprises one of the most effective mechanisms to: (i) create additional value and (ii) to prevent an accelerated flow rate through the whole system. The incentive is the increasing need for low cost personal computers among the ever-increasing group in the Indian population that uses computers. This market demand creates jobs and business in a second hand industry and at the same time decreases the overwhelming load of PC waste.

The precious metal flow is one of the key economic drivers of the system. The high material value of gold and concentrations of this metal of up to 4 grams per PC create strong incentives to recover this material fraction.

The study has shown that the main material flows for the recycling processes split into glass, plastic and metal fractions. The glass fraction creates little economic incentive, as the material is extremely cheap and cannot be used for high quality products without better separation techniques. In terms of volume, however, the glass fraction outweighs all other flows.

Similarly, the plastic recycling creates raw materials for other industries, but does not gain in quality or price. Although the selling price of recycled plastic pellets depends on the cost of primary plastic production - and hence on fossil fuel prices, the study reveals the existence of effective plastic recycling for several different plastic fractions.

The metal flows split into ferrous metals (the second largest group of the whole system), aluminium, copper and mixed and precious metal flows. The first three flows most likely go to specialised smelters, as the material can be regained quite easily during such processes. The considerable amount of these flows will certainly be of interest to the smelting industries, although the overall generation of value through copper, iron and aluminium recovery contributes less than 10% to the value added.

The fact that lead is potentially environmentally hazardous means that a future examination of the mixed metal flow must be undertaken, especially as lead constitutes a large fraction of this flow. Another metal of potential interest in this flow may be nickel.

Although the data base was not optimal, the methods applied in this study (such as the combination of a systematic analysis of material flows and economic values, as well as the field assessment) showed the potential to generate robust results. To develop a concise economic model of the whole MFA, detailed economic data on the informal industry will be required.

The model created allows the researcher to plan future assessments in a more focused way. Another research step will be the development of a dynamic model. Such a dynamic model would make the integration of data possible to describe (i) the continuously changing material composition of EEEs and (ii) the different life spans of EEEs, including changes in consumer behaviour.

The results of this research will be fed into the "Indo-Swiss-German national WEEE project" in India. In addition to this study, a research partnership project has been established among the University of Cape Town, the Bangalore based NGO "Resource Optimisation Initiative", the Swiss Laboratory for Materials Testing and Research, St. Gall, and the Federal Institute of Technology, Zurich. This study will contribute substantially to the further development of the model, as well as a monitoring tool for WEEE management and recycling.
Acknowledgements

The authors would like to thank the two anonymous reviewers for their helpful comments.

References


Abstract

Waste of electrical and electronic equipment, otherwise known as e-waste, is one of the fastest growing fractions in the worldwide municipal waste stream. As this e-waste contains valuable resources which can be easily recycled, as well as hazardous substances which have to be treated in an environmentally sound manner, many countries have launched programs to deal with this challenge. These recycling systems have to be cost efficient and recover material or energy whilst still complying with environmental standards. Switzerland has two such e-waste recycling systems which were established on a voluntary basis and have been operating since 1991. This paper evaluates the historical data of one system: SWICO and assesses the development of the system’s costs. It also forecasts the development of waste volume for personal computers until the year 2020. During the setting up of SWICO many pragmatic decisions had to be made, one of which resulted in the introduction of an advanced recycling fee on sales for each electronic item. From 1994 to the present moment, SWICO has expanded its activity, lowered its fees and increased its return rate to almost 100 %. In this work a comparison is made between SWICO and a similar e-waste system from Norway. Although the two systems differ somewhat in their calculation of recycling reimbursement - the Norwegian system couples these costs to actual metal and plastic prices- both systems have achieved high return rates and lowered advanced recycling fees. They are accepted nationwide and comply with high environmental standards. In addition to this, the Norwegian system boasts the lowest fees in Europe whilst still maintaining a high degree of transparency.

Keywords: waste of electrical and electronic equipment; WEEE; advanced recycling fee; WEEE recycling system; MFA; PC
Introduction

Waste of electrical and electronic equipment (WEEE) is the fastest growing type of refuse, accounting for 8% of all municipal waste in Europe [1]. The information and communications technology (ICT) industries are constantly adding to the panoply of electronic and electrical equipment (EEE), both in terms of volume relevant material stock and in the raised level of material complexity. Many components of this waste stream contain hazardous substances, which should not be disposed of in landfill sites or incinerated in waste-treatment plants but, rather, treated as hazardous substances. Conversely, components also contain valuable materials, such as precious metals and copper, which are of considerable economic value to a national economy.

Consequently, many countries have established systems which are specialized in the recycling of WEEE. These systems try to ensure that recycling and waste treatment (i) complies with environmental standards, (ii) is cost efficient and (iii) generates high material recovery rates. On an international scale the systems vary considerably; nevertheless, a worldwide tendency towards increasing material recovery can be detected. Each system faces a variety of challenges. Not only is financial security a must but voluntary WEEE recycling systems have to make sure that they are accepted by producers, consumers and recyclers, whilst still taking regional particularities into account. Consequently, a profound understanding of the driving forces for cost efficiency and for material recovery is required. This study aims at creating such an understanding based on a specific case study region (Switzerland) and makes a first attempt towards formulating best practices by comparing the Swiss and Norwegian WEEE recycling systems. It also assesses the material flow of ICT equipment and WEEE in Switzerland and evaluates the economic structure of the WEEE systems.

WEEE recycling systems are often organized in the form of a foundation, a spin off of an industry association or an independent trust. In general, they are non profit organizations. In this paper they will be referred to as WEEE recycling systems. Recycling is used in this study as an umbrella term for both material and energy recovery.

The Swiss WEEE recycling systems: SWICO/S.EN.S

The Swiss WEEE recycling systems, SWICO/S.EN.S, look back on a 14 year history. S.EN.S (Swiss Foundation for Waste Management) began organizing refrigerator recycling in 1991. It covers small and big household appliances as well as gardening equipment and tools and processed around 40'000 tons of WEEE from these categories in the year 2004 [2]. SWICO (Swiss Association for Information, Communications and Organization Technology) has been recycling office electronics since 1994. SWICO coverage includes EEE from: offices, ICT, dentists, graphics industry and consumer electronics as well as accessories and consumables. From 1994 to 2004, the amount of annual WEEE recycled by the SWICO system increased more than tenfold to over 35'000 tons [3]. For the past four years, the systems have operated under a unified tariff system with one mode of systematic monitoring.

How does the system work? According to their importing or sales statistics, manufacturers and importers of EEE pay an advanced recycling fee (ARF) to the SWICO/S.EN.S system. The tariff system categorizes EEE and allocates each category an ARF, which ideally corresponds to the necessary recycling expenditure. These fees are passed on to distributors, retailers and finally to the consumers, who pay an ARF with the purchase of any EEE. Consumers can bring back obsolete EEE free of charge to any retail store or special collecting point. Depending on the geographical region, SWICO/S.EN.S invites tenders from recyclers and subsequently estimates its costs for reimbursement for each kilogram recycled. The systems organize the collection and distribution of WEEE to cer-
tified recycling firms. They guarantee the recycling, thus fulfilling specific environmental legislative prescriptions. The recyclers and transport firms are commercially run companies which make profit by material recovery and by reimbursement for the recycled amount of WEEE from the SWICO/S.EN.S system.

In order to charge the sufficient amount on each sold item, SWICO has to estimate the sales of EEE and the amount of WEEE return. Under the SWICO system a provision for cross financing of different product categories has not been planned. Consequently, the SWICO management must take into consideration that increasing return rates or falling sales of one product category could result in a deficit for the entire system. Experience gained from SWICO has shown that financial liquidity over a six month period for any product category is needed in order to balance out the insecurities of the estimates. Today, the systems cover almost 100 % of all WEEE covered by SWICO. Fig. 1 illustrates the directions of financial and material flows.

The state of recycling systems of WEEE in the European Union

Since the release of the EU directive on waste electrical and electronic equipment by the European Council and Parliament, many European states have launched initiatives for the recycling of EEE. The directive has been in force since August 2004 and will continue to dictate national implementation beyond the passed deadline of August 2005. It obliges EU member states to install a recycling system for EEE with the objectives of (i) reducing the quantity of WEEE that ends up in landfills, (ii) increasing the re-use, material recovery and energy recovery of WEEE and (iii) mandating an extended producer responsibility for the whole life-span of EEE. "Member States shall ensure that producers or third parties ... set up systems to provide for the treatment of WEEE using best available treatment, recovery and recycling techniques. The systems may be set up by producers individually and/or collectively." The material recovery rates vary between 70 and 80 %. For ICT equipment "the rate of recovery shall be increased to a minimum of 75 % by an average weight per appliance..." [4].

To enforce this, the EU directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment bans the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). At the same time it stipulates the substitution of hazardous containing components with safe or safer materials when technically or economically feasible.

![Figure 1. Material and financial flows of the SWICO/S:EN.S systems](image-url)
The WEEE Forum is an association of voluntary, industry-driven collective WEEE recycling systems. According to this forum, 30 such operating systems are currently counted in Europe. "This brings the number of countries being covered in Europe by one or more collective WEEE take-back system to a total of 20: Austria, Belgium, Czech Republic, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Luxembourg, Netherlands, Slovakia, Spain, Sweden, UK, Norway and Switzerland." [5]. In their transposition of the EU directives into national laws, three countries make an ARF mandatory, seventeen leave the decision to levy a fee to the systems, and four countries mention no ARF at all [6]. Norway and Switzerland are non EU states; nevertheless, they have considerable experience with WEEE recycling systems and comply fully with both EU directives.

Methods

Material flow assessment (MFA) is a method of investigating flows of specific materials or substances through an economic system in a specific geographic area during a certain period of time. These flows are defined in mass units per time period. MFA applies a general mathematical description of the process network based on the mass conservation law.

For this study a MFA for personal computers (PCs), including desk top terminals and laptops, was applied in Switzerland. In addition to this, the MFA structure was extended to include data on material prices and product related fees -in this case an ARF. To understand the cost efficiency and the recovery rates of a WEEE recycling system, the combined analysis of material and financial flows are compulsory. As PCs are products with a long life-span, an analysis of the development of consumer stock and its influence on recycling processes is particularly relevant. Fig. 2 illustrates the MFA model for 2004, indicating the material and financial flows [3].

The input material flows are documented through the import-export statistics. Switzerland has no significant national production of EEE. Nevertheless, a considerable amount of PCs have been assembled in Switzerland -which have not, however, been counted in the import-export statistics. Consequently, data from an independent consultant provided valuable additional information as to the real PC penetration rate [7]. The SWICO system receives detailed import and sales data from importers and manufacturers, who are required to pay ARF to the system accordingly. Each recycler has to report their balance of processed material and quantities of output fractions annually to an independent monitoring body.

![Diagram](image)

Figure 2. PC recycling under the SWICO system in 2004
For the period 1994 until 2004, the average life-span was assumed to decrease from nine to seven years. This corresponds with the nine year calculated medium life-span of all EEE categories, which SWICO calculated using twenty years of import-export data and recycling volumes. The decrease of PC life spans was assumed, based on the results of other studies which indicated such a development [8]. The medium life-span describes the existence of a PC as an entire unit including first use, reuse and stockpiling. Sales of one year, minus the obsolete recycled items per year, describe the annual change of the PC consumer stock. For the validation of the annual change from 1994 until the present, the PC penetration rate of personal computers per 1000 capita in Switzerland was consulted [7], [9] and [10].

To forecast the development until 2020, two scenarios have been chosen:

- A constant penetration rate of PC per 1000 capita for the steady state and
- An increasing penetration rate of 2% for the growth scenario.

According to [10] Switzerland is a high-end, mature consumer market for electronic and electrical products. In terms of per capita ICT, it has consistently ranked at the top, spending US$ 3'618 per capita in 2001. This suggests a steady-state scenario. On the other hand, a shift in consumer preference from PC terminals to portable laptops can be observed. This may well lead to an increased penetration rate due to the fact that consumers may use laptops and desktop terminals. This would point to a growth scenario.

The calculation of the ARF under SWICO coverage follows a simple procedure. The following formula illustrates the calculation of the fee for any product category:

\[
ARF = \frac{(r \times O + R)}{S} \tag{1}
\]

- ARF = ARF (in monetary units per item)
- \(r\) = reimbursement (in monetary units per kilogram)
- \(O\) = Obsolete items (in kilogram)
- \(R\) = reserves (in monetary units)
- \(S\) = sales (in units)

All variables are included in this calculation time series. Sales (S) are monitored with import-export statistics and questionnaires [7]. Obsolete items (O) and reserves (R) are estimated by the SWICO body. The reimbursement (r) is the cumulative unit of all costs (recycling, transport, collection and administration) and depends on contractors' offers. The same variables plus the medium life-span of PCs (l) were used to calculate the scenarios. Sales of one year determined the obsolete items in a later year:

\[
o(t_x) = s(t_{x+1}) \tag{2}
\]

The annual sales of the future are calculated inversely. To keep the PC penetration rates for each scenario at the assumed level, the obsolete PCs can be forecasted. With (2) the necessary sales to balance out the obsolete PCs can be calculated. Following was assumed:

3. A moderate growth of population of 0.5 % per year.
4. 2 % growth of the 2005 sales for the growth scenario and 0.37 % growth of 2005 sales steady state.
The financial flows are documented by the SWICO/S.EN.S bodies. They are created by (i) advanced recycling fees which were raised from 1994 onwards, (ii) reimbursement per recycled kilogram of WEEE paid to the collectors, transporters and recyclers by the SWICO system and (iii) revenues from material recovery or expenses from final deposition (see Fig. 2). The economic evaluation is based on reimbursement per kilogram paid by the SWICO system and the material values of metals contained in a PC. Historical data from the London Metal Exchange was used for the following metals: gold, silver, palladium, platinum, copper, aluminum, zinc, lead and nickel.

