



Electronic Industry Pollutants (E-Waste)

Chemical characteristics and their potential risks

Introduction

In today's throw-away society, the desire, for devices with faster and newer state-of-the art technology is leading to a continuous expansion of the electronic market and to shortened innovation cycles for electrical and electronic equipment (EEE). Much of this EEE has a short lifespan and fast turnover. Frequently, obsolete or damaged EEE is not recycled or repaired, but, more likely, is simply thrown away. Thus the amount of waste electrical and electronic equipment (WEEE), such as superseded personal computers, mobile phones, entertainment equipment, and electronic consumer equipment has proliferated immensely during the last decades. The increased production and disposal of EEE represents an emerging and growing problem that can adversely affect environmental and human health. This holds especially true, since WEEE is transported from high income countries (HICs) to low- and middle-income countries (LAMICs) such as Brazil, China, India, Mexico, Nigeria, Pakistan, and Thailand (International Labour Organization, 2012; Lewis, 2011; Skinner et al., 2010; Silicon Valley Toxics Coalition, 2014). Here, the waste is discarded or processed (dismantled and recycled) under poor and inappropriate conditions, since this type of waste comprises a wide range of hazardous compounds (these are discussed in more detail in the section **E-waste pollutants of environmental concern**; Widmer et al., 2005; Wong et al., 2007c; European Parliament and Council of the European Union, 2012).

Today, the generation of WEEE is the fastest growing waste stream worldwide (about 4% growth per year; International Labour Organization, 2012) and accounts for up to 8% of all municipal waste (Streicher-Porte et al., 2005). In general, the recent global production (data from 2006 and 2009) of WEEE is estimated to be between 20 and 50 million tonne, a large portion of which, as has already been mentioned, is sent to LAMICs (United Nations Environment Programme, 2006a; Robinson,

2009; Schluep et al., 2009). The production of WEEE in 2014/15 is predicted to be between 40 and 70 million tonne (Jain, 2008). This high variation in the volume of WEEE to be produced predicted in the literature underscores the difficulties in estimating the global generation of WEEE and the amounts of environmentally friendly or unfriendly compounds in it.

According to the Directive 2002/96/EC of the European Parliament (revised at the end of 2011) and of the Council (January 2003) on WEEE, this superseded EEE is defined as: "WEEE, which is waste, including all components, sub-assemblies and consumables, which are part of the product at the time of discarding." (European Parliament and Council of the European Union, 2012). WEEE was divided into 10 categories (Widmer et al., 2005):

- large household appliances
- small household appliances
- IT and telecommunications equipment
- consumer equipment
- lighting equipment
- electrical and electronic tools
- toys and sports equipment
- medical devices
- monitoring and control instruments
- automatic dispersers.

Although, presumably, this categorization system is becoming a broadly accepted standard, there is no international standard definition for electronic waste (e-waste) available yet. There are several forms of WEEE which may or may not be normally considered as e-waste compounds as shown in the literature (Robinson, 2009). This makes it even more difficult to assess the amounts of e-waste that are produced, or shipped, at a global scale. There are international initiatives to prevent the export of and the trade in e-waste and other hazardous products. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (which came into force in 1992) is a good exemplar (United Nations Environment Programme, 2014). However, there is evidence that companies from industrial countries are searching for loop holes in the regulations in or-

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der to ship e-waste to LAMICs for cheaper recycling and cheaper disposal, or to offer obsolete EEE as secondhand goods. In some cases, unusable EEE is disguised as secondhand goods and shipped to LAMICs although it is useless or never used in the receiving countries (Jain, 2008; International Labour Organization, 2012). All in all, about 181 countries are supporting the Basel Convention and of these, 53 have signed it. Other countries – Angola, Fiji, Haiti, Myanmar, Sierra Leone, Solomon Islands, South Sudan, Tajikistan, Timor-Leste, United States of America, and Vanuatu – have not even confirmed the Basel Convention, which suggests that they are probably not willing to stop their exports of hazardous e-waste to LAMICs yet. For the USA, one of the challenges might be that all federal states need to fulfill the requirements of the Basel Convention to enable the affiliation of the USA to the Basel Convention. In addition, the implementation of the Basel Convention is mainly driven by the poorer countries affected by it and not by the HICs with strong economies. This might be another reason why the USA has not ratified the Basel Convention, yet (Martin Streicher-Porte (FHNW); personal communication). However, the International Labour Office (International Labour Organization, 2012) and Smith et al. (2006) have shown that 80% of all e-waste that is sent to LAMICs for recycling ends up in informal e-waste recycling sites. In addition to the e-waste which is shipped into LAMICs, domestically produced WEEE is increasing as well as a consequence of economic development, especially in regions such as India, China, and Africa. This further amplifies the burden

of e-waste pollutants that needs to be handled by these countries (Jain, 2008).

