Insights from a decade of development cooperation in e-waste management

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ABSTRACT

This paper presents insights from a decade of development cooperation projects in electrical and electronic waste (e-waste) management and associated research activities, conducted by Empa's Technology and Society Lab together with a number of international partners. The quantification of e-waste volumes is a prerequisite for the development of sustainable solutions in developing countries. Challenges include getting an understanding of the accuracy of data and the dynamic behavior of e-waste flows and their constituents. In addition, the thermodynamic and physical properties of the material mix found in e-waste needs to be understood in order to achieve efficient recovery of the material resources. The past and still on-going application of hazardous substances in electrical and electronic equipment will remain a dominant issue in sustainable e-waste management systems in the future, if environmental, health and safety hazards, as well as cross-contamination into recovered secondary resources, are to be avoided. Furthermore, tailored solutions will have to take into account the informal nature of e-waste recycling in developing countries. Although continuing miniaturization of electronic devices can be observed, overall volumes and mass flows are expected to increase steadily in the future, as appliances are getting cheaper and hence more accessible, especially in the non-saturated markets of developing countries.

Keywords

Waste electrical and electronic equipment, e-waste, ICT hardware, developing countries, informal sector, recycling, hazardous waste, waste flows, waste management

1. INTRODUCTION

Access to Information and Communication Technology (ICT) is pivotal for a country's economic and social development and is currently improving throughout the developed, but also the developing world. However, ICT is also contributing to the ever growing amount of electronic waste (e-waste). E-waste has been recognized as a complex waste stream containing both hazardous substances and valuable secondary resources [1]. Serious health, socio-economic, and environmental problems that arise from the improper management of e-waste have been widely documented [2]. While in OECD countries the paradigms of a "closed loop economy" and "extended producer responsibility (EPR)" have paved the ground for a professionalizing e-waste recycling sector [3], developing countries and countries in transition often lack the infrastructure as well as the financial and institutional resources for the sustainable management of e-waste.

Investigations by NGOs such as The Basel Action Network [4], [5], Toxics Link [6] or Greenpeace [7], [8] about informal e-waste recycling in developing countries started to make their way to the mass media in the early 2000s. Poor people in the slums of megacities in developing countries started to recover valuables from the e-waste stream, putting themselves and their environment at considerable risk [2]. As a result of the public attention, various international cooperation projects in e-waste management were launched by multilateral (UN) organizations (e.g. in Africa [9–11]), producers from the ICT industry (e.g. Hewlett Packard [12]), NGOs and governmental organizations, mainly between 2003 and 2010. Amongst them was the Swiss e-Waste Programme, initiated by the Swiss State Secretariat of Economic Affairs (SECO) and implemented by Empa together with local organizations in the partner countries. It has been a pioneering initiative, addressing the challenges of sustainable e-waste management in various developing countries and countries in transition. In synergy with this initiative, the following supporting research activities, grouped into four topical areas, were pursued in order to address the main challenges and issues that were identified in the first years of development co-operation:

- Assessing e-waste volumes
- Assessing and treating hazardous substances in e-waste
- Understanding informal recycling and assessing its efficiency and impacts
- Understanding and predicting long-term trends

This paper recapitulates the lessons learned from a decade of research and implementation activities in e-waste management in the context of Empa's programmes in developing countries and related projects. Each of the chapters 2-5 relates to one of the four challenges mentioned above.

2. E-WASTE VOLUMES

Experiences in developing countries have shown that e-waste management has to meet a number of requirements which go beyond pure technical implementation and which demand for a comprehensive and structured approach. The starting point for any approach to e-waste management is to understand the current framework conditions, with the quantification of current and prospective e-waste volumes being the most important piece of information on which tailored and sustainable solutions can be

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built. Hence Empa developed an e-waste country assessment methodology [12] which has been applied in various countries (Table 1).