Results

MFA of PCs in Switzerland

From 1983 up to the present moment the PC penetration rate per 1000 capita has increased to 863. The sales of PCs during the same period increased accordingly. The calculated numbers of obsolete PCs are illustrated, according to (2). The strong increase of the PC penetration rate corresponds to this development. Due to the decrease in PC life-span from 1983 up until the present, the numbers of obsolete PCs per year accumulate. Hence, the number of PCs sold in 2002 with an eight year life-span is exceeded by the number of obsolete units in 2010. Nevertheless the sales dictate the future amount of produced waste per year.

Figure 3. PC sales (1983 to 2005), recycled PCs and PC penetration rate of PC per 1000 capita in Switzerland (1983 to 2020).
1.1 million PCs can be expected to become obsolete in 2006. From 2007 until 2012, an annual average of 1.3 million PCs will enter the waste stream. Beyond this period the number of obsolete PCs will exceed present levels. Assuming a steady state penetration rate, the annual numbers of obsolete PCs will exceed 1.5 million. In the case of the growth scenario, in 2020 it will rise to almost 1.8 million PCs per year (Fig. 2).

**Economic evaluation of the SWICO system**

Aside from transport (14 %), collection and packaging (12 %) and administration (4 %), recycling costs account for the biggest financial obligation of the system (70 %) [3]. Fig. 4 illustrates the development of reimbursement for recycling paid by the SWICO system from 1993 to 2006. The amount paid per kilogram of processed WEEE was seen to vary in a certain range (band width, Fig. 4) due to the fact that recyclers who process large volumes offer lower prices per kilogram (production of scale effect) than recyclers with smaller capacities. Apart from the variation of reimbursement in one year, a clear decrease of reimbursement per kilogram recycled WEEE can be detected. The 2006 prices range between 22 and 31 of the 1993 indexed reimbursement level. The decreases of the payments are illustrated lineally, in reality these adjustments have been negotiated on a two year interval [13].

If we compare the reimbursement for recycling to the material value, a clear tendency can be seen. Fig. 5 shows the change of the Indexed 1993 value of elements contained in a PC, as well as the 1993 indexed reimbursement, paid for a PC with a medium weight of 12.3 kilogram. The material value increased between 1993 and 2006 to 177, whereas the reimbursement per PC came down to 32 of the indexed value. In real values the reimbursement came down from 20.8 to 6.7 CHF (75 % to 35 %), whilst the material value increased from 7.1 to 12.7 CHF (25 % to 65 %) over the same period. It should be mentioned that Swiss recyclers are not recovering pure metals. The recyclers' output fractions are material mixtures which have to be processed by smelters. Consequently, the revenue for recyclers will be lower than the mentioned amount. Nevertheless, in 2005 the revenues from material recycling of a PC exceeded the reimbursement. As a result of this, SWICO was able to lower the ARF between 1993 and 2006.

With (1) we calculated the overall reimbursement per kilogram (r) for recycling, transport, collection and administration in 2006. The actual ARF in 2006 for a PC is 9 CHF. We supposed that 2 % of the ARF would be held back as reserve (R) and that average PC weight would be 12.3 kilogram. This results in a reimbursement (r) of 1.2 CHF per kilogram WEEE. To calculate the future development of the ARF for both scenarios, the assumptions for reimbursement (r) and medium PC weight were first held constant, and then varied. The sales numbers (S) for 2020 were taken form the MFA model (fig.3).

In the case of a steady state, by 2020 the recycling system can be expected to be recycling roughly as many PCs as are sold. This would increase the ARF by 71 % from the 2006 level. In the case of the growth scenario, more PCs would be sold than recycled, resulting in a 55 % increase of the ARF. If we assume a decrease in the reimbursement (r) to 0.8 CHF per kilogram and a decrease in medium PC weight to 11 kilogram, both scenarios forecast a lower ARF. From 2006 onwards a 6 % ARF decrease was calculated for the steady state, for the growth scenario, 15 %.
Discussion

The SWICO recycling system will face increasing waste loads in the ICT category. The sales levels of the past years indicate a strong increase for PC waste in the coming five years. Assuming a decrease in medium life-span from nine to seven years, SWICO will be paying reimbursement for the 'historical WEEE' of PCs for some time to come. This waste originates from EEE, which no levy has been raised on. The flows in Fig. 2 support this statement. One can conclude, that the system is still in a transitional stage, during which (i) the ARF per sold item is used to cover costs of items upon which no levy was raised and (ii) increasing WEEE volumes have to be handled.

From the beginning on, SWICO calculated the ARF carefully, enabling it to grow rapidly and reach its current level of almost 100 % take back. Despite increasing processing volumes and the coverage of historical WEEE, SWICO lowered the reimbursement costs and the ARF for almost all EEE categories. This was mainly due to two reasons: (i) the increasing WEEE volumes allowed SWICO to organize collection, transport and recycling more efficiently; (ii) the increase in metal prices over the surveyed period resulted in high profits for recyclers.

One can assume that metal prices will stay at a high level. Similarly, there is no reason to believe that in the future manufactures, producers, importers or consumers will not participate in the system. This would offer the SWICO system opportunities to adjust the ARF to the real cost and profits of recycling and material recovery. Such a system would enable the recyclers to make profits from material contained in EEE, charging consumers for substances or materials which are hazardous or impossible to recover.

Sales numbers indicate a change in consumer preference towards using laptops rather than desk top terminals. The earlier mentioned calculations of decreasing reimbursement and decreasing medium weight reflects such a development. Laptops are definitely lighter than terminals. To make the ARF calculation more accurate, it is necessary to ascertain whether laptops contain more valuable materials for recycling and have a different life-span than desk top terminals.

The forecast of the ARF indicates that a recycling system like SWICO has to consider the transition into a steady state, during which sales correspond with the recycled amount. The reimbursement costs and the recycling volume are crucial for the present ARF calculation. As seen in the past, the costs depend on the material composition of EEE. The more valuable and recyclable the materials contained in EEE are, the lower the reimbursement cost for WEEE will be. Similarly, the medium weights of the recycled
products will determine the future volume of WEEE. To forecast costs and volumes more accurately, a better understanding of each EEE category is necessary. This study proposes both the monitoring of material composition and the medium weight of EEE, as well as the penetration rates of EEE per capita.

**Comparison with Norway**

The 1998 Norwegian regulations on WEEE hold producers and importers in Norway responsible for the environmentally sound processing of scrapped EEE products. In 1996, the Norwegian authorities initiated an extensive study of the estimated future volumes of WEEE per year within the different product groups. In accordance with the national WEEE directive, the main trade organizations made an agreement with the environmental authorities, promising to collect and treat in an environmentally sound manner 80% of the estimated volumes of waste per year within a five year period.

The collective WEEE recycling system, EIretur, has been operating since July 1999 and is of a similar design to that of the SWICO/S.EN.S systems, with the collective system covering all equipments listed under the WEEE directive. EIretur not only includes historical waste - upon which no levy was raised - but also charges an ARF for all new products. It is an independent, non-profit organization, founded by several Norwegian industries and trade organizations.

When EIretur negotiated with the transporters and recyclers for the initial contracts, it set up a ‘price ladder’ stating that the complete amount of reimbursement for the first year should balance 25% of the estimated total amount of waste. In order to reach the 80% goal, a similar scheme was to be implemented for the remaining years. In the case of the yearly increase being met, recyclers would receive an agreed reimbursement per kilogram of processed WEEE. In the case of return rates exceeding the yearly increase, recyclers would receive less, whereas if the return rates were less than the target, more than the agreed tariff would be given. Recyclers were given a platform for planning their activities and investment in recycling facilities.

A significant departure from the Swiss system can be seen in EIretur’s calculation of recycling-activity reimbursement and of the ARF. To minimize the risk of changing material prices, a particular mechanism was applied. When contracts were signed with recyclers, the market price of each fraction (metals, glass, plastics etc) was defined according to indexed prices of the base year for each fraction (from the London Metal Exchange etc.). In addition to this, part of the contract between EIretur and recyclers stated that profits or losses incurred by higher or lower material prices from the base year onwards would be shared equally.
Today the return rates of Norway, together with those of Sweden, are the highest amongst European countries. Thus, the first discussed risk of guaranteed volume became irrelevant as more than 80% was achieved. In the case of the second risk, quite the contrary occurred. EIretur has been able to lower the ARF continually due to the coupling of reimbursement for recycling to profits from material recovery. The system regularly adjusts the ARF according to its liability to the recyclers. Like all other WEEE recycling systems in Europe, the Norwegian take-back system benefits from the high metal prices, but in contrast to its counterparts, EIretur shares the benefits with the consumers by the adjustment of the ARF. Currently the Norwegians profit from such a cost sharing model by having the lowest ARF in Europe. To avoid price dumping, EIretur requires recyclers to be both profitable and fully transparent in their recycling activities, including the sampling of all recycling fractions. The setting up of this system has triggered a cost optimized recycling system, resulting in the equal sharing of risks and a greater transparency of the actual recycling costs and benefits. EIretur currently runs an online monitoring system and has five full time employees [14].

Conclusions

The Swiss recycling system of WEEE, SWICO/S.EN.S has created a common understanding between importers and producers of EEE. It became evident to participating companies that a voluntary collective system for the recycling of WEEE does not impede competition. On the contrary, it provides a good opportunity to guarantee environmentally sound recycling, as it minimizes costs and is also transparent.

When SWICO set up the system, it agreed on an apportionment procedure to cover costs for WEEE treatment with levies charged on sales. This typical feature of a waste managing system for products with relatively long life spans (e.g. batteries) carries the difficulty of being underfinanced - particularly if products are covered upon which no levy was raised. At the same time, decreasing sales and increasing return rates also pose a problem, a lower income being insufficient to cover cost expenditures. The managing bodies of such a system have to estimate the development of returned rates and effective recycling costs. SWICO did just this and was, consequently, able to lower costs whilst still increasing the recycled volumes and maintaining environmental standards.

In addition to the SWICO calculation, the Norwegian system, EIretur, includes the adjustment of recycling reimbursement, depending on actual material prices (metals and plastic). Such a procedure creates more transparency. WEEE recycling systems of this kind can pass profit from material recovery and the cost for non-recyclables and hazardous substances on to the consumer, thus guaranteeing a proper treatment of what WEEE. This includes the option to increase fees if material prices fall.

In their ARF calculation, both systems included the increase of processed volume and the developments of raw material prices. The first improves the recycling efficiency, the latter shares the risk of changing material prices between all stakeholders. In contrast to EIretur, SWICO did this without the explicit inclusion of material prices in the ARF calculation. It is interesting to note that despite the different business decisions made, in both cases, a similar development in the adjustments of the ARFs occurred.

The future development of WEEE volumes depends utterly on the consumer's buying behavior of EEE. All WEEE recycling systems which would like to guarantee the environmentally sound treatment, create transparency and operate with little governmental intervention must understand the market. To estimate their financial needs, WEEE recycling systems have to know whether they are dealing with a saturated market with mature products or a craze market with new products [15]. The cost of recycling for mature products could be easily extrapolated from its production costs or market sales value [16]. For immature products, the suggested MFA assessment might create a bet-
ter understanding, provided that the material composition, life spans, sales data of EEE categories and recycling costs of WEEE are available.

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Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies

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Abstract

Electronic waste sent to developing countries for processing and recycling poses high risks to the local environment and human health. Presently the waste processing and recycling from PCs is managed by informal recycling businesses. This sector bares high risks of environmental and occupational hazards and, at the same time, looses valuable materials form applying inappropriate techniques. Formal recycling industries have to compete with the informal businesses and simultaneously comply with environmental and occupational regulations. The presented model applies a dynamic stock-driven material flow model and an economic evaluation of gold and copper flows to the Indian PC recycling sector. The metal concentration per PC and value of these metals mainly determine the profits for recyclers. The study introduced threshold values for formal and informal gold and copper recycling according to their recycling cost per PC. At present level of metal concentration per PC and metal prices the formal sector will not become active. Two scenarios, one with double metal prices and a second with reduced threshold values for formal recycling, have been calculated. Also under these scenarios the formal recycling sector will not overtake a majority of the recycling. The model proves that a stock-driven dynamic material flow model can be combined with an economic evaluation of material flows. The analysis included a calculation of error propagation and a sensitivity analysis.

