Recycling of ICT Equipment in Industrialized and Developing Countries

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Abstract. The increasing penetration of society with Information and Communication Technologies (ICT) is resulting in growing waste volumes. Typical of this waste is the combination of its intrinsic value due to the high content of basic and precious metals with health and environmental hazards caused by the occurrence of toxic substances in combination with inadequate recycling practices. Based on the principle of Extended Producer Responsibility (EPR), industrialized countries have legislated WEEE (Waste Electrical and Electronic Equipment) management. As a consequence, producers established take-back schemes. In developing countries, the absence of a legal framework and formal recycling infrastructure as well as the presence of the self-organized informal sector has complicated similar efforts. In some countries, progress could be achieved through the promulgation of a legal framework and the establishment of basic recycling infrastructure. The environmental and social aspects associated with the improper recycling of WEEE and the sustainable reintegration of secondary resources demands strong efforts from industry, government, and civil society.

Keywords: WEEE, E-Waste, ICT Waste, Formal Recycling, Informal Recycling, Secondary Resources

1 Introduction

The use of Electrical and Electronic Equipment (EEE) has grown rapidly in recent decades. Expanded functionalities and decreasing prices have influenced consumer behavior. The trend toward embedding Information and Communication Technologies (ICT) into different goods used daily has widened the range of EEE. As a consequence, Waste Electrical and Electronic Equipment (WEEE) has become the fastest-growing waste stream worldwide [1].

This is particularly the case for ICT equipment, where sales of new technologies have outperformed growth in other sectors [2]. In industrialized countries, this phenomenon could be observed as early as the 1990's, while developing countries have

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been lagging behind. In recent years, however, growth rates of ICT sales in developing countries have exceeded the corresponding rates in industrialized countries. According to the International Telecommunication Union (ITU), the number of mobile-phone subscriptions in industrialized countries grew by 14% from 2009 to 2013, whereas growth in developing countries reached 48% during the same period [3]. Similar trends can be observed for computer penetration in households or for per capita use of the Internet.

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal [4] regulates among others the export of ICT waste to non-OECD countries. However, this international treaty could not prevent such exports since not all countries have ratified it, among others the United States as the largest generator of ICT waste worldwide. Furthermore, illegal exports are difficult to detect.

Media reporting on environmental and social conditions witnessed in recycling activities in developing countries has startled the public and led to calls for stricter control and regulation of EEE exports from OECD countries. A working group of the Basel Convention has drafted technical guidelines with the aim of providing clarity on the distinction between EEE and WEEE in order to better prevent their illegal shipment. The guidelines are based on a mandatory functionality test which is to be performed for all equipment designated for export. A similar requirement has been formulated in the recast of the European WEEE Directive [5].

2 ICT Waste: Volumes and Composition

2.1 WEEE and ICT Waste

According to the European WEEE Directive [5], WEEE is grouped into the following ten categories:

1. Large household appliances
2. Small household appliances
3. IT and telecommunications equipment
4. Consumer equipment and photovoltaic panels
5. Lighting equipment
6. Electrical and electronic tools
7. Toys, leisure, and sports equipment
8. Medical devices
9. Monitoring and control instruments
10. Automatic dispensers

The category "IT and telecommunications equipment," mostly also referred to as "ICT," includes end-of-life equipment such as computers, printers, and scanners as well as mobile and fixed communication devices.

2.3 Volumes of ICT Waste

Usage of ICT products in a society and the corresponding stocks and flows are important elements for the design of management systems, both from a waste and from a material management perspective. Quantitative models for predicting WEEE flows incorporating technological substitution and multiple-unit product stewardship have been tested and validated, for instance for the case of cathode ray tube (CRT) TVs being crowded out by flat screen TV sets in Switzerland [6].

Industrialized Countries. Recent statistics estimate the worldwide quantity of EEE put on the market in 2012 at roughly 65 million tons and the corresponding generation of WEEE at almost 49 million tons [7].