Prior to the quantification of e-waste volumes, the assessment methodology requires the definition of scope (geographical focus, product categories) and objective (e.g. obtain a reliable overview of the e-waste landscape in the selected country). A thorough stakeholder assessment, considering the processes import/ production, consumption, repair, refurbishment, collection, dismantling, recycling, refining and final disposal, identifies all actors involved and their role and interest in the management of electrical and electronic equipment (EEE) and the resulting e-waste. Along with the knowledge of how stakeholders are interlinked, a material flow system can be developed that forms the basis for the material flow analysis (MFA). For concrete examples, please refer to the sources cited in Table 1.

Table 1: Available e-waste country assessment according to the Empa methodology.

Country	Year	References
Benin	2010/11	[13]
Burkina Faso	2010/11	[14]
Côte d’Ivoire	2010/11	[15]
Ghana	2010/11	[16]
Nigeria	2010/11	[17]
Tanzania	2010	[10]
Uganda	2008	[11]
South Africa	2008	[18]
Morocco	2008	[19]
Chile	2007	[20], [21]
Colombia	2008	[22]
Peru	2008	[23]
Brazil	2009	[24]
Kenya	2008	[25]

Due to limited data availability, the quantification of e-waste volumes in developing countries is an iterative process, often based on a mixed 'top-down' and 'bottom-up' approach. Figures on imports or production of EEE are commonly available from statistical data while the consumers' stock of EEE is best quantified by surveys. The predominantly informal waste collection and management systems are the least documented, for which reason e-waste quantities are often assessed by assigning lifetimes to specific products (for details see e.g. [12], [26]). Through additional field investigations and interviews, meetings and workshops with the stakeholders, valuable information such as transfer coefficients between processes, downstream processes of materials and material quality can be obtained.

Challenges related to the quantification of e-waste volumes in developing countries are, among others, the absence of previous studies to serve as local reference and baseline information for purposes of comparison, poor reliability of data from official sources and the informal nature of the e-waste sector. Furthermore, surveys are often conducted in a limited area not always representative for the assessed country as a whole. E-waste assessment studies thus often highly rely on expert judgments or assumptions to arrive at coherent mass flow quantification. In literature, data uncertainty of MFA is often dealt with by propagation of uncertainty, least square fitting, sensitivity analysis or uncertainty intervals [27], [28]. If most available data are single values from different sources (measurements, interviews, official statistics), as in our case, it is even difficult to estimate the uncertainty. Most of the existing e-waste assessment studies thus limit this discussion to plausibility considerations in order to confirm the results (e.g. [16], [17]).

The studies listed in Table 1 are all static MFAs that present only a snapshot in time. Dynamic MFAs of e-waste in developing countries are difficult to accomplish due to limited data availability. Production or import quantities of selected EEE are often the only data available as time series. Although this information, together with lifetime distributions assigned to the different types of EEE, is in principle sufficient to calculate the resulting e-waste volumes [12], [26], the reliability of the data is often low and thus provides a poor basis for extrapolations (e.g. [10], [11], [16], [17]). In developed countries, dynamic MFAs of e-waste exist, but are usually limited to one or a few products, such as computers in the U.S. [29] or computers, TVs, washing machines, refrigerators and air conditioners in Beijing [30]. A new study from the Netherlands presents results based on dynamic MFA for all e-waste categories [31].

Quantitative models for predicting e-waste flows based on diffusion and obsolescence were developed and discussed in [32], namely the “delay model” and the “reverse diffusion model”. Using the example of CRT monitors crowded out by flat screen technologies, the models were validated based on data for Switzerland. These models can be used to forecast the disposal of durable hardware products in the market that are rendered obsolete by the next technological generation [32], [33].

At a global level, free available data such as the ITU World Telecommunication/ICT Indicators Database [34] give valuable information on penetration rates of selected products. Based on these indicators, a study on global e-waste generation from computers was built [26].

However, it is not sufficient to know the e-waste flows alone to find ways for efficient resource recovery. Products entering the e-waste stream are featuring a variety and complex material mixes. Regarding the various metals contained in e-waste fractions, for example, it is of great advantage if they are mutually compatible with respect to their thermodynamic and physical properties, or to other impurities, so that the metallurgical processing technologies used by metals producers and refiners can recover the metals well economically. If not, mixed alloys, sludges, slimes and slags of low economic value are produced, which have a dumping or storing cost attached to them [35]. Hence, assessed e-waste flows also need to be attributed with information about their material composition and their thermodynamic and physical properties, as well as the uncertainties related to this information.