Abbreviations

BAT - Best Available Technology
EEE - Electrical and Electronic Equipment
ITOPS - Indian IT Hardware Market Study
ICT - Information and Communication Technology
IMRB - International Market Research Bureau
ITU - International Telecommunication Union
MAIT - Manufacturers Association for Information Technology
MFA - Material Flow Assessment
MMFA - Mathematical Material Flow Assessment
PC - Personal Computer
SWICO - Swiss Association for Information, Communication and Organisational Technology
WEEE - Waste of Electrical and Electronic Equipment
1 Introduction

In the last decade the number of personal computers (PCs) sold increased continuously to more than 210 million in the year 2005. Such appliances will eventually become obsolete and enter the waste stream. PCs contain first, valuable materials for recovery and recycling and second, hazardous substances which run the risk of being toxic to humans and the environment if not handled properly. The focus of this paper is on these two important problems. In Europe, a number of different recycling systems for waste of electrical and electronic equipment (WEEE) have been put in place, motivated by the EU directive on WEEE (EU 2002a). This directive obliges EU member states to install a recycling system for electrical and electronic equipment (EEE) with the objectives of (i) reducing the quantity of WEEE that goes to landfills, (ii) increasing the recovery, re-use and recycling of WEEE, and (iii) mandating extended producer responsibility for the whole life-span of EEE. The directive has been in force since August 2004 and continues to dictate implementation beyond the original deadline of August 2005. Similar WEEE recycling systems can be observed, such as in Japan and several USA states. Moreover the EU directive on reduction of hazardous substances bans the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) and stipulates the substitution of hazardous containing components for safe or safer materials where technically/economically feasible. Thus, this directive is of greater international relevance than that of the WEEE Directive, as producers will not be able to import products to Europe before having proved that they have not used any of the mentioned substances.

Many emerging economies; however, have not yet started to install WEEE recycling systems. One hindrance for the setting up of such systems is that the dominant informal economies in WEEE recycling do not comply with regulations for preventing damages to human health or the environment. (Puckett et al. 2002, ToxicsLink 2003, 2004, Puckett et al. 2005). Although low labour costs in the informal economy result in optimised recycling activities in terms of economic profit, such recycling activities cause a multitude of environmental and human toxicological effects. Many independent publications have recently devoted much attention to the subject of uncontrolled WEEE recycling, which was brought to light by the research undertaken by non governmental organisations (Puckett et al. 2002, Steiner 2004, Brigden et al. 2005, Hicks et al. 2005, Keller 2006, Wong et al. 2006a, Wong et al. 2006b). Pressure from international regulations, such as the Basel Convention (1989) and environmental activists (e.g. The Basel Action Network, Silicon Valley Toxics Coalition, and Toxics Link) does encourage developing countries to improve their WEEE recycling systems but, as yet, little progress has been made.

A number of studies on production, use and recycling of WEEE using Material Flow Assessment have estimated the future amount and composition of WEEE (EEA 2003). In addition, Life Cycle Assessment and Life Cycle Costing are used to evaluate regulations of WEEE recycling (Huisman 2003, Williams and Sasaki 2003). Several studies applied models that estimate future WEEE generation. From the information gained from collected sales data over a period of several years and assumptions about the medium life-spans for different categories of EEE, they estimate the volume of WEEE in the future (Matthews et al. 1997, Matthews and Matthews 2003, Jain and Sareen 2006). An overview is given in Lohse et al. (Lohse et al. 1998). However, an input driven model does not describe correctly the cause effect relations underlying the demand for durables such as electronic devices. Input driven approaches are appropriate to describe expendable goods like food or cosmetics, which are characterised by a short period of life span (days, weeks), while they deliver the intended service. The reason is that consumers use a certain amount of an expendable good per time, i.e. they determine the input of the good into use. In contrast, durable goods, which provide a service during a longer life span (years) have to be modelled by a stock driven approach. For durable goods, consumers are interested to have continuous access to a certain amount of those, i.e. they
determine the stock. The input representing stock increase and replacement is determined according to the life span of the good.

In this paper we will introduce a dynamic MF model for PCs in India that is driven by the development of the stock of PCs in households and industries. This model aims at better understanding the driving forces behind the generation of WEEE in India and the decisions made concerning specific pathways of WEEE recycling. To achieve a system understanding and collect data systematically, the following questions to be answered are:

- What are the main characteristics of WEEE systems in emerging economies and how can an appropriate model best represent them?
- What forces drive WEEE systems in emerging economies?
- What do we learn from model calculation about the design of a data collection scheme for future studies?

Such a model approach assumes future stock developments as well as the development of certain key parameters such as commodity prices, material composition and the weight of PCs. Such assumptions may seem somewhat arbitrary; yet they have been set making conservative assumptions about the stock development as well as the material prices. The assumed stocks describe a bottom line for the minimum stock of PCs reached in 2050. For the first assumption, the material prices remain at their present levels—a conservative prediction if we take into account the recent rise of metal prices.

The time horizon 2050 was chosen in order to go beyond the trend development of recent years which frequently tend only to look at the very near future. The suggested model implies both a stock driven approach for medium and long lived consumer goods as well as a recycling model determined by technological and financial parameters.

Unfortunately, little data on the current WEEE recycling systems in India is available. The actual in-use stocks of EEE have hardly been assessed and the illegal imports of WEEE cannot be quantified, as those active in this business always find ways to mislabel or hide container loads. The whole recycling sector in emerging economies is dominated by the informal business sector, which typically does not use standardised accounting tools. Only the sales figures and import statistics collected provide any sort of systematic data. This study will bridge the gap between the lack of reliable information and the need to systematically assess the present and the future situations.

The paper is structured as follows. In following second section, the material flow modelling is introduced as method of investigation. The third section provides a description of WEEE recycling in India with special emphasis on PCs. The forth section shows how the studied system is represented in a material flow model for India. In the fifth section, this model is used to calculate different scenarios for the future development of the Indian WEEE system, whilst the final section is devoted to discussion and conclusions.

2 Methods

The method applied to support the material and substance flow management of WEEE is the Material Flow Assessment (MFA). MFA is a method to analyse material flows (chemical elements, compounds, materials or commodities) which are based on material balancing representing the law of material conservation. In general, three different types of MFA have been presented in recent literature: (i) Substance Flow Assessment (SFA), which is primarily used to relate critical emissions of substances to processes, products and material inputs in the system (Baccini and Brunner 1991, Baccini and Bader 1996, van der Voet 1996, Spatari et al. 2003, Vexler et al. 2004) (ii) Process-based MFA, which is primarily used to analyze specific questions on resource and waste management (Baccini and Bader 1996, Bringezu...
2000a) and (iii) Industry-based MFA, which is a tool used to assess the environmental impact of economic development by analyzing the total material throughput of a system (Adriaanse et al. 1997, Matthews et al. 2000, Bringezu 2000b, Daniels 2002, Daniels and Moore 2002).

In this study, a process-based MFA is applied. This method was chosen for its ability to give a systematic overview of the system by describing and simulating the material flows of the whole system, including the flows at the sources and not only the emissions to the environment. Therefore this method is suitable for "early recognition": by considering the flows at the sources it is possible to "act" and not only to "react" if emissions exceed the thresholds. The process-based MFA links material flows (resources as well as waste) to consumer needs, economic structures or technological development and has been used traditionally to describe the current state (Baccini and Bader 1996) (Baccini and Brunner 1991, Müller 1998, Kohler et al. 1999, Redle 1999, Faist 2000, Hendriks et al. 2000, Faist et al. 2001, Hug and Baccini 2002). Process-based MFA studies deliver indicator values for a system's characteristics (e.g. recycling rates), performance (e.g. resource efficiency, rates of resource depletion) and impacts (e.g. range of available resource deposits or landfill capacities). This method taps into its full potential by applying a mathematical formulation and modelling as suggested by (Baccini and Bader 1996). In the last 10 years mathematical MFA's called MMFA have been applied in numerous studies in different fields: (Real 1998, Kohler et al. 1999, Zeltner et al. 1999, van der Voet et al. 2000, Johnstone 2001, Bader et al. 2003, Hedbrant 2003, Sörme 2003, Hug et al. 2004, Müller et al. 2004, Schmid et al. 2004, Kwonpongsagoon et al. 2005, Bader et al. 2006, Hilty et al. 2006) and others and ongoing works respectively.

3 System analysis for metal recovery from obsolete PCs in India

The analysis of the WEEE recycling system in India aims to describe and understand the material flows linked to the use of PCs, including their main driving forces. The first step is an analysis of the system. It is used to define the system (see section 3.1), select indicators to depict its specific behaviour (see section 3.2) and define evaluation criteria to assess the system's performance (see section 3.3).

3.1. System Analysis

The system was defined on the basis of the PC process chain of consumption, trade and recycling activities. However, this system definition can vary in different business environments. To assess the specific characteristics of the Indian WEEE systems, we reviewed the relevant literature and documents and carried out a field study in Delhi - including non-participatory observations and interviews. These field studies were performed in close cooperation with local partners.

The system consists of the following processes (see Figure 1), defined according to the functions they provide:

A. Consumption

As is well known, PCs are in industries, business, and private households. In India we observed a rather large market for second hand PCs or PC components. PCs are; thus, used for a long period of time -by different users- and a large variety of different PC types are in use (Streicher-Porte et al. 2005). This cascade use is brought about by large differences in income between the different social strata in Indian society. The Indian business sector and rich Indian households can afford to buy the newest PC types that are replaced after a certain life time. These will still be very attractive for lower income groups, after which, yet poorer people will take them on, despite their being out-of-date. These patterns of con-
sumption in a society can be described as a 'cascade use' (see (Binder et al. 2001, Matthews and Matthews 2003, Peralta and Fontanos 2006).

B. Trade

This process includes collection, transport, re-use and segregation of waste PCs. PCs are replaced for different reasons such as operational failure or insufficient performance. Replaced PCs are collected by private enterprises or public services. Collectors transport and distribute these items to either re-use, dismantling or waste treatment. In dismantling, various components in a PC are separated, such as printed circuit boards, cables, plastic and metal casings etc. These components are traded on, either for re-use or for recycling.

In India, the waste collectors from households are called 'raddiwallahs'. They pay the owner of the waste and sell the collected waste to specialized second hand traders or recyclers, making their living from the minimum profits gained. This profession lies between formal and informal business. Another major source of replaced ICT equipment is the auctions, in which equipment from business, industries or state organisations are sold. Private enterprises bid for offered ICT equipment and have to make revenues from reuse of whole units or components, or from material recovery.

C. Recycling

Recycling consists of pre-processing of PC components, material recovery, energy generation and final deposition. There is a large variety of technical processes that can be used for recycling. Developed countries tend to apply capital intensive processes such as metal smelting with appropriate waste treatment. In India, however, almost all recycling of PC components is carried out by small enterprises using processes with low capital costs and not complying with state regulations regarding taxation, environmental protection or safety standards. Certain preliminary studies have shown that uncontrolled WEEE recycling is a risky business for recyclers themselves, both in the immediate vicinity of the recycling locations and in areas further away, especially when emissions are carried by air or water (Steiner 2004, Toxics Link 2004, Brigden et al. 2005, Saahas 2005, Toxics Link 2005). To represent this phenomenon in the MFA system definition, we differentiate between informal and formal recycling. These terms are further specified in sub-section 0.

Figure 1 shows the system definition in detail. The cascade use is captured in the sub-system 'consumption' with n processes each including a stock of PCs in-use in a specific age group. The PC supply comes either from domestic production and imports or from the second hand market. Imports of PCs are, therefore, represented in the individual stock developments as long as reliable data is available. When PCs are no longer used -later called PC scrap- they are collected by EEE traders (second hand market) who decide over reuse of still functional units and sort out obsolete PCs to WEEE Traders. WEEE Traders dismantle PCs and sell the components to specialised recyclers, who carry out the final material recovery. However, the international trade of PC scrap - whether imported illegally or legally- is not considered in the model. Thus, the waste volume of obsolete PCs considered in the recycling model is generated by the consumption model. This is due to the fact that waste generation from national EEE consumption in countries with a fast growing economy outnumbers the volume of imported WEEE. Refurbishment activities involving the reuse of whole PC parts or individual components are not represented in the system definition. Such activities do, however, take place, but go beyond the scope of this model. The analysis of the recycling processes focuses on metal recovery of copper and gold. All PC components including sufficient amounts of copper and gold are sold to processes in the sub-system 'recycling' by the WEEE trader. The remaining components are either recycled (e.g. glass, plastics) or deposited in landfills. The sub-system 'recycling' is further differentiated between recycling processes in the formal and in the informal economy as mentioned above (see sub-section 3.3).
3.2 Selection of indicators

In MFA, indicators are selected for the following reason: to analyse pathways of certain substances through an economy. For example, it can be sufficient to select one specific substance whose behaviour in chemical reactions is representative for a whole group of other substances. Baccini and Brunner (1991) generalized this idea by suggesting that indicator substances or goods can be selected not only for chemical reactions but also for resource management in general: carbon, for example, can be used as an indicator for biomass consumption; phosphorus serves as an indicator for food.