In Europe, the share of ICT equipment in relation to total EEE equipment put on the market ranges between 9% (Norway) and 23% (Belgium), whereas the share of ICT waste collected in relation to WEEE collected varies between 13% and 35% (Table 1). ICT waste collected per capita varies between 0.3 kg/year and 3.5 kg/year (Table 2).

Table 1. EEE/ICT put on the market and WEEE/ICT waste collected in 15 selected European countries in 2010 [8]

Country	EEE put on the market	ICT put on the market		WEEE collected	ICT waste collected	
	(t)	(t)	(%)	(t)	(t)	(%)
Austria	165,810	28,656	17%	74,256	16,332	22%
Belgium	294,530	66,446	23%	105,557	18,626	18%
Denmark	147,557	27,165	18%	82,931	18,325	22%
Finland	148,157	20,603	14%	50,867	8,034	16%
France	1,635,493	201,576	12%	433,959	63,407	15%
Germany	1,730,794	285,285	16%	777,035	217,917	28%
Greece	178,260	20,410	11%	46,528	7,242	16%
Italy	1,117,406	110,221	10%	268,216	38,237	14%
Latvia	15,290	2,117	14%	4,288	562	13%
Norway	181,579	16,055	9%	107,767	16,496	15%
Portugal	157,065	16,316	10%	46,673	7,272	16%
Romania	151,317	31,944	21%	26,247	6,460	25%
Spain	746,801	83,215	11%	158,100	25,924	16%
Sweden	232,403	42,212	18%	161,444	31,756	20%
United Kingdom	1,534,576	338,838	22%	479,356	165,626	35%

Table 2. Collection of ICT waste per capita in 15 selected European countries in 2010 [8]

Country	Population (millions)	ICT waste collected (t)	ICT waste collected per capita (kg)
Austria	8.4	16,332	1.9
Belgium	10.8	18,626	1.7
Denmark	5.5	18,325	3.3
Finland	5.4	8,034	3.4
France	65.4	63,407	1.0
Germany	81.8	217,917	2.7
Greece	11.3	7,242	0.6
Italy	60.3	38,237	0.6
Latvia	2.2	562	0.3
Norway	4.9	16,496	3.4
Portugal	10.6	7,272	0.7
Romania	21.5	6,460	0.3
Spain	47.0	25,924	0.6
Sweden	9.4	31,756	3.4
United Kingdom	62.0	165,626	2.7

Developing Countries. Due to limited data availability, the quantification of WEEE volumes in developing countries is an iterative process, often based on a combined top-down and bottom-up approach. Figures on imports of EEE equipment can often be derived from statistical data, while consumer stocks and disposal volumes need to be assessed through surveys. Informal waste collection is least documented, for which reason WEEE quantities are often assessed by assigning lifetimes to specific products. Through additional field investigations as well as interviews, meetings, and workshops with stakeholders, valuable information such as transfer coefficients between processes, downstream processes of materials, and information about material quality can be obtained.

Various WEEE assessments performed between 2005 and 2012 have revealed figures on Personal Computer (PC) imports and PC waste as shown in Table 3. The data on PC waste are indicative and are derived from material flow assessments.

Table 3. PCs put on the market and estimated PC waste generation in selected developing countries according to various country assessments

Country	Assess-ment year	Popula-tion (millions)	PCs put on the market (t)	PC-waste generated (t)	PC waste generated per capita (kg)	References
Ghana	2009	24.3	16,650	6,400	0.3	[9]
Kenya	2007	40.9	5,200	440	0.01	[1], [10]
South Africa	2007	50.0	32,000	19,400	0.4	[1], [11]
Uganda	2007	33.8	700	1,300	0.2	[1], [12]
China	2007	1,339.2	419,100	300,000	0.2	[1]
India	2007	1,184.7	140,800	56,300	0.01	[1]
Brazil	2005	193.4	no data	96,800	0.5	[1], [13]
Chile	2010	17.1	12,600	5,300	0.3	[14], [15]
Colombia	2006	45.6	13,600	6,500	0.1	[1], [16]
Peru	2006	29.5	7,000	6,000	0.2	[1], [17]