Existing regulations and their enforcement

Many international regulations exist. However, these are not followed or still not approved in every country. Hence, although there are several international initiatives, such as the Basel Convention or the Basel Action Network Amendment, the trade and sale of e-waste, particularly from HICs to LAMICs and informal recycling businesses, still represents a major issue. Although the enforcement of these initiatives should help to inhibit the trade in WEEE or to better understand the transboundary movements of WEEE, the WEEE trade patterns are still difficult to assess, especially in LAMICs (Widmer et al., 2005; International Labour Organization, 2012; Lu et al., 2015). For instance, India has endorsed the Basel Convention, but it has not ratified the Basel Action Network (BAN) Amendment. Until now, in India there are no specific laws or guidelines framed for the trading and recycling of e-waste (International Labour Organization, 2012). On a global scale, the controls for the shipping of e-waste containers are still not efficient enough yet to control the trade completely (International Labour Organization, 2012). At the national and local levels, there is a serious lack of governmental authorities and regulations. Where they do exist, the poor implementation of legal instruments, corruption, the absence of standards for the recycling of e-waste, and the poor participation of stakeholders in supporting/applying sustainable and more environmentally-friendly recycling methods, especially in LAMICs, further promote the informal recycling of e-waste. These deficiencies make it even easier to trade and deal in e-waste. In addition, the definition of and legislation for controlling WEEE differ considerably from country to country (International Labour Organization, 2012; Lu et al., 2015).

One of the main incentives resulting in poor compliance with international and national regulations and the informal collection, trade, and recycling of e-waste is the profitable extraction and sale of valuable compounds – platinum group elements, gold, silver, and copper (Wong et al., 2007a; Robinson, 2009).

Poor facilities and obsolete techniques

Given the large amounts of e-waste imported by LAMICs – 20 to 50 million tonne (United Nations Environment Programme, 2006a; Robinson, 2009; Schlupep et al., 2009) – these countries are receiving disproportionate loads of e-waste without having the knowledge, capacity, appropriate facilities, and techniques to handle them properly (International Labour Organization, 2012).

Main Issues

The main issues associated with the displacement, disposal, and processing of e-waste in LAMICs are (International Labour Organization, 2012):

- Regulations at international, national, and local level are still lacking or they are not observed
- Often unsuitable facilities and obsolete techniques are used to process e-waste in LAMICs
- E-waste contains a wide mixture and variety of compounds making separation and treatment complex
- Employees are working under bad labor conditions
- The toxicological potential of pollutants, released through the disposal and recycling processes, is high