In our analysis, we follow this idea and select copper and gold as indicator substances for WEEE recycling. This choice is motivated by the high material value of copper and gold in PCs. A first rough estimate is given in Table 1. Currently, recovery of copper and gold are the two main sources of income for recyclers (Streicher-Porte et al. 2005). WEEE recycling activities are therefore very sensitive to the magnitude of gold and copper flows originating from PCs.

<table>
<thead>
<tr>
<th>Material composition, metal prices and maximum expected revenues</th>
<th>Maximal expected revenues (US cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Ceramics and fiber</td>
<td>6.8</td>
</tr>
<tr>
<td>Plastics</td>
<td>13.0</td>
</tr>
<tr>
<td>Iron</td>
<td>66.2</td>
</tr>
<tr>
<td>Aluminium</td>
<td>6.6</td>
</tr>
<tr>
<td>Copper</td>
<td>6.5</td>
</tr>
<tr>
<td>Lead</td>
<td>0.2</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.1</td>
</tr>
<tr>
<td>Tin</td>
<td>0.3</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.1</td>
</tr>
<tr>
<td>other metals</td>
<td>0.2</td>
</tr>
<tr>
<td>Gold</td>
<td>24</td>
</tr>
<tr>
<td>Silver</td>
<td>107</td>
</tr>
<tr>
<td>Palladium</td>
<td>9</td>
</tr>
</tbody>
</table>

Non-ferrous metal prices: (London Metal Exchange 2006) accessed on October 26, 2005
3.3. Evaluation criteria

Evaluation criteria are introduced to evaluate whether a certain development is preferable to the status quo or not. In this study, the evaluation focuses on issues of environmental protection and resource conservation. Comparable analyses often use evaluation criteria which try to capture the system’s impacts on the environment (e.g. Huisman 2003). This was, however, not possible in our study as data collection in informal WEEE recycling businesses is very difficult. Informal recycling processes have not, as yet, been quantified or described in any kind of detail. Emissions have equally not been measured, nor the degree of and consequences of human exposure to the different processes involved. The great number of enterprises active in trading and recycling, as well as the variety of practices used, makes such a task impossible. In addition to this, it is difficult and even dangerous to collect data in the informal economic sector which dominates WEEE in India today.

We, therefore, use system orientated criteria as suggested by Bringezu. Such criteria indicate the deviation of present systems from a desired system or from one which should be prevented (Bringezu 2000b). In the case of WEEE recycling, two main requirements have to be met: a material recovery rate as high as possible and an appropriate waste treatment ensuring damage prevention for human health and the environment. The first evaluation criterion, therefore, is material recovery. We consider the choice of a WEEE strategy to be preferable, if material losses are to be kept as low as possible. In our system definition, material losses are represented by the flow of material from the WEEE Trader to landfills.

The second evaluation criterion is not as evident because the environmental sound treatment of the waste stream is much harder to assess. There is strong evidence that informal recycling as it is currently practiced is neither environmentally compatible nor harmless for health.

Indeed there are numerous studies showing that there are uncontrolled emissions and risks for health caused informal recycling techniques such as open burning of the burning of cables and printed circuit boards (Steiner 2004, Brigden et al. 2005, Wong et al. 2006a), roasting of printed circuit boards over burners for component separation or for solder recovery (Brigden et al. 2005, Wong et al. 2006a), toner sweeping, plastic chipping and melting, burning wires to recover copper, heating and acid leaching of printed circuit boards (Leung et al. 2006), gold recovery from printed circuit boards with cyanide salt leaching or nitric acid and mercury amalgamation (Keller 2006), and manual dismantling of cathode ray tubes and open burning of plastics (Puckett et al. 2005, Jain and Sareen 2006). Therefore the current informal recycling should be replaced by recycling techniques preventing damages to human health and the environment. Clearly formal recycling has to be done according to global Best Available Technology (BAT) standards. For metal recovery these are, for example, complex metal refining plants combine the capabilities of a smelter, refinery, recycling plant or other specialized metal-recovery process into one integrated facility. Such integrated metal smelters are capable of recycling non-ferrous metals and precious metals, not only from ore-concentrates or metallic scrap but also from mixed metal concentrates, metal-plastic mixtures and compound material such as printed circuit boards (Hagelüken and Kerckhoven 2005).

The equations 'informal = hazardous' and 'formal = BAT', however, are rather crude assumptions that will have to be verified and adapted in future. Only recently, the Karnataka State Pollution Control Board approved E-Parisaraa as the first officially recognised WEEE treatment plant. The company has been audited and certified for ISO 14001 standards and independently certified by several multinational companies. An ongoing research project will

ferrous metal prices: (MEPS International LTD 2006) accessed on January 11, 2006
deliver first results on the performance of this process (Keller 2006). Yet, no data is available up to now. So far the argumentation was only concerning environmental and health standards. Another important aspect is that the informal recycling is the basis for life of a lot of people. The transition from informal to formal recycling should not destroy their basis for life. How this can be done is a difficult question. One way could be to employ such people in formal recycling companies.

4 Model description

MF models are based on balance equations for each process in the system and model equations describing the system behaviour. In our model, we assume that the system of WEEE recycling for PCs in India is basically driven by two processes. First, consumption provides the input into the trade and recycling processes (see sub-section 4.1). Second, the WEEE trader determines the pathways of PC waste through the process chain of recycling activities (see sub-section 4.2). Both EEE trade and metal recovery process a given input and deliver their products to the subsequent processes according to the current standards. We therefore focus the model description for consumption and WEEE trader and refrain from giving all equations for the processes shown in Figure 1.

The model is generally defined for three different levels of analysis: material flows of PCs and substance flows for copper and gold. The substance flows are derived from the mass flows as follows: 1. each mass flow has to be subdivided into "age-subflows" according to their age. 2. These "age-subflows" have to be multiplied with the corresponding concentration of gold and copper in order to give the corresponding "substance-age-subflows". 3. These flows have to be summed up resulting in the substance flows. However, the substance flow systems are not only 'derived systems' following the system behaviour determined by PC flows. They also influence the system behaviour by their own means by determining the activity levels of metal recovery processes (see sub-section 4.2). In the following sub-sections, we provide a general description of the model not differentiating between the different levels of analysis.

4.1 Consumption

The consumption I is described by the three variables Input $I_i(t)$, Output $O_i(t)$ and stock $M_i(t)$.

The demand for PCs (inputs) and the number of obsolete PCs going to second-hand and recycling markets (outputs) are determined by the development of the PC stock in-use over time, the medium life-span of PCs in-use and the age of entering the successive PC stock.

The mathematical formulation of this stock-driven approach is as follows:

Stock for PCs:

$$M_i(t) = P_i(t)$$

Balance equation:

$$\dot{M}_i(t) = I_i(t) - O_i(t)$$

Replacement of PCs:

$$O_i(t) = \int_0^t k_i(t,t') I_i(t') dt'$$
\( P(t) \) is the stock (number of PCs) in class I at time \( t \).

\( k_i(t,t') \) is the transfer function or life-span distribution of the PCs in class I, installed at time \( t' \) and replaced at time \( t \).

We assume the life span of each stock to follow a Gaussian distribution, namely: (see Figure 2)

\[
\begin{align*}
    k_i(t,t') &= \frac{1}{N_0(t')} e^{-\frac{(t-t')^2}{2(\sigma(t'))^2}} \\
    \tau(t') &= \text{the mean life-span of PCs of class I, put into operation at time } t' \\
    \sigma(t') &= \text{the standard deviation of the life-span of PCs of class I, put into operation at time } t'
\end{align*}
\]

This life-span distribution has been discussed in detail in Baccini and Bader (Baccini and Bader 1996) and applied in many case studies (Zeltner et al. 1999, Hug et al. 2004, Müller et al. 2004, Bader et al. 2006).

These three parameter sets are given for each PC stock, \( 1...n \)

The PC stock development \( P(t) \) as well as the life-span distribution \( k_i(t,t') \) have to adequately represent past time series for stock development and input flows. Clearly, these time series for the past do not uniquely determine the parameter functions \( P(t) \) and \( k_i(t,t') \). In addition, assumptions of future behaviour have to be used. Of course, many different strategies are possible: linear growth (no saturation of consumer needs), logistic growth (saturation of consumer needs at a given level) and others. The choice of an appropriate parameter function for PCs in India is described in section 4.2. In general, the model can include various assumptions of stock development.

![Figure 15: Gaussian distribution of life-span for age group 'x' and entrance age to the subsequent age group 'x+1'.](image)

4.2 WEEE traders

4.2.1 Recycling of copper and gold

The recycling of PC components containing copper and gold is primarily driven by the amount of money a recycler gains by selling the recovered amount of metal to metal processing industries. This amount is included in the model as the 'value concentration' per PC defined as the product of metal content per PC and metal price. We assume that the metal recyclers will start processing metal-containing PC components once the 'value concentration' exceeds a certain threshold value. Obviously, the total number of PCs available for re-
cycling is another important factor. However, in light of the fast-growing number of obsolete PCs in India, we refrained from explicitly including such a parameter in our model. This means that recycling activity will increase with growing 'value concentrations' until all available PC components have been processed. This behaviour has been simulated using a logistic growth curve as follows (see Figure 3):

\[
k_{\text{rec}}(x,t) = \frac{k_{\text{rec}}}{1 + e^{-a(t)(x - \frac{x_{5\%}(t) + x_{95\%}(t)}{2})}}
\]  

(5)

where:

- \(k_{\text{rec}}\) is the maximum recycling rate
- \(x_{5\%}(t)\) is the value concentration for 5% of the maximum recycling at time \(t'\)
- \(x_{95\%}(t)\) is the value concentration for 95% of the maximum recycling at time \(t'\)

Mathematically \(x_{5\%}\) and \(x_{95\%}\) are defined as follows:

\[
k_{\text{rec}}(x_{5\%}(t), t) = \frac{5\%}{100\%} \cdot k_{\text{rec}}
\]  

(6)

\[
k_{\text{rec}}(x_{95\%}(t), t) = \frac{95\%}{100\%} \cdot k_{\text{rec}}
\]  

(7)

Thus the threshold values always consist of a pair of numbers describing the activity of the relevant recycling sector, starting with a lower value (5%) and rising to the saturation value (95%). Between these ranges, the recycling sector becomes active (Figure 16). Value concentrations are given in US cents per PC.

From equation (5) and the definition of \(x_{5\%}\) and \(x_{95\%}\) follows for the reciprocal growth factor \(a(t)\):

\[
a(t) = \frac{2}{x_{95\%}(t) - x_{5\%}(t)} \cdot \log\left(\frac{95\%}{5\%}\right)
\]  

(8)

\[\text{Threshold values for metal recycling activity level} \]

\[\text{value concentration (US cent/PC)}\]

Figure 16: Threshold level for metal recycling activities
We assume that formal and informal recycling rates can be described by such a logistic threshold function. The threshold values for informal recycling are lower than for formal recycling, as informal businesses can start their activity with almost no investment. Informal recyclers will be the first players on the market, but, with growing value concentrations, formal recyclers will eventually follow. When both informal and formal recyclers are active, we assume that formal recyclers have superior access to supply of obsolete PC components. Consequently, the model gives priority to formal recycling.

In addition, a maximal recycling rate is introduced to represent material recovery of gold and copper. Material recovery from obsolete PC components depends on (i) effectiveness of collection of recyclable material and (ii) the technically determined recovery rates in material recovery processes. The parameter $k_{\text{rec}}^{\text{max}}$ in equation (5) expresses the technically determined recovery rate. A further parameter is introduced to capture the effectiveness of the collection system for both formal and informal recycling. It shows the share of all obsolete PCs available for recycling. This parameter is not represented in equation (5).

### 4.2.2 Recycling of all other materials

We further assume that the material recovery rate for the sum of other materials depends on the activity levels of both formal and informal recycling. If no gold or copper are recycled, at least plastic casing, ferrous-metal components, and aluminium parts are dismantled and transferred to recycling processes. This amount of material is represented by the flow recycled material. If gold and copper are recovered, an additional amount of material is added to the flow recycled material. This is due to the fact that other materials from PC components containing copper and gold are recycled while copper and gold are recovered, e.g., plastic from cable insulation or ferrous metal from copper coils. Yet, formal recyclers use techniques which are much more effective in recovering other materials than informal recyclers, especially in recovering other precious metals. Additionally, formal recyclers use non-metal material as fuel and flux material (Hagelüken 2005), which is also considered as material recovery in our model.

Therefore, the total amount of recycling can be seen to have a bottom line, which is the minimum recycling rate and is the same for both recycling practices. The maximum recycling rates depend on the ratio between formal and informal recycling of copper and gold. The transitions from the minimum recovery, with no copper and gold recycling, to the maximum material recovery, with maximum copper and gold recycling, are assumed to be linear.

Mathematically, then, the total recycling rate is a linear function in the four recycling rates for copper and gold of formal and informal recyclers, defined by equation (5). Since no data was available we made the assumption as a first approximation.

### 4.3 Calibration

This procedure aims at finding parameter functions that fit the available data. Obviously this is in general not uniquely possible and not independent of subjectivity of the investigator. However, our choice of parameter functions aims at simplifying the model in an appropriate way to guarantee a minimal set of necessary parameters. In this sense the following parameter functions were found to be most suitable.