3. HAZARDOUS SUBSTANCES

E-waste can contain a broad variety of hazardous substances, including heavy metals and Persistent Organic Pollutants (POPs) [36]. Although some of these substances were regulated and phased out over the past years, they are still present in older equipment. Other hazardous substances are still legally used in new products, such as mercury, which can be found in a range of today’s EEE. Due to the presence of these substances, e-waste is generally considered hazardous waste under the Basel Convention [37]. If improperly managed, as often happens in the informal sectors of developing countries and countries in transition, e-waste may pose significant human and environmental health risks.

These risks are not only induced by the original hazardous substances contained in the products (e.g. brominated flame retardants), but also by auxiliary substances used in recycling techniques (e.g. cyanide for leaching of gold) and by-products formed by the transformation of primary constituents (dioxins through burning of cables) [2]. Brominated flame retardants (BFRs) as an original constituent of e-waste and dioxins as a by-product are of special concern due to their toxicological properties and their persistency to environmental degradation (i.e. POPs).

Brominated flame retardants: Empa studied current concentrations of BFRs in mixed plastics from e-waste and their implications for an environmentally sound recovery with extensive sampling campaigns in various European countries [38]. The results of the sampling campaigns show that no mixed plastics fraction from European e-waste is completely free from regulated BFRs. High average concentrations of BFRs mainly originate from the treatment of small household appliances for high temperature applications, CRT monitors and consumer equipment, in particular CRT TVs. This pattern can also be observed outside Europe [39], especially in developing countries which import second-hand appliances from OECD countries in large quantities [9]. A recent assessment of plastics from CRT monitors and TVs in Nigeria shows concentrations of brominated flame retardants in the same range as or above the levels measured in the European study [40]. A recent sampling campaign in the informal plastic recycling sector in Delhi, India, indicates that recycled plastic fractions are often cross-contaminated with brominated flame retardants by mixing plastics from e-waste with nonhazardous plastic fractions from other waste types [41].

Dioxins: The release of dioxins is the most relevant emission from the burning of plastics, especially PVC plastics and plastics containing BFRs [42]. Open-burning is a widely used technique in informal recycling sectors to recover metals, such as copper, steel, and aluminum from wires and other EEE components. Dioxin emissions from cable burning in the greater Accra region, for instance, are estimated to correspond to about 0.3% of total dioxin emissions in Europe [16]. While that number may sound small, it yields to substantial amounts if Accra’s tiny proportion is extrapolated to a larger region of concern, such as the whole African continent. Recent measurements in Accra indicate increasing levels of BFRs in breastmilk associated with the informal recycling of e-waste [43]. A review of various studies presenting dioxins measurements in China and India highlights very high levels in air, bottom ash, dust, soil, water and sediments in informal e-waste recycling areas of the two countries [2]. The concentration levels found sometimes exceed the reference values for the sites under investigation and pollution observed in other industrial or urban areas by several orders of magnitude.

Policy implications: Our results related to BFRs in plastics from e-waste and the possible formation of dioxins through improper recycling were considered in various policy frameworks. The European WEEE Forum of collective e-waste management schemes created clauses in its normative requirements [2] specifying that plastic fractions containing brominated flame retardants should be removed and treated separately from other plastic fractions . On international level our study results are also in support of the development of guidance documents under the Stockholm Convention on Persistent Organic Pollutants [44]. Related to BFRs listed in Annex A, two guidance documents, one for the Inventory of new POPs and one on best available techniques and best environmental practices for the recycling and disposal of articles containing BFRs, are currently being established [45], [46].

Related to POPs are emission reduction schemes or international financing mechanisms, such as UN Environmental Finance Facility programmes (e.g. the Global Environment Facility – GEF). Such international financing mechanisms will be crucial in implementing sustainable e-waste management systems through the support of initial investments and by creating market incentives to avoid improper processes and to drain the secondary resources market from internationally banned chemicals.