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Often, the informal e-waste recyclers are using inappropriate, unsafe, and obsolete treatment, disposal, and e-waste recycling technologies and methods, which are posing a risk to environmental and human health. For instance, in LAMICs, pyro-, hydro- and bio-metallurgical processes are commonly used to recover valuable metals (Cui and Zhang, 2008). Pyro-metallurgical processing includes the incineration and smelting of e-waste containing valuable target precious metals and non-ferrous metals, such as platinum, gold, silver, and copper. More efficient processes are strongly linked with appropriate investment. Therefore, because resources are scarce, especially in LAMICs, these obsolete pyro-metallurgical methods are applied without using any emission filters or emission control systems. This leads to a release of toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, and halogenated hydrocarbons, into the environment mainly as aerosol particles. It is the employees of these informal businesses, the local community, and the environment in the vicinity of these e-waste recycling sites that are most affected (Tue et al., 2010; International Labour Organization, 2012). In particular, the low-temperature, open burning in the fields of halogenated flame retardants and the incomplete combustion of the plastics and organic matter contained in the burned WEEE are causing an aerial exposure to highly toxic and carcinogenic PAHs, such as benzo[a]pyrene, dioxins, and furans in particulate form (Yu et al., 2006b; Cui and Zhang, 2008). In addition, the emission of these compounds leads to the contamination of the soil and water following dry and wet disposal methods. According to the investigations of the Blacksmith Institute, the burning and melting of plastic-sheathed cables to isolate and recover the copper is one of the main activities in Ghana that is of the highest concern from a public health perspective. This is because copper acts as a catalyst for dioxin formation during incineration processes (Cui and Zhang, 2008; Sepúlveda et al., 2010; Blacksmith Institute and Green Cross, 2013). Hydro- and bio-metallurgical processes are used to dissolve and recover the target metals. For hydro-metallurgical processing, acids and chemicals, like cyanide, halide, thiourea, and thio-sulphate, are used. For bio-metallurgical processing, microbes, pyritic compounds, oxygen, and water are used to accelerate the natural leaching process of metals from e-waste heaps (Leung et al., 2008). At hydro- and bio-metallurgical processing sites, the leakage of acids, solvents, and heavy metals during the recycling and the extraction processes or the inappropriate disposal and dumping of e-waste can contaminate soils and drinking water resources in the vicinity.

The diverse composition of e-waste presented in Table 7, the different materials which are blended, glued, fixed, or clamped together, and the scarcity of financial resources are making the efficient recycling of plastic and individual types of metals very difficult (Mundl, 2010). Today, sustainable and more environmentally-friendly recycling technologies, which enable a sound recycling of e-waste, are just as applicable and economic in larger middle- and higher-income countries. But they require a large capital investment, qualified and well educated employees, and high quantities of e-waste to be available. For these reasons, in lower income countries and in most of the middle-income ones, informal recycling business are more prevalent. The pyro-metallurgical, state-of-the-art recycling of e-waste comprises three steps (Empa, 2009f):

1. Removal of critical components from the e-waste in order to avoid dilution of and contamination with toxic substances during the subsequent recycling processes
2. In large-scale operations, mechanical processing is used to further concentrate the specific components to be recovered from the e-waste and to further separate hazardous materials
3. Refining of resources in the e-waste to recover the raw material with minimal environmental impact.

Mixture and variety of different compounds

Heavy metals, metalloids, halogenated hydrocarbons, and other persistent and hazardous pollutants are to be found within the e-waste. The burning of e-waste at low temperatures produces PAHs, such as dioxins and furans, or is causing the release of further halogenated flame retardants. These compounds are known to pose a high risk to environmental and human health (Robinson, 2009). In addition to these toxic compounds, e-waste consists of a broad range of other material, such as glass, ceramics, plastics and rubber, rare earths, non-ferrous metals (aluminum, copper, and lead), ferrous metals (steel and iron), and precious metals (platinum group metals, gold and silver; International Labour Organization, 2012; Lu et al., 2015). The composition of the e-waste is strongly dependent on its type; there is high variation among the 10 different categories of WEEE of Directive 2012/19/EU of the European Parliament (European Parliament and Council of the European Union, 2012). In addition, the EEE industries, especially the ones located in higher-income countries, have been put recently under increased pressure to avoid or ban the use of highly toxic compounds, such as cadmium and mercury. Such was not the case in the past. Hence, older e-waste often contains more hazardous compounds than recently produ-

ced waste (Mundl, 2010). Table 7 shows the composition of the different types of WEEE. 'Large household appliances' includes refrigerators, freezers, and washing machines; 'small household appliances' includes vacuum cleaners, clocks, fryers, and toasters; 'information and communication technologies' includes personal computers, laptops, and telephones; and 'consumer electronics' includes televisions, cameras, and audio amplifiers (Empa, 2009a).