Within this study, no research on data has been performed. Instead, data from already existing studies have been used, and only few additional data was collected selectively if necessary.
4.3.1 Consumption

Database

In India, only little is known about the current in-use stock of PCs and its development in the past. Yet, the pervasiveness of IC technology is of general interest, for India as well as on global scale. The International Telecommunication Union (ITU) regularly collects statistical data on this issue (International Telecommunication Union 2006a). A core set of indicators informs about the amount of ICT infrastructure and its access per capita. In the case of India, they serve as unique source of information for the World development indicator: personal computer per 1000 capita, which is used in the study on hand under the term 'PC penetration rate' (Gray 2006). The number of Personal computers includes "PCs, laptops, notebooks etc, but excludes terminals connected to mainframe and mini-computers that are primarily intended for shared use, and devices such as smart-phones that have only some, but not all, of the functions of a PC (e.g., they may lack a full-sized keyboard, a large screen, an Internet connection, drives etc)" (International Telecommunication Union 2006b).

To obtain the necessary data, ITU sends out questionnaires to national authorities, generally ministries, regulating authorities or organisations which are mandated to collect ICT data. In India, the information is collected by means of household surveys, which are conducted Ministry of Communication and Information Technology and a subsidiary organisation: the Telecom Regulatory Authority of India (Kumar 2006).

On this basis, the in-use stock of PCs in India is estimated by multiplying the penetration rate of a given year with this year's population. In this study the total population data from the World Bank was used. The data is culled from various sources including census reports, the United Nations Statistics Division's Population and Vital Statistics Report, country statistical offices, and the Demographic and Health Surveys which is coordinated by a private organisation (ORC Macro International Inc.) (World Bank 2006a).

To project the development of the in-use stock of PCs in the future, we use population prospects for India published by the United Nations Population Division. Out of the scenario set given in this publication we choose the projection variant 'medium', assuming a medium fertility, normal mortality and normal international migration (World Bank 2006b). Yet, no information is available for the projection of PC penetration rates.

An additional data set for PC consumption in India is available from the International Market research Bureau (IMRB), a market research consultancy offering research services in the field of telecommunication, office automation, information technology. Since 1999, this organisation carries out the Indian IT Hardware Market Study (ITOPS), a biannual study covering in 2004/05 more than 20'500 establishments and 35'000 households across 22 cities. ITOPS investigates on the demand side by sending out questionnaires to a selection of businesses and households. The study takes in account the changing patterns of ICT use in business and access to ICT equipment for different social strata. The findings from ITOPS are accepted as the official market performance of Indian IT hardware market by Manufacturers Association for Information Technology (MAIT). The published sales data include ICT equipment from national production, assembly of equipment in India as well as imports form multinationals companies.

Yet, no data is available on the average life span for PCs in India.

Calibration

Based on this set of data (ITU and IMRB), it is not possible to capture the cascade use of PCs in India as suggested in the system analysis (see sub-section 3.1). We, therefore, simplify the system by comprising the process 'consumption' into one single in-use stock.

We further assume that the development of this stock follows a logistic growth curve (see Figure 4). Such growth curves are typical for industrial goods. The given data, 1980 to 2004, suggest an exponential growth. But obviously, the need for IT services in India will be satis-
fied at some point in the future. Looking at the number of PCs which have been installed in India since 2005, it can be said that this process is still in an early "growth phase" (i.e., a 'turning point' is as yet far from being reached). A nonlinear fit of a logistic curve can not find the saturation volume. Moreover, it is not possible to foresee the accurate level of saturation. Consequently, the assumed stock development does not claim to be a forecast. Rather, the conservative assumption of until 2050 intends to go beyond a trend analysis and draw a bottom line of the least reached Indian PC penetration. Yet, Indian PC penetration rates will hardly reach the level of industrialized countries in the coming decades. We, thus, chose a conservative estimate for the saturation level of 150 PCs per 1000 inhabitants in 2050, compared to 15.4 in 2005. (see Figure 5). In comparison, more than 800 PCs are currently available per 1000 inhabitants in Switzerland. The conservative assumption describes a growth of Indian PCs saturation by a factor of ten until 2050. Any higher PC saturation will affect the stocks but will not disturb the fundamentals of the suggested model. Based on this time series and the assumed saturation level, a curve fit for the following logistic growth curve has been performed:

$$P(t) = P_{\text{sat}} - P_{\text{init}} + \frac{P_{\text{init}} - P_{\text{sat}}}{1 + e^{-\alpha(t-t_{\text{turn}})}}.$$  

(9)

$P_{\text{init}}$ is the initial value in the past, $P_{\text{sat}}$ the saturation value, $\alpha$ is proportional to the maximum growth rate and $t_{\text{turn}}$ is the turning point of the growth curve respectively. The result of the fit is presented in Figure 4 and shows that the logistic growth curve fits the available data well. The value 0.275 for $\alpha$ is quite high but not unusual for large growing economies (Bader et al. 2006).

Figures 4 and 5: Installed PCs in India according to World Development Indicators from 1980-2005. Suggested scenario of installed PCs in India up to 2050. The level reached between 2040 and 2050 corresponds to a 150 PCs/1000 capita saturation rate assuming a medium growth rate of the population.

To obtain values for the average life span of PCs in India (mean and standard deviation) the data set for PC sales (IMRB data set) has been fit to the input of PCs into consumption (see figure 1). The calculation has shown that $\tau = 8$ and $\sigma = 2$ fit best the available data. This result is presented in Figure 6. The uncertainties of the growth curve and the life span have again been set at a conservative level, in the sense that the uncertainty range covers all available data for installed PCs and sales data.
4.3.2 WEEE traders

4.3.2.1 Threshold values

Database

We have basically no data on the threshold values for formal and informal recycling of copper and gold containing PC components in India (see section 4.2.1). Such information could only be gained by disclosing the profit and loss accounts of WEEE recyclers. Even in industrialized countries, such as Switzerland, such information is not available (Streicher-Porte 2006). In India, data availability is even more restricted: access to informal recyclers is limited and, informal recyclers will most likely not even keep any kind of systematic profit and loss account. Formal recycling, however, has not yet been established in India. Only one pilot plant in Bangalore has been set up (see section 3.3) and it is yet impossible to judge whether it is representative for formal PC recycling all over India in future.

Yet, the prices paid by recyclers for WEEE provide some information about the threshold values. Field surveys and interviews show that the prices paid by informal recyclers per PC vary from 5 to 10 Indian Rupees per kilogram of scrap material. Recyclers do not pay additional costs for collection and transport, organising such services themselves. Hence, the market value of an obsolete PC which enters the informal recycling market as a complete unit varies between one and three US dollars per PC. For the formal recycling plant in Bangalore, however, the actual costs for the waste material range between 20 and 40 Indian Rupees per kg, including costs for collection, packaging and transport. Only scrap from the ICT sector is considered in this calculation (Rochat 2006). Consequently, the threshold level for gold and copper recycling in the formal sector ranges from 560 to 1120 US cent per PC calculated for a 12.8 kg medium weight from 1997. This value is relatively high compared to the existing recycling costs of the European WEEE systems. According to a study of Hewlett-Packard, European WEEE systems offer recycling prices between 50 US cent and 800 US cent per PC (Martens 2006). This means that some European systems offer recycling at even lower levels than those assumed for the informal sector, and that the upper level of the Indian threshold values is above the highest costs of the most expensive European system. The HP study compares very different WEEE recycling systems and also different costs declared by each of the individual systems. In light of this, the comparison should not be stretched too far.

Another source of information is the value concentration per PC that can be interpreted as expected revenues from metal recovery (see section 4.2.1). To calculate value concentrations we need data on gold and copper content per PC (mass per unit) and gold and copper prices.

---

9 Calculated with exchange rates: USD/INR of 45.92 and the USD/CHF of 1.23 on the 5th of July 2006
Table 2: Various literature sources on the gold and copper content in PCs.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>20</td>
<td>Average from 521 entries in 2002</td>
<td>500 ppm</td>
<td>2 ppm</td>
<td>? ppm</td>
<td>56 ppm</td>
</tr>
<tr>
<td>Gold in printed circuit boards</td>
<td>-</td>
<td>250 ppm</td>
<td>288 ppm</td>
<td>360 ppm</td>
<td>- ppm</td>
<td>56 ppm</td>
</tr>
<tr>
<td>Copper in PCs</td>
<td>5.69 %</td>
<td>-</td>
<td>6.12 %</td>
<td>6.21 %</td>
<td>6.93 %</td>
<td>0.51 %</td>
</tr>
</tbody>
</table>

Data for the metal content of PCs has been collected in several studies motivated by an interest in WEEE recycling (see Table 2). Most data for the gold content is consequently given as metal concentrations of printed circuit boards rather than per unit PC. Additional data is thus required for the weight of a PC per unit and the relative weight of printed circuit boards in mass percent. PC weight data was taken from a study conducted on PCs recycled in 2006. It gives a mean weight of 12.3 kilograms per recycled PC (sample size n=500) (SWICO 2006). The weight of PCs that are currently sold and will enter the recycling markets in the coming years was estimated by additional market investigations carried out by the authors of this paper. It revealed a mean weight of 11.1 kilograms (sample size n=54). Data on the relative weight of printed circuit boards was taken from SWICO (2006). This study revealed a share of 8.1 mass percent per kilogram of PC.

Data on gold and copper prices is taken from the London Metal Exchange (London Metal Exchange 2006).

**Calibration**

In 2006, almost all recycling activities for PCs were carried out by the informal sector. Informal recyclers seem to operate profitably - even when dealing with very low levels of valuable materials. According to expert interviews, they took care of all obsolete PC available on the WEEE market in the last 15 years which corresponds with an activity level of 100%. Yet, it is impossible to obtain data on the business environment which encouraged informal recyclers to start their business in the past (lower threshold value) or the development of recycling activities before informal recycling reached the maximum activity level.

In consequence, we have to make an "informed guess" on threshold values for informal recycling. We do so by setting the 50%-activity of informal recyclers for each metal at the lowest-theoretical value concentration over the last 15 years. This value is determined by the lowest annual gold and copper prices in the last ten years and the lowest concentration of each metal per PC in this period. For gold, this is 320 US cent/PC (year 1980 with 11.14 US$ per gram gold and 0.287 gram gold per PC). In the case of copper, this is 115 US cent/PC (year 2005 with 0.22 US cent per gram copper and 670 gram copper per PC). It was observed that recycling businesses make their decision to buy obsolete PCs on a "rule of thumb", according to commodity prices and their knowledge of the PCs material value. This lead us to the additional assumption that formal and informal recycling businesses start their activity within a price range per PC. This range was set at 100 US cent per metal and PC. From a technical point of view, the threshold function only makes sense if a range of between 5% and 95% value is covered. Hence, the margins for the informal sector for gold ranges between 270 (5%) and 370 (95%) US cent per PC and for copper between 65 (5%) and 165 (95%) US cent per PC. These assumptions suggest that informal recycling today operates with expected revenues above the upper threshold values for copper, and within the margin of the threshold values for gold. The sum of both upper threshold values for copper and gold (535 US cent) is in the range of the current market value of an obsolete PC, which is roughly between two and three US dollars. Thus, revenues of informal recyclers only from gold and copper cover more than the costs of an obsolete PC. Other materials
such as aluminium, ferrous metals or plastics can add to the profits. In consequence, these parameter function tends to underestimate informal recycling activities.

For formal recycling, we assume that the lower threshold values must be above the currently expected revenues as almost no formal recycling activities can be observed in India today. Only data from the pilot plant for WEEE recycling in Bangalore give some indication on threshold values (see values given above). Based on these data, the threshold level for gold and copper recycling in the formal sector is assumed to range from 560 (5%) to 1120 (95%) US cent per PC calculated for a 12.8 kg medium weight from 1997. We justify the higher range of the threshold values because of higher investments costs in the formal sector. This conservative assumption means that formal businesses have a longer start-up phase than their informal counterparts, having to cover their investment costs. The threshold value function was introduced in chapter 4.2.1 and figure 3; the values are listed below in table 3.

The model determines the development of recycling activities using the parameter functions for threshold values and the value concentrations of PCs in the WEEE market (see subsection 4.2.1). To obtain value concentrations of PCs we need data on the development of gold and copper prices as well as gold and copper contents in the waste stream. Gold and copper prices were calibrated by estimating a parameter function for price development based on data series from the London Metal exchange from 1900 to 2005 (London Metal Exchange 2006). The time series of the prices for gold and copper from 1900 to 2005 seem to follow logistic growth behaviour (see Fig.7 and Fig.8). It is hardly surprising, then, that the fit procedure results in logistic growth curves best reflect the behaviour of the data in function of time. These curves reach the saturation value for gold in 1980 and copper in 2000. In contrast to the fit of the growth curve for the stock in section 4.3.1, the saturation value was also a result of the fit. Although the time series data show a high fluctuation in prices over recent years, it seems reasonable to smooth out such short term phenomena to get the long term trend. As with PC stocks, conservative assumptions were also made for commodity prices. The recycling model intends to distinguish between the distributions between formal and informal recycling. The fitted functions for gold and copper prices are relatively low in comparison to current prices. This conservative assumption shows that the recovery of these metals will remain attractive for the informal sector. Any increase in prices will make the recycling more attractive for the formal sector. This case will be investigated in the scenario analysis later on. Yet, price fluctuations might have a significant influence on the development of recycling activities and this influence will be discussed at the end of this paper. The model takes these large fluctuations into account by assuming confidence intervals of 99.99% and 99.9% for gold and copper prices, in contrast to the common used value of 95%.