4. INFORMAL RECYCLING

Developing countries and countries in transition are characterized by informal activities along the e-waste recycling chain [1]. Collection, manual dismantling, open burning to recover metals and open dumping of residual fractions are normal practice in most countries. In smaller and less developed economies, these activities are usually performed by individuals, as volumes are too small to trigger the informal sector to specialize in e-waste recycling at large scale. Larger economies, especially countries in transition like India and China [2], [47], [48], as well as countries which are subject to the intense trade of second-hand equipment and illegal waste shipment, like Ghana and Nigeria [9], reveal a large organized informal sector.

Emissions from informal recycling activities have already been assessed in many studies (see [2] for a review) and their impacts on the environment and health are evident. However, people in the informal sector depend on this work to ensure their minimal livelihood. Therefore the Swiss e-Waste Programme and related research activities focused on understanding the functioning and

Figure 1: Typical recycling processes applied in the informal sector of developing countries (open burning of cables, leaching of gold from PWB, desoldering of PWB)

Table 2: SWOT analysis of the e-waste recycling chain in formal vs. informal scenarios

SWOT	**Formal scenario**	**Informal scenario**
Strengths	Access to state-of-the-art end-processing facilities with high metal recovery efficiency	High collection efficiency Efficient deep manual dismantling and sorting Low labor costs gives advantage to manual techniques over mechanical technologies in the pre-processing steps
Weaknesses	Low efficiency in collection Often low efficiency in (mechanized) pre-processing steps	Medium efficiency in dismantling and sorting Low efficiency in end-processing steps coupled with adverse impacts on humans and the environment
Opportunities	Improvement of collection efficiency Technology improvement in pre-processing steps	Improvement of efficiency in the pre-processing steps through skills development for dismantling and sorting Implementation of alternative business models, providing an interface between informal and formal sector
Threats	"Informal" activities in the collection systems	Bad business practice (bribery, "cherry picking" of valuables only, illegal dumping of non-valuables, etc.) Lacking government support (no acceptance of informal sector, administrative hurdles for receiving export licenses, etc.)

efficiency of the informal sector and the development of alternative business models to allow the sector to transform themselves towards sustainable operations. The key results can be grouped into the three main stages of the recycling chain (collection, pre-processing and end-processing) and concluded with a description of the "Best-of-2-Worlds" philosophy.

Collection: In contrast to formalized take-back schemes, as found in Europe, where consumers pay (indirectly) for collection and recycling, in developing countries it is usually the waste collectors who pay to consumers for their obsolete appliances and scrap material [35]. As a result, informal waste sectors are often organized in a network of individuals and small businesses of collectors, traders and recyclers, each adding value, and creating jobs, at every point in the recycling chain [49]. As many poor people rely on small incomes generated in this chain, impressive collection rates of up to 95% of waste generated are achieved [9], which is far above what can be achieved by todays formalized take-back schemes [50].

Pre-processing: As labor costs are low in developing countries and countries in transition, informal and formal recyclers apply labor intensive pre-processing technologies, such as manual dismantling, as the primary treatment to separate the heterogeneous materials and components. A comparative study [48] of pre-processing scenarios revealed that material recovery efficiency improves along with the depth of manual dismantling. Purely mechanical treatment options, as typically applied in western countries with high labor costs, lead to major losses of precious metals, in particular, in dust and ferrous fractions [51], [52]. Hence manual recycling practices in developing countries bear advantages, such as low investment costs, creation of jobs and higher material recovery efficiency [1].

End-processing: Subsequent to manual pre-processing practices, further "refining" techniques, such as de-soldering of Printed Wiring Boards (PWB) and subsequent leaching of gold, have been observed especially in the informal sectors in India and China [2], [4], [47], [53]. There are indications that such processes are also applied in other larger developing countries, such as Nigeria [17]. In a pilot project in Bangalore, India, Empa has demonstrated that besides being hazardous, informal end-processing or refining practices are also inefficient. Improper sorting of printed wiring boards and subsequent wet chemical leaching processes for the recovery of gold, for example, revealed a combined yield of only 25%. In contrast, today's state-of-the-art integrated smelters, as used in most formalized recycling systems, achieve recovery efficiencies as high as 95% [51].