Inadequate labor conditions

The use of obsolete and unsafe methods for e-waste collection and recycling is posing a high risk to human health. The LAMIC workers often are not aware of the toxic compounds contained in the e-waste they are collecting, dismantling, and disassembling. They are mechanically shredding electronic and electrical equipment for recycling without wearing any goggles, gloves, masks, or protection clothes. In LAMICs, children and women often may be involved in collecting e-waste, such as plastic coated cables, cathode ray tubes, and printed circuit boards and in manually separating out the desired components. Sometimes, mainly because of financial constraints, they are involved in the burning activities (Prakash et al., 2010). Children and women constitute one of the most susceptible at-risk groups exposed to the heavy metals, flame retardants, and PAHs, which are contained in e-waste or which are released by open e-waste burning activities. During the smelting, leaching, and other extraction processes for the target metals, the informal workers often do not wear masks or adequate protective clothing. In addition, often there are no emission control devices or emission filters being used and hence they are exposed to toxic fumes and solvents that continuously endanger their health (Leung et al., 2008; Li et al., 2008c; Robinson, 2009; International Labour Organization, 2012).

Elevated levels of contaminants associated with e-waste are measured in the blood, breast milk, hair, and placentas of people involved in collecting and processing e-waste or who are living in the vicinity of e-waste storage or processing sites. In this latter instance uptake mainly happens through the inhalation of contaminated air, dust, and fumes and the drinking or eating of contaminated water and food – rice, eggs, milk, and meat (Darnerud, 2003; Zhao et al., 2006; Chan et al., 2007; Leung et al., 2008, 2010; Robinson, 2009; Tue et al., 2010). Additionally hazardous compounds are transmitted via people's hands during eating because an adequate system of running water for hand washing is lacking (International Labour Organization, 2012). The occupational and public exposure and the bioaccumulation of toxicants that are emitted and leached from e-waste, especially

Table 7: Material composition of the four main e-waste categories [%] (Empa, 2009a)

Material	Large household appliances	Small household appliances	ICT ^A and consumer electronics
Ferrous metal	43	29	36
Aluminum	14	9.3	5
Copper	12	17	4
Lead	1.6	0.57	0.29
Cadmium	0.0014	0.0068	0.018
Mercury	0.000038	0.000018	0.00007
Gold	0.00000067	0.00000061	0.00024
Silver	0.0000077	0.000007	0.0012
Palladium	0.0000003	0.00000024	0.00006
Indium	0	0	0.0005
Brominated plastics	0.29	0.75	18
Plastics	19	37	12
Lead glass	0	0	19
Glass	0.017	0.16	0.3
Other	10	6.9	5.7
Total	100	100	100

^A information and communication technologies

if they are stored and burned in the open air, can lead to acute and chronic health disorders. These disorders include skin and eye irritation, respiratory diseases (such as coughing, choking, pneumonitis and lung cancer, tuberculosis, and asthma), mental disorders, and diseases of the central nervous system (tremors, convulsions, and cancer) (Yu et al., 2006a). Moreover, increased incidences of birth defects, infant mortality, underdevelopment of the brains of children, blood diseases, anomalies of the immune system, and malfunction of the kidneys were found in regions with high informal e-waste collection, storage, and processing activities (Prakash et al., 2010).

Toxicological potential

As already mentioned, informal e-waste businesses in LAMICs are mostly associated with a considerable release of a diverse cocktail of highly toxic compounds. In general, about 1000 individual chemicals have been identified in e-waste streams. These include heavy metals and metalloids (A), PAHs (B), and halogenated hydrocarbons and flame retardants (C). These pose high risks to environmental and human health (Empa, 2009b; International Labour Organization, 2012). Currently, there are few studies and limited data on the impacts on the environment of the informal disposal and processing of e-waste. The adverse effects on human health, especially after long-term exposure, have not been investigated either. Nevertheless, it is known that many of the single compounds that are found in e-waste, on their own, act as

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neurotoxins, endocrine disruptors, allergens, or carcinogens. Also many of them are slowly degraded by natural processes and have a high potential for bioaccumulation (International Labour Organization, 2012). The adverse effects caused by exposure to mixtures of these hazardous compounds has not been sufficiently investigated at the present time. Since the composition of e-waste varies enormously, not every substance that is released into the environment from e-waste storage and processing can be considered in this report. The major groups and main substances of highest environmental concern that are contained in e-waste are summarized below and in Table 8, Table 9, and Table 10.

E-waste pollutants of environmental concern

A) Heavy metals and metalloids.

Antimony, arsenic, barium, beryllium, cadmium, cobalt, copper, chromium VI, indium, lead, lithium, mercury, nickel, thallium, tin, rare earth elements (yttrium, europium), and zinc sulfide are the metals and metalloids contained in e-waste that are of the highest environmental concern (Empa, 2009b; International Labour Organization, 2012; Table 8).