Raw data

Figures 7 and 8: Historical gold and copper prices and best fit of future development.
The development of copper and gold contents in PCs is determined as follows.

For gold, we assume that the gold content per unit remains stable over time. Although, the gold content of circuit wire boards tends to decrease per unit, this development is counteracted by the use of bigger motherboards, additional sound components, graphic and memory cards and other newer media drives (Schischke and Kohlmeyer 2005, Hagelüken 2006, SWICO 2006). We thus determine the parameter function for gold content per unit by multiplying the gold content in circuit wire boards (288 ppm, see table 2) the share of circuit wire boards in PCs (8.1 mass-%) and the medium weight of a PC (12.3 kg per unit). All data is taken from one single study, (SWICO 2006), to ensure data consistency. We assume a standard deviation of 20% for all three parameters.

For copper, we assume a decreasing copper content per unit which is brought about by a decreasing weight of PCs. The copper concentration per kilogram of PC is kept constant (6.05% with a standard deviation of 20% according to table 2). The parameter function of PC weight per unit is based on two data points, 12.3 kg per unit for a PC sold in 2001 and 11.1 kg for a PC sold in 2006. Both data sets represent a mix of different types of PCs ranging from large and heavy units to small and light PCs. We assume that this mix is representative for both years and will not change significantly in future. For the early years form 1980 to 1990 we assume an upper limit of PC weight: 18 kg in 1990 and 20 kg in 1980. In addition, we assume that the decrease of weight per unit will slow down over time and reach a saturation value at 8 kg per unit. This assumption is not based on data and can be interpreted as a conservative estimate assuming that the prevailing trend of miniaturisation of electronic devices will not continue for PCs.

Based on this information, we again fitted a logistic decrease function for the development of PC weight (see Figure 9) -note that the logistic decrease function differs from the logistic growth function only by the + sign in the exponential term.

![Development of PC weight](image)

Figure 9: Development of mean PC weights and standard deviations.

4.3.2.2 Recovery rates

Database

The information on recovery rates can be differentiated into two types: (a) technically determined recovery rates in material recovery processes, and (b) data on the effectiveness of the collection of recyclable materials. (a) can be further divided into recovery rates from formal and informal recycling.
Gold and copper recovery

Information on (a) can be obtained from Huisman (2003). He collected literature data for the average recovery rates of metals at copper smelters and gives material recovery rates of 95% for copper and 98% for gold. In addition, (Hagelüken and Kerckhoven 2006) provide data on recovery rates of other materials in formal gold recycling. No published data has hitherto been available for the recycling of gold and copper in the informal sector. However, a recent diploma thesis on gold recovery in India shows that metal recovery rates are significantly lower in informal than in formal recycling (Keller 2006).

Recycling and recovery of all other materials

In India, no data is available for (b), the effectiveness of the collection of recyclable materials. The collection of WEEE is organized by small scale enterprises which are part of the free market. No official statistics are kept.

Yet, no additional data was collected in this study for recycling of other materials such as plastics and ferrous metals. The calibration of recycling rates for these materials is solely based on data on material composition of PCs from (Schischke and Kohlmeyer 2005, SWICO 2006).

Calibration

Recovery rates in collection are assumed to be 90%. This is a very optimistic estimate assuming that a market based collection system works very effectively. We further assume that recovery rates in collection for informal recycling equal recovery rates in collection for formal recycling.

We further take the data given by Huisman (2003) as best estimated for recovery rates in formal copper and gold recycling. For informal recycling we assume metal recovery rates of 50% for both copper and gold.

For other materials, we assume that about 70% of PC weight is recycled comprising mostly plastic casing, ferrous metal casing and aluminium parts which are easy to dismantle and recycle. This assumption is based on the material composition of PCs taking all components into account which do not contain copper or gold. The implications of this assumption will be discussed at the end of the paper.

From the gold containing components (motherboard, PWBs from drives and gold containing pins), formal recycling processes can, at the least, recover gold, silver, palladium and copper. In addition to this, formal processing uses the non-metal material as fuel and flux material in the smelting process. As a result, the recovery rate for other material increases by 9%, which is roughly the total amount of weight of all gold containing components (SWICO, 2006). The same logic is followed for copper containing parts. If copper recycling is conducted by the formal sector, an increase of 10% of the total recycling is assumed, as copper smelters can use plastics as fuel (6.1% copper and 6% other materials). Informal recycling, however, does not recover any other materials. To sum up, informal recycling can achieve a recovery rate of 76.1% (70% other materials and 6.1% copper and gold), whereas formal recycling can reach that of 91.1% (70% other materials separately recovered, 9% of gold containing components and 12.1 of copper containing components).
5 Application of the model

The model, described mathematically by equations (1)-(6), has been implemented in the computer program SIMBOX. SIMBOX using the Newton Raphson algorithm to solve the system of integro-differential equations numerically. All calculations have been performed on a Pentium IX PC.

5.1 Baseline and selected scenarios

Table 3 shows all parameters used in the baseline scenario. They have been introduced and discussed in the previous chapter 4 Model description. The table links the parameter to the relevant figures and tables and also gives an overview of the consulted literature sources.

Table 3: Parameter values used in the baseline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>1980</th>
<th>2050</th>
<th>Data source or explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium life span</td>
<td>Years (sigma in years)</td>
<td>8 (2)</td>
<td></td>
<td>Calibration results, expert interviews, Culver 2006, Matthews et al. 1997 and 2003</td>
</tr>
<tr>
<td>Medium weight per unit</td>
<td>Kilogram</td>
<td>19.6</td>
<td>8.0</td>
<td>Decrease from 1980 until 2050 according to Figure 9, SWICO batch examination and own estimates</td>
</tr>
<tr>
<td>Metal content per unit</td>
<td>Gram %</td>
<td>0.288</td>
<td>6.1</td>
<td>SWICO 2006 batch examination, Hagelüken 2006, Schischke and Kohlmeyer 2005</td>
</tr>
<tr>
<td>Metal prices</td>
<td></td>
<td></td>
<td></td>
<td>As shown in Figures 7 and 8 for gold and copper price developments</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gold</td>
<td>US cent per unit</td>
<td>270</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>Formal</td>
<td>560</td>
<td>1120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Informal</td>
<td>65</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>560</td>
<td>1120</td>
<td></td>
</tr>
<tr>
<td>Maximum recycling rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gold</td>
<td>Transfercoefficient</td>
<td>0.5</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Formal</td>
<td>0.5</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Informal</td>
<td>0.5</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Minimum recycling without gold and copper recovery</td>
<td>Transfercoefficient</td>
<td>0.7</td>
<td></td>
<td>SWICO 2006 batch examination, Schischke and Kohlmeyer 2005 and own assumptions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional recycling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gold</td>
<td>Transfercoefficient</td>
<td>25*10^6</td>
<td>0.090</td>
</tr>
<tr>
<td></td>
<td>Formal</td>
<td>0.061</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Informal</td>
<td>0.121</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To represent the main driving forces of PC recycling in India, two scenarios have been selected: 1. a price scenario for both metals and 2. a threshold scenario for formal recycling. The main motivation to select these scenarios is the urge to investigate under which conditions formal recycling becomes profitable. Fact is that the value of the waste stream from obsolete PCs is influenced to a great extent from raw material prices, mainly those of metals. It is also known that an organised recycling sector has great potentials to lower costs for recycling by means of increasing its efficiency.

Price scenario:

For the Price scenario we assumed a linear increase of copper and gold prices from 2005 until 2050. We have assumed that the prices in 2050 will be twice as high as the saturation value of the base line. This means that in 2050 the gold price will reach 2400 US cent per gram, the copper price will reach 470 US cent per kilogram. The prices until 2050 are the same as in the base line in order to prevent distortion of the historical data.
Threshold scenario:

In the threshold value scenario the threshold levels for formal recycling were decreased by 50%. Only the threshold levels for formal recycling were altered as only this sector has the potential to increase the efficiency or to profit from subsidies for environmental sound recycling. Both measures are decreasing the level at which formal recycling becomes profitable. Therefore, the threshold values for formal recycling were set at 280 (5%) and 560 (95%) US cent per PC.

5.2 Results

The results of the model calculations are presented in the same graphic, allowing a direct comparison of the three scenarios. With respect to the evaluation criteria, environmental sound treatment and material recovery, we have focused on the following variables.

1. Total material recycling
2. Formal gold recycling
3. Informal gold recycling
4. Gold losses
5. Formal copper recycling
6. Informal copper recycling
7. Copper losses.

Figure 11-16 show the annual creation of waste, recovered substances per sector and losses per sector. The corresponding accumulated values are listed in Table 4 later in the text. Fig. 11-16 clearly show the distribution of gold and copper in obsolete PCs to the 3 paths losses, informal and formal recycling. For both scenarios, the “price” as well as the “threshold” scenario, formal recycling is still small, namely about 15% for gold and 0.2% for copper in 2050. From the point of view of environmentally sound treatment this is far too low. This clearly demonstrates that “doubling” the metal prices or “halving” the threshold values for formal gold and copper recycling is not enough to reach an environmentally sound treatment of PC residues.

The uncertainty ranges of the variables for the baseline scenario are quite high for the future -after about the year 2015. This is a well known phenomenon if imprecise data from a short time period (here 1995-2005) is used for simulations of the distant future (here ~2050). In this study, the first rough estimates of the parameter uncertainties were accurate enough for the calibration period 1990-2005, see Fig.4-16. However, for the simulation of the more distant future ~2020-2050 it turned out that these estimated uncertainties were too inaccurate. The following procedure has been applied to reduce the uncertainty: (1) The confidence intervals of the available time series such as gold and copper prices were reduced to the usual 95% instead of 99.9% and more; (2) the uncertainties of the parameters where no time series were available such as threshold values were also reduced. This was justified on the grounds that those parameters are scenario-like parameters, since no data was available. In conclusion, the shown uncertainty range of the baseline scenario has to be considered as an uncertainty of a scenario rather than a prognosis. The effect of these parameters will be further elaborated in the discussion.

The future volumes of annually obsolete PCs will increase to over 250 millions tons in 2050. The material going to landfill will increase to almost 70 millions tons per year. These values are the same for each scenario as the input from the stock remains unchanged (not shown in the figures).
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Figure 10 Total recycling volumes for the baseline (with uncertainties) and the two scenarios.

Figure 11 Gold recycling in the formal sector for the baseline (with uncertainties) and the two scenarios.

Figure 12 Gold recycling in the informal sector for the baseline (with uncertainties) and the two scenarios.

Figure 13 Gold losses for the baseline (with uncertainties) and the two scenarios.

Figure 14 Copper recycling in the formal sector for the baseline (with uncertainties) and the two scenarios.

Figure 15 Copper recycling in the informal sector for the baseline (with uncertainties) and the two scenarios.

Figure 16 Copper losses for the baseline (with uncertainties) and the two scenarios.
The total recycled material will increase as shown in Figure 10. The three scenarios differ only slightly. In the base line the recycled material from PCs will reach 179 Mio tons per year, 183 Mio tons per year for the threshold scenario, and 186 Mio tons for the price scenario.

Volumes of gold recycling of the different sector vary. Under the base line almost no formal recycling is present (42.7 kilogram per year). 1'250 kilogram of gold per year becomes recovered by the formal sector under the price scenario, and 1'330 kilogram of gold per year under the threshold scenario (Figure 11). Nevertheless, the biggest share of recovered gold is generated by the informal sector. 3'230 kilogram under the base line, 3'410 kilogram under the price scenario and 2710 kilogram of gold per year under the threshold scenario become recovered (Figure 12).

But almost double the amount of gold is lost in each scenario. These losses are a combination of not collected material as well as material losses from recycling. 5'700 kilogram of gold per year will be lost under the base line. The losses are also very high under the threshold scenario (4'930 kilogram per year) and under the price scenario (4'310 kilogram per year) (Figure 13).

For copper the situation is even more extreme. The majority of copper is lost either from not being collected or from losses during the recovery process. The formal sector by far does not reach the size of the informal one.

Formal recycling of copper will only reach 6.4 tons per year (base line), 21.0 tons per year (price scenario) or 21.5 tons per year (threshold scenario) as shown in Figure 14. Informal copper recycling will recover 6'867 tons of copper per year under the price scenario, whereas almost no difference could be detected between the base line (3'470 tons) and the threshold scenario (3'466 tons), shown in figure 15.

The volume of copper lost exceeds the sum of both recycling volumes. Again, no substantial difference can be seen between the losses of copper per year under the base line (11'830 tons) and the threshold scenario (11'820 tons). The losses under the price scenario are lower due to the higher informal recycling at 8'414 tons of copper per year.