2.2 Composition of ICT Waste

The perception of WEEE has developed over the years from a waste problem which can cause environmental damage and health issues to an opportunity: ICT components, for example, contain a variety of metals for which recovery is economically attractive (Table 4). The metal concentrations often exceed the concentrations found in natural ores [18]. The Kloof gold mine in South Africa, for instance, has gold concentrations of approx. 6 ppm gold [19], whereas in mobile phones this concentration can be up to 100 times higher. Similar situations can be found when comparing Silver and Palladium concentrations in natural ores with concentrations in ICT components.

Table 4. Content of Au, Ag, and Pd in ICT devices [20]

Device	Au		Ag		Pd	
	(mg)	*(ppm)*	*(mg)*	*(ppm)*	*(mg)*	*(ppm)*
PC	316-338	21-23	804-2,127	54-142	146-212	10-14
Laptop	246-250	85-86	440	152	50-80	17-28
Tablet	131	215	26	43	no data	no data
Mobile phone	50-69	455-627	127-715	1,155-6,500	10-37	91-336

Compared to annual production volumes, the demand for metals used in EEE reaches significant levels (Table 5). This highlights the relevance of WEEE as a secondary resource. Consequently, inefficient treatment of WEEE may lead to a systematic loss of secondary materials [1]. Hence, the appropriate handling of WEEE both prevents environmental and health issues and contributes to more sustainable use of raw materials.

Table 5. Important metals used for EEE [1]

Metal	Primary production* (t/y)	By-product of	Demand for EEE (t/y)	Demand/ production (%)	Main applications
Ag	20,000	Pb, Zn	6,000	30	Contacts, switches, solders…
Au	2,500	(Cu)	300	12	Bonding wire, contacts, integrated circuits…
Pd	230	PGM	33	14	Multilayer capacitors, connectors
Pt	210	PGM	13	6	Hard disks, thermocouples, fuel cells
Ru	32	PGM	27	84	Hard disks, plasma displays
Cu	15,000,000		4,500,000	30	Cables, wires, connectors…
Sn	275,000		90,000	33	Solders
Sb	130,000		65,000	50	Flame retardants, CRT glass
Co	58,000	Ni, Cu	11,000	19	Rechargeable batteries
Bi	5,600	Pb, W, Zn	900	16	Solders, capacitors, heat sinks…
Se	1,400	Cu	240	17	Electro-optic devices, copiers, solar cells
In	480	Zn, Pb	380	79	LCD glass, solders, semiconductors
Total			**4,670,000**		

*based on demand in 2006; acronyms: PGM= Platinum Group Metals; CRT= Cathode Ray Tube; LCD= Liquid Crystal Display

WEEE also contains toxic and hazardous substances, for example, heavy metals such as mercury, cadmium, lead, and chromium, or Persistent Organic Pollutants (POPs), which can be found in plastic casings or in Printed Wiring Boards (PWB) [21]. Some of these substances have been regulated, and their use has been restricted for new equipment through the European RoHS[1] directive [22]. Other substances have been banned, but are still allowed for certain applications (for instance, mercury in energy-saving lamps) or are still present in older equipment. WEEE and its components may therefore pose a significant health risk not only due to their primary constituents, but also as a result of improper management of byproducts either used in the recycling process (such as cyanide for leaching gold) or generated by chemical reactions (such as dioxins through the burning of cables). Due to its properties, WEEE is generally considered to be hazardous waste under the Basel Convention.

1 Restriction of Hazardous Substances Directive 2002/95/EC

3 Objectives, Challenges, and Approaches

3.1 Objectives and Challenges

The main services a WEEE management system has to deliver are (a) separate and efficient collection, (b) recovery of secondary resources, and (c) segregation and safe disposal of hazardous components. Although recycling the valuables contained in WEEE may generate income, other processes such as the removal and disposal of toxic components as well as system administration, monitoring, and control to ensure quality may incur expenses.