Use

The amounts of the individual heavy metals and metalloids that are used for the production of EEE in the electronic industry is not assessable. The amounts of the elements that are used in the semiconductor or the electronic industry have increased significantly – from the 12 elements that were used in 1980 to the 60 elements used in the 21st century (Appendix Figure 5; Theis, 2007). For instance, information about specific agents and compounds that are used in mobile phones and tablets and their specific purposes in these electronic devices are not easily accessible and are generally unknown to the public. Often, these details are secret or this information is not made available because of patent laws. In addition, complex alloys of different chemical compounds, metals, and metalloids are blended together, which makes it more difficult to get an overview of the chemicals used in EEE (Brunning, 2014). Although data about compounds used in such EEE as mobile phones and tablets are limited, some necessary elements which constitute parts of this EEE can be assumed. For instance, mobile phone and tablet screens often contain a mixture of indium and tin oxides which acts as an electrical conductor and ena-

bles users to control the devices using their hands. The glass of the screens often comprises aluminosilicates and potassium ions. In addition, several rare earth elements, such as yttrium, lanthanum, terbium, praseodymium, europium, dysprosium, and gadolinium, are used to produce the screen colors. In modern mobile phones, often lithium ion batteries are used. These often contain lithium cobalt oxides or manganese and carbon. The micro-electrical parts in the mobile phone often consist of copper wires and gold, silver, and platinum group elements. The microphone and the speaker often contain nickel, praseodymium, gadolinium, neodymium, terbium, and dysprosium. Silicon is one of the main compound in chips, while other compounds, such as antimony, arsenic, and gallium, are used as well as electrical conductors. Often tin and lead solders are used, while lead-free solder contains metals such as tin, copper, and silver. The cases of the various devices are mainly made of magnesium compounds or plastics with flame retardants. For example, more than 30 elements are used in the manufacture of mobile phones and tablets. Additionally, data from Umicore Precious Metal Refining showed that more than 40 elements are used during the production of mobile phones (Schluep et al., 2009). These examples emphasize the large variety of compounds used in electrical devices. Table 8 details the major metals and metalloids that occur in EEE. It lists their intended uses, human toxicity, their maximum contaminant levels (MCLs) for drinking water, and their acute (MAC-EQS) and chronic (AA-EQS) environmental quality standard for aquatic organisms in surface water bodies.

Environmental behavior and occurrence

The release and distribution of metals and metalloids into the environment depend on several factors. The use of rudimentary e-waste recycling approaches, like incineration or the burning of e-waste in open fires, or using acids (cyanides and halides) to leach and extract the desired components in an open field without any controls and regulations, results in a serious release of hazardous metals and metalloids and other toxic substances into the environment (International Labour Organization, 2012).

In general, after low-temperature incineration processes in the absence of any filter systems, these compounds are emitted into the air mainly as fumes or as airborne particles bound to soot or other organic matter. Subsequently, metals and metalloids can precipitate via dry or wet deposition after rain events and contaminate surface water systems, natural and agricultural soils, or they can adsorb to the cuticles of plants that are in the vicinity of e-waste processing sites. In addition, metals and metalloids can directly diffuse into soils and groundwater from

landfills as a result of natural processes or rudimentary recycling techniques via chemical or biological seepage and thus contaminate soils, agricultural crops, and drinking water resources. The distribution of metals and metalloids in soils and their uptake and incorporation by plants via roots is dependent on water availability, soil and plant type, pH, redox potential, organic content, and the metal species (Adriano, 2001; Steiner, 2004; Luo et al., 2011).

The different solubilities and bioavailabilities of the individual metals and metalloids are highly variable. The environmental behaviors of Cd, Cr, Cu, Pb, Hg, Tl, As, and Sb – the most serious and relevant metallic pollutants of environmental concern – are described in more detail in the section **Mining pollutants of environmental concern** (p. 70).