The accumulated material values, listed in table 4, allow for an estimation of the overall material intensity of the PC market as well as for potential losses from applied techniques. The monetary values of the accumulated amounts of gold and copper are also shown. They have been calculated with the metals prices of the corresponding year.

*Table 4: Accumulated recycling volumes, share of formal and informal recycling, losses as well as monetary value of gold and copper volumes over the whole research period.*
The accumulated material losses which have to be deposed of in landfills until 2050, add up to over 2'000 millions tons. The total volume of obsolete PCs is the sum of recycling volume and losses. It is the same for each scenario.

For all scenarios the losses of gold and copper, and consequently the financial losses, exceed the amount of recovered material or earned profits. This is even the case if the volumes of informal and formal recycling are summed up.

By comparing the threshold scenario with the base line, only a slight improvement of gold recovery can be detected, for both, formal and informal recycling. If the same set of scenarios is compared for copper recycling, also only lightly higher volumes become recovered. Reason for this is a situation under which formal and informal recycling are competing for recycling material. An increase of volume in the formal sector decreases the volume processed in the informal sector.

The comparison between the base line and the price scenario shows that more volumes become recovered in both sectors. But even in this scenario the sum of informal and formal recycling never reaches the volume of the losses. Reason for this is that under both scenarios formal and informal recycling are not fully active and, therefore, do not recycle their maximum level.

6 Discussion

The main goal of the presented study was to describe the characteristics of PC recycling in India in a model. The gained system understanding was then analysed in a structured way, in order to understand the underlying cause-effect chains and to identify the main driving forces of the system.

The results are discussed in the light of the research question:

- What are the main characteristics of WEEE systems in the emerging economies and how can they be best represented by an appropriate model?

In emerging economies we observe a large second hand market for PCs. The model captures this phenomenon by defining a cascade use of PCs, driven by the development of different stocks of PCs representing the behaviour of different consumer types. Understanding this cascade is crucial to obtain information on average PC life spans for the entire systems, the levels of saturation and the underlying drivers. Therefore, a stock-driven dynamic MFA model is a most suitable tool. Due to restricted data availability, however, we were not able to calibrate a cascade model in consumption. This means that the cascade use of PCs is described implicitly in a one box model for consumption, which does not allow any separate analysis of the individual stocks or flows. To calibrate a cascade model, first, the single stocks and, second, the single inputs to the different stocks are required. The reuse of PCs could, therefore, not be quantified. Yet, the model reveals the waste volume of obsolete PCs taking into account the time shift between purchase and dumping of PCs and thus allows assessing alternative recycling schemes.

The recycling model depicts the competition between two recycling sectors, formal and informal. They compete for material according to their ability to make profits from the recovered material. This describes accurately the present situation under which many informal recyclers deal with the majority of waste, while some first formal recyclers start to build up facilities and try to get hands on material.
Finally, material prices and material concentration in obsolete PCs define whether a specific treatment is profitable or not. These dynamics have been represented in the model as gold and copper flows from recycling were analysed.

Yet, some very important characteristics of WEEE recycling in India are not represented in the model.

First, the prevailing pattern of trading and recycling facilities is much more complicated than the one shown in figure 1. An obsolete PC undergoes many dismantling and sorting steps. Components that are still required on the market are sold as used replacement parts; components that are not required are traded as waste material. Consequently, the phase 'trade' in our model is simplified, insofar as we have reduced the net of trading relationships to only two traders. Intensive trade affects the revenues of final material recyclers, due to the fact that the intermediate trading steps increase the costs of the secondary resource.

Second, the model is not apt to capture all technology changes in ICT. The scenario calculations show projections of the past development into the future in order to present alternative pathways for future development. Yet, there can be no doubt that in the field of ICT changes will occur, some of which will be the continuous miniaturisation of appliances and a diversification of ICT devices, for example in radio frequency identification (RFID) smart labels. The model can only compensate tendencies, miniaturisation and diversification, to a certain extent.

Consumer stocks and the in-use-stock of material might change considerably. But the relative changes in the demand, use and output of the system as outlined will happen, with or without a technology revolution. Thus, an appropriate waste treatment system will be required.

What forces drive WEEE systems in the emerging economies?

Without the model, the calculation of the uncertainty ranges of the variables and the sensitivity analysis of the parameters, one can only guess at which forces drive the system. The model has shown that mainly following parameters influence the distribution of PC treatment in formal and informal recycling:

1. content of valuable materials
2. market value of these
3. economic threshold level for a recycling activity
4. size of the PC stock
5. mean life-span and
6. maximum recycling rates.

This is not surprising as the metal content, the metal prices and the threshold level determine which recycling sector becomes active. However, with a dynamic model not only qualitative dependencies on parameters can be discussed, but also the quantitative sensitivities in function of time—in particular for the "transition phase" such as that involving the introduction of formal recycling.

For the first two parameters a close look on the development of medium metal content and naturally of the metal prices is of great importance. Bodies which are in charge of setting up, monitoring and supervising recycling systems should, therefore, be aware of the material composition of the products of concern.

For metal prices, we have decided to not use the annual fluctuations in our calculation but a best fit. This best fit of the metal prices is supposed to balance out some of the losses and
The profits recyclers make. It may leave out some of the opportunities for recyclers which arise from high metal prices, but it represents the actual situation recyclers, mainly formal one, have to deal with. Formal recyclers must build up financial reserves that secure their survival over periods with low prices or gives them the chance to do brokerage and hold back material at periods with low prices. Informal recyclers react much faster and do not have so many liabilities, which is one of the biggest competitive advantages of this sector.

The third two parameters, the threshold values, are of great interest to recyclers, ICT industry and policy makers. Therefore, to confirm the actual necessary costs for formal recycling as well as the profits gained in the informal sector would be very useful. Formal recycling is under the set conditions, not able to squeeze the informal recyclers out of the market. Also the results of the two scenarios show how far the formal sector is away from being competitive with informal recyclers. Under the base line as well as the both scenarios, the formal sector was not able to overtake a substantial level of the market. A combination of price scenario and the threshold scenario could deepen the analysis and give hints, how much the formal recyclers have to increase in efficiency, to receive subsidies for environmental sound recycling and to profit from high metal prices. Formal recycling will only increase if the sector dramatically lowers the cost for recycling.

What do we learn from the model calculation about the design of a data-collection scheme for future studies?

Obviously, the focus on data collection in future should be on parameter values for the most sensitive parameters discussed above: gold and copper content per PC, metal prices and threshold values.

In addition, future research should aim at better covering some important issues that our model application excluded explicitly. As general system understanding was the goal, some important parameters for monitoring or management purposes were not looked at. These are:

First, some spatial parameters should be included to apply the model to a specific region. The model application presented in this paper depicts the whole PC market in India, but excludes collection and transport parameters. The sheer size of India as well as experiences for WEEE recycling systems in Europe indicate that collection and transport are important elements while setting up a recycling system. Therefore, spatial data on WEEE generation as well as data on collection patterns should be included in a future analysis.

Second, reuse is an important characteristic of the PC use in emerging economies. Reuse of appliances means the use for which they were conceived, including the continued use of the equipment or components thereof which are returned to collection points, distributors, recyclers or manufacturer. Such processes have been described for the recycling of cathode ray tubes from televisions and PC monitors in India (Jain and Sareen 2006). In our model, reuse has not been explicitly considered. Reliable data of PC reuse numbers would enable researcher to model two consumer stocks: first users and second users.

Third, the recycling volumes for PCs in our model are very high. Not only the return rates of obsolete PCs are set at 90%, also the minimum of material recycling that happens without any gold and copper recycling was set at 70%. Both levels contribute to this very high recycling rate. The system characteristics on which these high return rate are based on, are the effective waste collection services in India, which delivers services especially to social higher strata having the potential to buy own ICT equipment. But to make an accurate estimate how much of materials are in fact recycled and how much material is lost during the process, separate studies are necessary.
7 Conclusions

With a model requiring a very limited amount of data, it was possible to get a quantitative understanding of the system PC consumption and WEEE in India. In particular, the key parameters representing the so called driving forces could be identified and quantified as well as the data gaps which should be closed. This is crucial in order to focus on collecting data which is really needed, instead of wasting human power and money with exorbitant unnecessary measuring campaigns. Such studies should focus on a better description of the use and reuse phases. By means of more specific PC stock data, individual stock development can be included in the calculation. If additionally recycling data of an emerging formal recycling sector is collected, let us assume, by a regulating authority, the presented model can be transformed into a powerful study and monitoring tool.

The study has revealed that at the present situation the formal PC recycling will not be able to squeeze informal recyclers out of the market. Also in the future formal recyclers have either to reduce dramatically their costs, or to benefit from continuous high metal prices for gold and copper. The calculation showed that even with doubling the metal prices, or lowering the threshold values for formal recycling by 50%, no substantial share of the waste volume was overtaken by the formal sector.

Informal recycling will attract more and more businesses as the amount of obsolete PCs will dramatically rise. This is even the case if only the historical sales data for PCs are taken into account, as the sales have increased exponentially. This will result logically in an exponential increase of PC waste in less than 8 years. The conservative prognosis we have made of the PC stock development until 2050 shows that presently there are far too little recycling capacities to deal with the waste.

If we assume that the informal sector will expand its activities as much as shown in the scenarios, urgent action is needed to upgrade and improve this recycling sector. Strategies which focus to improve the informal sector seem to be more suitable that investing in expensive infrastructure. One can be that the informal sector is shifting to towards pre-processing and sorting. But such initiatives have to be well coordinated and backend up with an appropriate legislation. It has to be also ensured that unproblematic pre-processing and separation processes are handing on the waste fractions to final material recovery or energy recovery processes which should be assiduously be monitored. Otherwise an upgrading or improving of informal recycling would only shift the problem. Some first interventions in this direction from development cooperation organisations are already happening. Additional studies on informal recycling are needed in order to confirm the first results and monitor the improvements of material recovery in the informal sector. What the study clearly showed is that the informal sector must become more sustainable, both in environmental and health terms, in order to enable the WEEE sector to attain higher environmental standards.

Literature


Hagelüken, C. 2005. Optimising the recycling chain - the contribution of an integrated metals smelter and refinery, conference proceedings full text. in International Conference on Mining and the Environments, Metals and Energy Recovery, Skelleftea.


van der Voet, E. 1996. Substances form cradle to grave - Development of a methodology for the analysis of substance flows through the economy and the environment of a region. Leiden University.


Annexure

A. Recovery and Reuse/recycling targets of the EU Directive on WEEE (EU 2002a)

<table>
<thead>
<tr>
<th>Product Category</th>
<th>Recovery (%)</th>
<th>Reuse/Recycling (%)</th>
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<tbody>
<tr>
<td>Large household appliances</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>Small household appliances</td>
<td>70</td>
<td>50</td>
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<td>IT and telecommunications equipment</td>
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<td>65</td>
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<tr>
<td>Consumer equipment</td>
<td>75</td>
<td>65</td>
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<tr>
<td>Lighting equipment</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Electrical and electronic tools</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Toys, leisure and sports equipment</td>
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<td>Medical devices</td>
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<tr>
<td>Monitoring and control instruments</td>
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<td>50</td>
</tr>
<tr>
<td>Automatic dispensers</td>
<td>80</td>
<td>75</td>
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</table>

NA: targets will be set at the end of 2008

B. List of Ozone Depleting Substances (ODS) controlled under the Montreal Protocol (UNEP 2006)

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<tr>
<th>Formula</th>
<th>Chemical name</th>
<th>ODP</th>
<th>Formula</th>
<th>Chemical name</th>
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<td>C3HF4Br2</td>
<td>HFC-138</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF4Br3</td>
<td>HFC-139</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF4Br4</td>
<td>HFC-140</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF4Br5</td>
<td>HFC-141</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF4Br6</td>
<td>HFC-142</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF5Br</td>
<td>HFC-143</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF5Br2</td>
<td>HFC-144</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
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<td>C3HF5Br3</td>
<td>HFC-145</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
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<td>C3HF5Br4</td>
<td>HFC-146</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
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<td>0.1-0.1</td>
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<td>C3HF5Br5</td>
<td>HFC-147</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
</tr>
<tr>
<td>C3HF5Br6</td>
<td>HFC-148</td>
<td>0.05-0.05</td>
<td>C2HF3</td>
<td>0.1</td>
<td>0.1-0.1</td>
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</table>
C. Different stages of e-waste recycling processes sampled in India and China (Brigden et al. 2005)

![Diagram](image)

D. WEEE relevant annexes of the Basel Convention (Secretariat of the Basel Convention 1989)

### E-waste listed in the Basel Convention under Annex VIII and e-waste not covered under Annex IX

<table>
<thead>
<tr>
<th>Annex VIII List A</th>
<th>Annex IX List B</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1150</td>
<td>Precious metal ash from incineration of printed circuit boards not included on list B</td>
</tr>
<tr>
<td>A1170</td>
<td>Unwanted waste batteries, excluding mixtures of only list B batteries. Waste batteries not specified on list B containing Annex I constituents to an extent to render them hazardous</td>
</tr>
<tr>
<td>A1180</td>
<td>Waste electrical and electronic assemblies or scrap containing components such as accumulators and other batteries included on list A. Batteries, glass from cathode ray tubes and other activated glass and PCB capacitors, or contaminated with Annex I constituents (e.g., cadmium, mercury, lead, polychlorinated biphenyl) to an extent that they possess any of the characteristics contained in Annex III (note the related entry on list B B1110)</td>
</tr>
</tbody>
</table>