3.2 Extended Producer Responsibility

Early experiences in industrialized countries showed that municipalities are not adequately equipped and staffed to handle a complex waste stream such as WEEE. New approaches had to be considered, and the concept of Extended Producer Responsibility (EPR) [23], where producers resume the end-of-life responsibility for their products, evolved as a broadly accepted alternative. Based on ERP, producers initiated take-back schemes, either individually, or collectively as a group of producers, or as members of national Producer Responsibility Organizations (PRO), to manage financing of WEEE flows and processing steps. National authorities started to address this concept in their waste regulations.

Formal WEEE management systems adhering to sustainability and extended producer responsibility principles were established approximately 20 years ago mainly in Europe [24–26]. The first European WEEE Directive [27] set the global pace and standard in regulating WEEE management. However, some countries had started to implement WEEE management policies before the EU WEEE Directive came into force. One of the earliest legislative frameworks is the Swiss Ordinance on the Return, Taking Back and Disposal of Electrical and Electronic Equipment (ORDEE) [28]. Its simple principles of mainly defining stakeholders' obligations (see Figure 1) have led to a consumer-friendly and environmentally sound take-back system with high collection and material recovery rates [29].

In developing countries and emerging economies, the concept of EPR was not adapted until recently. Reports from NGOs on the environmental and health issues related to poor WEEE management as well as various international cooperation projects addressing those challenges [30] increased the priority of WEEE management among environmental issues requiring special legislative attention.

As a result, WEEE legislation based on EPR has been established in a number of developing countries in recent years. Summaries of rapid developments can be found as global overviews [26, 31] or in publications focusing on specific regions: Africa [32, 33], Asia [34], and Latin America [35]. Since 2011, a few African (i.e., Ghana and Kenya) and Latin American countries (i.e., Colombia and Peru) have introduced EPR as the core principle in their national WEEE legislation. Kenya, for example, published draft WEEE regulations in 2013 for public consultation. In Peru, the

"Reglamento de Gestión y Manejo de Residuos Eléctricos y Electrónicos – RAEE" introduced EPR as a new principle in national waste legislation in 2012 [36].

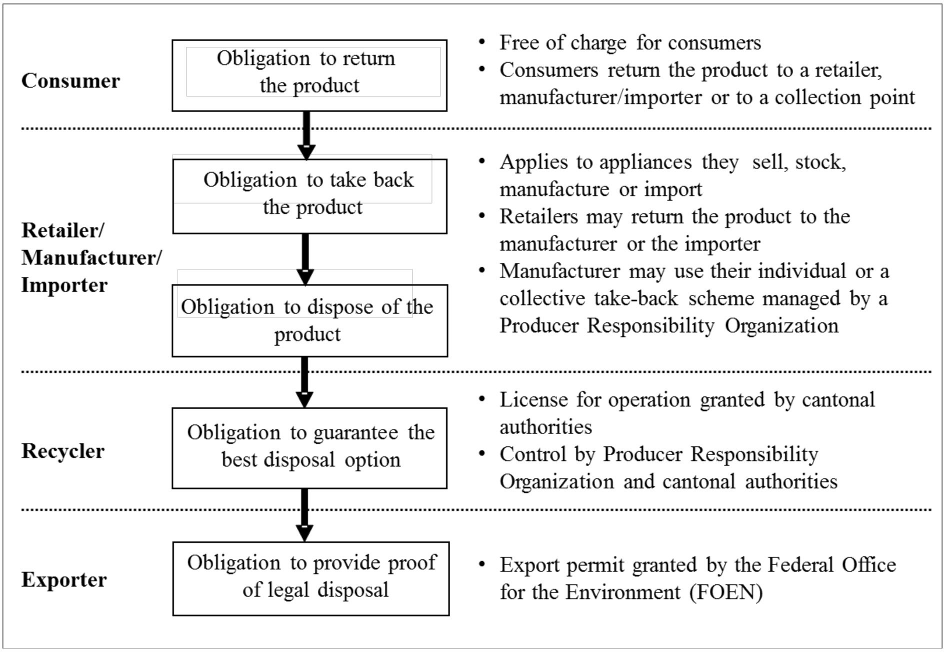

Fig. 1. Flow of WEEE and related stakeholders' obligations according to the Swiss WEEE legislation ORDEE [28].