In south China, concentrations of Cd of 17 mg/kg, of Cu of 11,140 mg/kg, of Pb of 4500 mg/kg, and of Zn of 3690 mg/kg were determined in soils of former e-waste incineration sites (mean values; Luo et al., 2011). The common background concentration of Cd was from 0.11 to 0.5 mg/kg (Fassett, 1975; Salomons and Förstner, 1984; Giuffré de López Camelo et al., 1997), that of Cu was from 50 to 55mg/kg (Taylor, 1964; Salomons and Förstner, 1984), that of Pb was from 13 to 26 mg/kg (Zimdahl et al., 1973; Salomons and Förstner, 1984; World Health Organization, 2011; Thomas Jefferson National Accelerator Facility, 2014) and that of Zn was from 52 to 79 mg/kg (Wedepohl, 1995).

Rice and vegetables, cultivated in the same region, showed elevated heavy metal concentrations which exceed the maximum level permitted in Chinese food (Leung et al., 2008). Children living in Guiyu, China, had significantly elevated blood lead levels (BLL) and blood cadmium levels. Of the children surveyed, about 71% (109 of 154) had a BLL higher than 100 µg/L (Zheng et al., 2008b). These values indicate that the release of metals and metalloids through rudimentary recycling businesses are posing a risk to environmental and human health and that they have a potential for bioaccumulation. Today, a reference BLL of 50 µg/L is used to identify children with BLLs that are much higher than most children's levels. If the BLL of a child between 1 and 5 years of age is equal to or higher than 450 µg/L, medical treatment is recommended (Centers for Disease Control and Prevention, 2014).

Toxicity

Several metals and metalloids are known or suspected to promote the formation of several forms of cancer. For instance, according to the International Agency for Research on Cancer (IARC), As, Be, Cd, and Cr(VI) are listed in group 1, carcinogenic to humans. In addition, Indium (In) and Pb are listed in group 2A, probably carcinogenic to humans. And antimony trioxides, Co, organic Hg compounds, and Ni are listed in group 2B, possibly carcinogenic to humans (IARC classifications see Table 8). As determined by the US Environmental Protection Agency, the MCL for drinking water for As is 0.001 mg/L, for Be and Cd 0.005 mg/L, for Cr(VI) 0.1 mg/L, for Pb 0.015 mg/L, and for Hg 0.002 mg/L. For In and Co there are no MCLs available yet. The MCLs of other metals and metalloids are presented in Table 8 as well. Several metals and metalloids act as neurotoxins and cause impairments of the nervous system. These include As, Cd, Hg, Li, Pb, and Tl. Other compounds, such as Co, Cr(VI), Cu, Li, and Ni, are known to act as skin and eye irritants or as allergens. The inhalation of As, Be, Cd, Co, Cr(VI), and Ni provokes the formation of pulmonary diseases affecting the respiratory system (Table 8).

The toxic effects to plants and animals of the metals Cd, Cr, Cu, Pb, Hg, and Tl and the metalloids As and Sb, are presented in Table 8. These heavy metals and metalloids are able to affect aquatic organisms in surface water bodies even at low concentrations. The lower the EQS values (in µg/L) of each individual compound, the higher is its potential to pose a hazard for aquatic organism. Li, Cd, Be, Tl, Co, and Pb have acute MAC-EQS of between 0.344 and 14 µg/L, while Be, Tl, Cd, Co, Li, and Pb have chronic AA-EQS ranging from 0.0092 to 1.2 µg/L (Table 8; European Parliament and Council of the European Union, 2008, 2013; van Vlaardingen and Verbruggen, 2009; European Chemicals Agency, 2015). Additional AA-EQS and MAC-EQS values of other relevant compounds are presented in Table 8.

The metals Cd, Cr, Cu, Pb, Hg, and Tl and the metalloids As and Sb affect aquatic organisms in surface water bodies even at low concentrations.