Best-of-2-Worlds: From these findings it can be concluded that recovery efficiencies in informal recycling processes can differ considerably from those of formal recycling systems, even though there are individual strengths and weaknesses on both sides (see Table 2). Analyses have shown that the average material recovery yield over the entire recycling chain can be in a similar (low) range in informal and formal systems [35], [48]. Taking this into account, an alternative business model for the informal sector has been piloted in Bangalore which aims to combine "the best of both worlds" by transferring informal wet chemical processes to state-of-the-art recycling technologies [1], [53]. Through financial incentives and training the informal sector was encouraged to concentrate on the preparation of the optimal fractions as input for the integrated smelter. A formal local cooperative was acting as an intermediate, buying the fractions from the small individual businesses in the informal sector on one hand, and selling it to an integrated smelter on the international market on the other hand. Similar projects have been carried out by other initiatives and have been summarized as the "Best-of-2-Worlds" philosophy by the StEP[1] community [48]: "*Under the observation of integrating best geographically distributed treatment options, the Best-of-2-Worlds philosophy helps to achieve the most sustainable solution for developing countries: to locally pre-process their domestically generated e-waste by manual dismantling; and to deliver critical fractions to state-of-the-art end-processing facilities in a global market.*"

This also highlights that the efficient and sustainable recovery of secondary resources from e-waste is a market opportunity for developing countries. This requires functioning 'reverse supply chains' with adequate capabilities for recycling and refining as well as sufficient control supported over their material quality and environmental and social impacts of the related processes. Hence the harmonization of international standards and the introduction of processes to distinguish "fair" secondary resources from

[1] Solving the e-Waste Problem (StEP) Initiative, a global platform for developing sustainable solutions for e-waste management. http://www.step-initiative.org

materials recovered under sub-standard conditions (e. g., burning cables to recover copper) will be instrumental to leverage these opportunities.

5. LONG-TERM TRENDS

It is likely that the quantities of discarded electronics will increase substantially in the foreseeable future as a result of fast innovation cycles and increased market penetration of cheap electronics, the latter being the main driver of e-waste volumes in developing countries and countries in transition.

An important long-term trend that affects the waste flows is the ever-higher integration and miniaturization of digital electronics and, related to this, an increasing complexity of the material composition. The physical mass needed to provide capacities for storing, processing and transmitting data is decreasing at a rapid pace (roughly along the lines of Moore's Law), which leads to a decrease of the average physical mass per device in use, despite increasing functionality. It has been observed using the example of mobile phones that this trend does not lead to a decrease in total mass flow, because at the same time the number of devices is increasing faster [54]. Historically, this "miniaturization paradox" can be explained by the general trend that processing capacity "is getting cheaper faster than it is getting smaller" [55] (p. 95). The miniaturization paradox has three effects on e-waste streams:

1. Total mass flow increases despite of smaller and more lightweight devices;
2. More devices enter other waste streams because they are small and unremarkable; this trend increases with embedded electronics [56–58];
3. Informal recycling becomes more difficult because of the higher integration density of the devices.

E-waste treatment and even the definition of e-waste will have to adapt to this general trend if the dissipation of valuable materials is to be slowed down in the long term.

Besides the development at the hardware level, software trends are affecting e-waste streams as well. The software innovation cycle usually renders hardware obsolete much faster than physical deterioration. Consumer lock-in can force the users to buy new software and hardware due to software compatibility issues. In an early study on desktop computers, Empa has shown that software innovation not only creates demand for new hardware, but in some cases even bilks the users of the higher performance they could theoretically expect from the new hardware [59], [60]. The external effects of e-waste are a high price we pay for a sometimes relatively low benefit.

These dynamics are slowly but steadily changing the nature of e-waste and requiring continuous adaptation of the formal and informal recycling industries around the world.

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