4 Formal Recycling

4.1 Collection

In formal WEEE schemes, municipal collection points and/or retailers' take-back obligations are the backbone of collection. In the European Union (EU), take-back obligations in the previous WEEE directive entailed only municipal collection points. As in some countries take-back quantities are still rather low, the recast of the WEEE directive [5] has defined responsibilities for distributors to take back equivalent equipment they sell on a one-to-one basis (obligation for the customer to buy equipment with an equivalent function) and free of charge. In addition, distributors with EEE sales areas larger than 400 m^2 have to take back WEEE of less than 25 cm external dimension free of charge without the obligation for the customer to buy a piece of equipment with an equivalent function. In 2010, the quantities collected in the EU ranged between 1.1 (Romania) and 15.9 kg/capita (Sweden), with 10 countries still not reaching the required 4.0 kg/capita minimum collection quantity [8]. From 2016 onward, a minimum collection rate of 45% of EEE placed on the market in the three preceding years has to be achieved by each member state.

4.2 Pre- and End-processing

Selective treatment of components like printed circuit boards, capacitors, batteries, mercury containing components and others in most cases requires initial manual dismantling steps. In countries with low collection quantities and low labor costs, manual dismantling is a preferred option, since mechanical treatment is not economically viable. In other countries, pretreatment is a combination of manual and mechanical process steps. Mechanical treatment includes crushing and separation of different metal- or plastic-rich fractions or mixtures of the two, which then undergo further segregation steps such as conductivity (eddy-current) or density separation (swim sink). End treatment of metal fractions is a combination of different wet-chemical and metallurgical processes with the aim of obtaining pure fractions that can become secondary commodities. Plastic fractions are separated into those suitable for material recycling and others that have to be finally disposed in incineration plants or landfills.

4.3 Health Hazards and Environmental Impacts

Formal recycling processes have the potential to endanger health and the environment. Direct impacts on health are caused by dust in indoor air generated during dismantling and mechanical treatment processes (e.g., from plastic shredding or treatment of CRT) or nonconformities with occupational health requirements. Indirect impacts on human health may be caused by air pollution related to incineration processes that are not equipped with adequate gas purification systems and dust retention.

Mixed plastics fractions from WEEE still contain regulated Brominated Flame Retardants (BFRs). High average concentrations of BFRs mainly originate from small household appliances for high temperature applications, CRT monitors, and consumer equipment, in particular CRT TVs [21].

Primary production of resources, i.e., mining, concentrating, smelting, and refining, is energy-intensive and hence has a significant carbon dioxide (CO_2) impact. “Mining” of old computers to recover the materials they contain – if done in an environmentally sound manner – needs only a fraction of this energy input [37].

5 Informal Recycling

5.1 The Informal Sector

In developing countries, waste management is mostly performed by a large urban workforce, usually referred to as the “informal sector,” making a living by collecting, sorting, recycling, and selling valuable materials recovered from waste [38]. The marginalized poor account for the majority of the informal sector. They often include groups from ethnic or religious minorities or rural migrants. Women and children constitute a significant proportion of the workforce, operating either illegally or in a legal gray zone and with different levels of organization [39].

Even though informality has been the subject of political and scientific discussions for decades [34], there is no clear definition of the informal sector. Yet all definitions point toward similar elements and patterns [40] generally described by the International Labor Organization (ILO) as including all economic units that are not regulated by the state and all economically active persons who do not receive social protection through their work [41].