- Annexes A1170 and A1180 are used to remove materials from the same components. All other processes shown here are included in Annex A1190 except in not controlled processes which apply to all locations and types of electronic equipment.

| A1190 | Waste metal cables coated or insulated with plastics containing or contaminated with coal tar, PCB, lead, cadmium, other organohalogen compounds, or other Annex I constituents to an extent that they exhibit Annex III characteristics |

| A2010 | Glass waste from cathode ray tubes and other activated glasses |

- Waste metal cables coated or insulated with plastics not included in list A1190, excluding those destined for Annex IVA operations or any other disposal operations involving, at any stage, uncontrolled thermal processes, such as open burning.
E. Persistent Organic Pollutants (POPs) regulated under the Stockholm Convention (EPA 2006)

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Industrial chemicals</th>
<th>Byproduct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certain insecticides which were once commonly used to control pests in agriculture and in building materials, as well as to protect public health (commercial names)</td>
<td>Substances which were used in hundreds of commercial applications, such as in electrical, heat transfer, and hydraulic equipment, and as plasticizers in paints, plastics, and rubber products.</td>
<td>Certain chemical byproducts which are produced unintentionally during combustion, including municipal and medical waste incinerators, open burning of waste, and industrial processes.</td>
</tr>
<tr>
<td>Aldrin</td>
<td></td>
<td>hexachlorobenzene</td>
</tr>
<tr>
<td>Chlordane</td>
<td></td>
<td>hexachlorobenzene</td>
</tr>
<tr>
<td>DDT</td>
<td></td>
<td>polychlorinated biphenyls (PCBs)</td>
</tr>
<tr>
<td>Dieldrin</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (dioxins)</td>
</tr>
<tr>
<td>Endrin</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (dioxins)</td>
</tr>
<tr>
<td>Heptachlor</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (furans)</td>
</tr>
<tr>
<td>Mirex</td>
<td></td>
<td>polychlorinated dibenzo-p-furans (furans)</td>
</tr>
<tr>
<td>Toxaphene</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (dioxins)</td>
</tr>
<tr>
<td>hexachlorobenzene</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (furans)</td>
</tr>
<tr>
<td>hexachlorobenzene</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (dioxins)</td>
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<tr>
<td>hexachlorobenzene</td>
<td></td>
<td>polychlorinated dibenzo-p-dioxins (furans)</td>
</tr>
</tbody>
</table>

F. Definition of Extended Producer Responsibility by the OECD

"OECD defines EPR as an environmental policy in which a producer's responsibility, physical and/or financial, for a product is extended to the post-consumer stage of a product's life cycle. There are two related features of EPR policy; (1) the shifting of responsibility (physically) and/or economically; (fully or partial) upstream to the producer and away from municipalities, and (2) to provide incentives to producers to incorporate environmental considerations in the design of their products.

A primary function of ERP is the transfer of the financial and/or physical responsibilities of waste management from local government authorities and the general tax payer to the producer. Environmental costs of treatment and disposal could then be incorporated into the cost of the product. This creates the setting for a market to emerge that truly reflects the environmental impacts of the product, and which consumers could make their decision accordingly." (OECD 2001)
G. List of 25 EU member states: Date when the transposition of the EU Directive on WEEE was completed, the allowance of a visible fee and the chosen compliance model. Twelve countries were given a temporary derogation from the collection, recovery and reuse/recycling targets due to a historical recycling deficit and low population density, which makes it hard to achieve the set target until the end of 2006. Theses are: Slovenia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Slovakia, Greece, Ireland Cyprus, Malta and Poland. (Savage et al. 2006)

<table>
<thead>
<tr>
<th>Country</th>
<th>Transposition completed until</th>
<th>Visible fee until</th>
<th>Compliance model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>12/2004</td>
<td>Allowed (2011/13)</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Cyprus</td>
<td>07/2004</td>
<td>NA</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Denmark</td>
<td>09/2005</td>
<td>NA</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Estonia</td>
<td>Expected 09/2005</td>
<td>NA</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Finland</td>
<td>08/2004</td>
<td>Allowed (2011/13)</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Germany</td>
<td>03/2005</td>
<td>Allowed (2011/13)</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Hungary</td>
<td>01/2005</td>
<td>Allowed (2011/13)</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Italy</td>
<td>Expected late 2005</td>
<td>Allowed (2011/13)</td>
<td>Clearing House</td>
</tr>
<tr>
<td>Latvia</td>
<td>12/2004</td>
<td>NA</td>
<td>Clearing House</td>
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<tr>
<td>Lithuania</td>
<td>10/2004</td>
<td>NA</td>
<td>Clearing House</td>
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<tr>
<td>Luxembourg</td>
<td>01/2005</td>
<td>Mandatory (2011/13)</td>
<td>Collective System</td>
</tr>
<tr>
<td>Malta</td>
<td>Expected late 2005</td>
<td>NA</td>
<td>NA</td>
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Literature


Cauchi, D. J. 2006. CRT glass cullets- commodity presentation. in Maximizing returns on materials, held in conjunction with the 2006 IEEE International Symposium on Electronics and Environment. Amandi Services Inc.


EMPA. 2003. eWaste Guide. in.


Knigge, C. 2006. Personal communication, January 2006. in. Public Waste Agency of Flanders (OVAM)


van der Voet, E. 1996. Substances form cradle to grave - Development of a methodology for the analysis of substance flows through the economy and the environment of a region. Leiden University.


Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
</tr>
<tr>
<td>ARF</td>
<td>Advanced recycling fee</td>
</tr>
<tr>
<td>ASEM</td>
<td>Advisory Services in Environmental Management</td>
</tr>
<tr>
<td>BAT</td>
<td>Best Available Technology</td>
</tr>
<tr>
<td>BDE</td>
<td>Bromodiphenyl ether</td>
</tr>
<tr>
<td>BFRs</td>
<td>Brominated flame retardants</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost Benefit Analysis</td>
</tr>
<tr>
<td>CET</td>
<td>Countries in economic transition</td>
</tr>
<tr>
<td>CFCS</td>
<td>Chlorofluorocarbons</td>
</tr>
<tr>
<td>CPU</td>
<td>Control processing unit</td>
</tr>
<tr>
<td>CRT</td>
<td>Cathode ray tube</td>
</tr>
<tr>
<td>EEE</td>
<td>Electrical and electronic equipment</td>
</tr>
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<td>EMPA</td>
<td>Swiss Federal Laboratories for Materials Testing and Research</td>
</tr>
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<td>EPR</td>
<td>Extended Producer Responsibility</td>
</tr>
<tr>
<td>GNP</td>
<td>Gross national product</td>
</tr>
<tr>
<td>GTZ</td>
<td>German Technical Cooperation</td>
</tr>
<tr>
<td>HCFC</td>
<td>Hydrochlorofluorocarbon</td>
</tr>
<tr>
<td>HIPS</td>
<td>High Impact Poly-Styrene</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>IMRB</td>
<td>International Market Research Bureau</td>
</tr>
<tr>
<td>INR</td>
<td>Indian Rupees</td>
</tr>
<tr>
<td>IOA</td>
<td>Input Output Analysis</td>
</tr>
<tr>
<td>ITOPS</td>
<td>Indian IT Hardware Market Study</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Analysis</td>
</tr>
<tr>
<td>LCC</td>
<td>Life Cycle Costing</td>
</tr>
<tr>
<td>LDCs</td>
<td>Least developed countries</td>
</tr>
<tr>
<td>LME</td>
<td>London Metal Exchange</td>
</tr>
<tr>
<td>MAIT</td>
<td>Manufacturers' Association of Information Technology India</td>
</tr>
<tr>
<td>MFA</td>
<td>Material Flow Analysis</td>
</tr>
<tr>
<td>NGOs</td>
<td>Non Governmental Organisations</td>
</tr>
<tr>
<td>ODS</td>
<td>Ozone depleting substances</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Cooperation and Development</td>
</tr>
<tr>
<td>OLPC</td>
<td>One Laptop Per Child</td>
</tr>
<tr>
<td>PBB</td>
<td>Polybrominated biphenyls</td>
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<tr>
<td>PBDE</td>
<td>Polybrominated diphenyl ethers</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
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<td>PCBs</td>
<td>Polychlorinated biphenyls</td>
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<td>PCDD</td>
<td>Polychlorinated dibenzo-dioxin</td>
</tr>
<tr>
<td>PCDF</td>
<td>Polychlorinated dibenzo-furans</td>
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<td>PROs</td>
<td>Producer responsible organisations</td>
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<td>S.EN.S</td>
<td>Swiss Foundation for Waste Management</td>
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<td>SFA</td>
<td>Substance Flow Assessments</td>
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<tr>
<td>SWICO</td>
<td>Swiss Association for Information, Communication and Organisational Technology</td>
</tr>
<tr>
<td>TA</td>
<td>Technology Assessment</td>
</tr>
<tr>
<td>TBBPA</td>
<td>Tetrabromobisphenol-A</td>
</tr>
<tr>
<td>TCLP</td>
<td>Toxicity Characteristic Leaching Procedure</td>
</tr>
<tr>
<td>UNEP</td>
<td>United Nations Environmental Program</td>
</tr>
<tr>
<td>USD</td>
<td>US Dollars</td>
</tr>
<tr>
<td>WEEE</td>
<td>Waste of electrical and electronic equipment</td>
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</table>
Many persons have contributed to the successful completion of this thesis, be it through the imparting of specific and detailed information or by means of moral and personal support. Without such contributions this work would have been much harder to complete. For all of those not mentioned explicitly below, I hereby thank collectively.

I particularly wish to thank Susanne Kytzia for her exceptional endurance in supporting the research, revising manuscripts and giving guidance. Her ability to be critical whilst not losing the human touch—so often lacking in the field of research—was invaluable.

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Thanks also to my parents for their continuous support and to Aaron for his “I’m game” attitude.

I owe deepest gratitude to Rosemary and dedicate this work to her.

Zürich
14.11.2006

Martin Streicher-Porte
Curriculum vitae

Martin Streicher-Porte
Born 7th July, 1967 in Stuttgart, Germany

Professional Activities:

Environmental Science


Preparation of a research project on e-waste for the Swiss National Research Foundation.

01-03/2004 Practical at UBS investment bank, department of economic research.

03-06/2003 Research Period in South Africa, Project co-operation with the Local Agenda 21 Initiative in Cape Town/South Africa.

2000 Practical at the secondary school Sargans/Switzerland in environmental education, department of biology.

2001 and 2002 Seasonal Work at the game resort Langenberg.

2000 and 2001 Practical for the Forestry Commission in Füssen/Germany Theme: Concept and Realization for a Forest adventure Park.

1999 and 2000 Assistance for Dr. B. Oberle in the ETH course: "Introduction to environmental problem solving", methodical and didactical coaching of student groups in case studies and during exercises.

Contemporary Dance

1997 Founding member of the Dance Theater Momentum, tours in Germany, Switzerland and Austria.

1992-1997 Member of the Joachim Schlömer Dance Theater in Ulm, Weimar/Germany and Basel/Switzerland.

Other

1988-1989 Civil Service in the Filderklinik, Ostfildern/Germany.

1997-1998 Voluntary work at the Street Children Care Unit "Ciudad Don Bosco" in Medellin/Colombia.
**Education:**

<table>
<thead>
<tr>
<th>Date</th>
<th>Course Details</th>
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<tr>
<td>03/2005–06/2006</td>
<td>Post Diploma Course in developing countries, NADEL, ETH Zurich</td>
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<tr>
<td>06-10/2004</td>
<td>Post Diploma Course in Spatial Information Systems, Institute for Photogrammetrie and Remote Sensing, ETH Zurich</td>
</tr>
<tr>
<td>09/2004</td>
<td>Further education in Project Management, Centre of professional development, ETH Zurich</td>
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<tr>
<td>10/2003-01/2004</td>
<td>Teaching degree in environmental science, Institute for environmental science, ETH Zurich</td>
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<tr>
<td>10/2003</td>
<td>Diploma in environmental science ETH (equivalent to a master degree): Evaluation of the Local Agenda21 Partnership Aachen-Cape Town</td>
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<tr>
<td>03/2003</td>
<td>Diploma in general and environmental didactics at Institute for behavioural science ETH, Zurich</td>
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<tr>
<td>1998/2000</td>
<td>Courses in presentation, tutoring, and guidance of groups and didactic support at the didactic centre, ETH Zurich</td>
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<td>Environmental Science Course at the Swiss Federal Institute for Technology, ETH Zurich</td>
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<tr>
<td>1989-1993</td>
<td>Dance Diploma at the Folkwang College of Dance and Choreography, Essen</td>
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<tr>
<td>1987</td>
<td>Graduated from Grammar School (Heinrich-Heine Gymnasium) Stuttgart</td>
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