Collection, manual dismantling, open burning to recover metals, and open dumping of residual fractions are the usual 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 WEEE recycling on a larger scale. Larger economies, especially countries in transition such as India and China [34, 42, 43], as well as countries subject to intense trade in second-hand equipment and illegal waste shipments, such as Ghana and Nigeria [32], display a substantial organized informal sector. The operations of the informal sector can be grouped into three main stages of the WEEE recycling chain: collection, pre-processing, and end-processing.

5.2 Collection

In contrast to formalized take-back schemes where consumers (indirectly) pay for collection and recycling, in developing countries it is usually the waste collectors who pay consumers for obtaining their obsolete appliances and scrap material [44]. As a result, the informal waste sector is 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 [45]. Since the valuable components of the products collected usually generate an income higher than the price to be paid to get the product, the informal waste sectors achieves collection rates of up to 95% of waste generated [32], which is far above what can be achieved by today's formalized take-back schemes [46].

5.3 Re-Use of Computers

Following a strategy to bridge the digital divide, some developing countries have taken great efforts to provide computers for schools. Initiatives include the provision of low-cost laptop computers as the One Laptop Per Child (OLPC) initiative or the refurbishment of secondhand computers in industrialized or developing countries. A comparative evaluation in Colombia based on Material Flow and Life Cycle Assessment and the application of Multiple Attribute Utility Theory concluded that local refurbishment of secondhand computers is the most favorable solution since it has relevant job creation potential and extends the use of already produced computers, whereas the provision of new computers leads to additional environmental impacts through the manufacturing process [47].

5.4 Pre- and End-processing

As labor costs are low in developing countries and in countries in transition and because of the lack of access to know-how and technology, informal and formal recyclers apply labor-intensive pre-processing technologies such as manual dismantling to separate the heterogeneous materials and components. A comparative study of pre-processing scenarios revealed that material recovery efficiency improves with the intensification of manual dismantling [43, 48]. Hence, manual recycling practices in developing countries do display advantages, such as low investment costs, creation of jobs, and high material recovery efficiency [1].

Subsequent to manual pre-processing, further "refining" techniques, such as de-soldering of Printed Wiring Boards (PWB) and subsequent leaching of gold, silver, and palladium, have been observed especially in the informal sectors in India and China [42]. A pilot project in Bangalore, India, demonstrated that besides being hazardous, informal end-processing or refining practices also have poor recovery efficiency. 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% [49, 50]. In contrast, today's state-of-the-art integrated smelters, as used in most formalized recycling systems, achieve gold recovery efficiencies as high as 95% [51].

Fig. 2. Typical recycling processes applied in the informal sector of developing countries (left to right: de-soldering of printed wiring boards, leaching of gold from printed wiring boards, open burning of cables) (Pictures: Empa)

5.5 Health Hazards and Environmental Impacts

Informal WEEE management often fills the void created by the absence of a legal framework as well as the lack of capacity and resources for a formal waste collection and treatment system.

Due to their daily contact with garbage, people working in informal waste management are exposed to various health threats, including injuries, diseases, and both acute and chronic health effects. Serious health effects and impacts on the environment are likely especially for workers processing waste streams containing hazardous substances, such as WEEE [42, 52]. Emissions stem from (i) hazardous substances which are constituents of the waste, (ii) auxiliary substances used in recycling techniques, and (iii) byproducts formed by the transformation of primary constituents. The activities of WEEE recycling in the informal sector involve sorting as well as separation with the final aim of extracting valuable materials such as copper, gold, silver, and other base and precious metals. The processes applied in the exploitation of metals are of particular concern since they cause a variety of health and environmental hazards. A literature review concerning emissions caused by informal recycling activities has shown high concentrations of lead, Polibrominated diphenyl ethers (PBDE), dioxins, and furans in all environmental pathways (soil, air, water, bottom ash, and river sediments) [42].

Practices for recovering metals such as copper, iron, and aluminum through burning of cables containing PVC insulation have been identified as a major source of dioxin [32]. Dioxin emissions from cable burning, for instance in the greater Accra region alone, are estimated to correspond to about 0.3% of total dioxin emissions in Europe [9]. In China and India, a review of various studies underlined very high levels of dioxin in air, bottom ash, dust, soil, water, and sediments in informal recycling areas, which sometimes exceeded the reference values generally observed in urban areas by several orders of magnitude [42].

Recent measurements in Accra also indicate increasing levels of BFRs in breast milk, which are associated with the informal recycling of WEEE [53].

BFRs contained in mixed plastics from WEEE are substances of concern due to the existing practices of plastic recycling in developing countries and the potential risk of cross-contaminating secondary plastics in applications where BFRs are not required or banned. A recent sampling campaign in the informal plastic recycling sector in Delhi, India, confirmed that secondary plastic is often contaminated with BFRs. This indicates that mixing of plastics from WEEE with additive-free plastics from other waste types does occur [54].

5.6 Socio-Economic Impacts

Based on the UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products [55], commonly referred to as the S-LCA guidelines, the assessment of socio-economic impacts in WEEE management follows a stakeholder approach based on indicators in the three following stakeholder categories: (1) workers, (2) local communities, and (3) society. Studies in Ghana [56] and Nigeria [57] were based on the framework of indicators shown in Table 6.

Table 6. Allocation of socio-economic indicators to stakeholder categories according to [56, 57]

Workers	Local community	Society
• Safe & healthy working conditions • Freedom of association and right to collective bargaining • Equality of opportunity and treatment and fair interaction • Forced labor • Child labor • Remuneration • Working hours • Employment security • Social security • Professional development • Job satisfaction	• Safe & healthy living conditions • Human rights • Indigenous rights • Community engagement • Socio-economic opportunities	• Unjustifiable risks • Employment creation • Contribution to national economy • Contribution to national budget • Impacts on conflicts

Safety- and health-related impacts were observed in both countries, leading to direct effects on the workers and the local communities as outlined in the previous section. As most of the workforce belongs to the informal sector, WEEE recycling does not feature formalized workers' participation mechanisms which results in the lack of worker rights as outlined in Table 6.

In Ghana, child labor was observed for cable-burning activities and for manual dismantling practices such as breaking CRT monitors. Using stones, hammers, heavy metal rods, and chisels to recover copper, steel, and plastic casings from CRT often results in the workers inhaling hazardous cadmium dust and other pollutants [56, 57].

Income levels vary depending on the profit which can be generated by selling the obsolete equipment to recyclers in relation to the price paid for acquiring the equipment. In Ghana, a collector can earn 70-140 USD per month, whereas recyclers can earn 175-285 USD a month. In Nigeria, the corresponding figures are 67-100 USD per month for collectors and recyclers. However, these figures are based on calculated incomes based on business profits and do not consider indirect costs and externalities.

In Pakistan, children 6 to 18 years old search for valuable materials in potentially toxic ash. They work in all stages of the chain, from collecting and dismantling equipment to burning wires and motherboards, separating metals, melting solders, and acid processes [58].

The International Labor Organization (ILO) states that the existing ILO conventions are intended to address the particular situation of WEEE management in the informal sector. A code of practice should cover, among other things, occupational health measures, best practices, formalization of the informal sector, and the formation of cooperatives [39].

6 Trends and Outlook

Rapid innovation cycles and growing volumes of cheap EEE have brought about steep increases in the quantities of WEEE. Technological advances include the switchover to digital-only television in Europe, North America, and other industrialized regions of the world, which will accelerate the disposal of obsolete devices and stimulate trade in used EEE with developing nations. In addition, the material composition of EEE is tending to become more complex and the raw material supply more critical. Technologies to recover them from WEEE streams are needed, but increasingly complex and expensive. In addition, the past and current use of hazardous substances in EEE will shape WEEE management systems for a long time to come.

It is encouraging that legislation for sustainable WEEE management is rapidly being adopted in many countries. However, with the implementation and enforcement of new regulations still ahead, the main challenges are yet to be faced, especially in developing and transition countries. It will be key to ensure a level playing field for all actors in order to make cannibalizing of WEEE solely for valuables impossible and to avoid harmful practices in WEEE recycling. In addition to existing waste policies and legal frameworks, WEEE-related regulations need to be enforced, likewise posing challenges to coordination between different regulatory bodies.

Increased Collection Rates and Improved Recycling Yields. Secondary resources are becoming more and more relevant given the shift of raw materials into products and the increasing demand for new raw materials. As outlined in this chapter, collection rates in industrialized countries are still far below their potential. Besides illegal exports of EEE or WEEE to non-OECD countries, one reason for this is the lack of access to take-back schemes, which results in consumers storing EEE for longer periods of time and/or disposal of EEE through the municipal waste stream or scrap dealers. Higher collection rates need to be achieved in combination with improved recycling rates. In developing countries, most products enter the recycling chain through the informal sector, which is characterized by high collection rates. An international division of labor in WEEE recycling could link geographically distributed treatment options, combining pre-treatment at the local level and end-processing in state-of-the art facilities as outlined in [43].

In the future, the development of WEEE take-back schemes will also need to address technical and operational aspects of recovery of scarce [59] and critical metals [60]. The predominant technology in WEEE recycling is mostly oriented toward the recovery of base and precious metals, whereas scarce metals such as indium, gallium, germanium, and neodymium are lost in today’s recycling system.

In addition, a comprehensive international approach is required to ensure sustainable recovery of secondary resources. Among other elements, this might include harmonization of international standards toward fair recovery and trade of secondary resources and applying international financing mechanisms.

International Standards toward "Fair" Secondary Raw Materials. Developing countries are suppliers of primary, but in recent years increasingly also of secondary raw materials. On the demand side, consumers in industrial countries are more and more concerned about production circumstances of imported goods and wish to have transparent product declarations. While quality, social, and environmental labeling is well established for some renewable commodities (e.g., Forest Stewardship Council labeling – (FSC)), it is nearly inexistent for non-renewable commodities (one of the few examples is XertifiX – "natural stone without child labor") and does not exist at all for non-renewable secondary commodities (e.g., precious metals from PWB recycling).

Environmental and social issues linked to informal and formal recycling also cause image problems for producers, usually multinational companies. As described in this chapter, many informal recycling processes involve low material recovery efficiency and risk contaminating commodities with hazardous substances. Hence efficient and sustainable recovery as secondary raw materials is a market opportunity that requires functioning "reverse supply chains" with adequate capabilities for recycling and refining as well as sufficient monitoring of the quality of the recovered material as well as the environmental and social impacts of the related processes. Therefore the harmonization of international standards and the introduction of processes to identify "fair" secondary resources will be instrumental for leveraging these opportunities.

International Financing Mechanisms. Some of the substances potentially released by improper WEEE treatment are classified as persistent organic pollutants (POPs), ozone depleting substances (ODS), or greenhouse gases (GHG) and are regulated under international treaties such as the Stockholm Convention, the Montreal Protocol, and the Kyoto Protocol. Related to these are emission reduction schemes and/or international financing mechanisms, such as UN Environmental Finance Facility programs (e.g. Global Environment Facility – GEF), Cleaner Development Mechanisms (CDM), and voluntary systems (e.g. Verified Carbon Standard - VCS), which may be used for financing parts of processing WEEE properly to capture and destroy POPs and ODS. In addition, recovering secondary resources from WEEE as an alternative to mining primary resources can lower GHG emissions and is subject to the Cleaner Development Mechanism. Such international financing mechanisms might play a crucial role in implementing sustainable e-waste management systems by supporting initial investments as well as by creating market incentives to avoid improper processes and to remove internationally banned chemicals from the secondary resources market.

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