Table 8: Metals and metalloids that occur in WEEE and their risks to humans and aquatic systems (Empa, 2009b; International Labour Organization, 2012)

Chemical	Examples of the occurrence of hazardous metals and metalloids in WEEE ^A	Health concerns (humans)	MCL ^B [mg/L]	Environmental quality standard (in surface water bodies) AA-EQS/MAC-EQS [$\mu\text{g/L}$] ^C
Antimony (antimony trioxide Sb_2O_3)	Sb_2O_3 : flame retardant in EEE, cathode ray tubes (old televisions and monitors) and printed circuit boards	The IARC classifies Sb_2O_3 in group 2B, possibly carcinogenic to humans (International Agency for Research on Cancer, 2015). Sb and Sb compounds are considered as priority pollutants (United States Environmental Protection Agency, 2014c). Sb seems to give rise to inducing disruption or breakages of chromosomes. Sb is toxic to blood, kidneys, lungs, the nervous system, liver, and the mucous membranes after inhalation or ingestion (Cooper and Harrison, 2009; Science Lab, 2013).	0.006	7.2/NA (Marion Junghans (Ecotox Centre); personal communication)
Arsenic (As)	As is used to make transistors, while gallium arsenide is used in light emitting diodes	The IARC lists inorganic As in group I, carcinogenic to humans (International Agency for Research on Cancer, 2015). Acute uptake of As can cause a decrease in the production of red and white blood cells, cardiac arrhythmias, blood-vessel damage resulting in bruising, and impaired nerve function (Agency for Toxic Substances and Disease Registry, 2007a).	0.01	50/NA (UK Technical Advisory Group on the Water Framework Directive, 2008)
Barium (Ba)	Getters in cathode ray tubes	No IARC classification. Short-term exposure leads to muscle weakness and affects heart, liver, and spleen. It causes brain swelling after short-term exposure (Osugwu and Ikerionwu, 2010).	2	9.3/220 (van Vlaardingen and Verbruggen, 2009)
Beryllium (Be)	Motherboards of computers and power supply boxes which contain silicon-controlled rectifiers and x-ray lenses	The IARC lists Be and its compounds in group I, carcinogenic to humans (International Agency for Research on Cancer, 2015). It can cause lung cancer. Inhalation of fumes can cause chronic beryllium disease (berylliosis) and skin diseases (Osugwu and Ikerionwu, 2010).	0.004	0.0092/0.83 (van Vlaardingen and Verbruggen, 2009)
Cadmium (Cd)	Chip resistors and semiconductors, rechargeable Ni-Cd batteries, fluorescent layer (cathode ray tubes), printer inks and toners for photocopying-machines	Cd is classified by the IARC in group I, carcinogenic to humans (International Agency for Research on Cancer, 1993). The uptake of Cd oxides by inhalation of smoke or occupational pollution causes acute respiratory distress syndrome or pulmonary edema. Long-term exposure leads to renal dysfunction, anemia, osteoporosis, and bone fractures (Friberg et al., 1985; Barbee Jr and Prince, 1999; Godt et al., 2006). In the human body, the kidney is the main target for bioaccumulation. There, chronic Cd uptake leads to tubulus cell necrosis (Orlowski and Piotrowski, 2003; Godt et al., 2006).	0.005	Class 1: 0.08/0.45 Class 2: 0.09/0.6 Class 3: 0.15/0.9 Class 4: 0.25/1.5 ^D (European Parliament and Council of the European Union, 2008)
Chromium (VI) (Cr(VI))	Corrosion protection of untreated and galvanized steel plates and as an alloy or hardener for steel housings containing data tapes and floppy discs	According to the IARC, Cr(VI) is classified in group 1 carcinogenic to humans (International Agency for Research on Cancer, 2015). Occupational exposure of Cr(VI) in the long-term leads to perforation of the nasal septum, asthma, bronchial inflammations, or lung cancer, and inflammation of the larynx and liver. Skin contact elicits allergies, dermatitis, dermal necrosis, and dermal corrosion (Lee et al., 1989; Straif et al., 2009; Bedi et al., 2013).	0.1	Cr(III): 4.7/32 Cr(VI): 3.4/NA (UK Technical Advisory Group on the Water Framework Directive, 2008)
Cobalt (Co)	Rechargeable batteries and coatings for hard disk drives	The IARC classifies cobalt and its compounds in group 2B, possibly carcinogenic to humans (International Agency for Research on Cancer, 2015). It acts as a skin irritant. Uptake via inhalation or ingestion, if repeated and prolonged, may have carcinogenic effects and is toxic to the lungs (animal study), or it can affect other organs (LabChem, 2009; International Labour Organization, 2012).	-	0.089/1.6 (van Vlaardingen and Verbruggen, 2009)
Copper (Cu)	Used as a conductor in cables and wires	The IARC classifies copper 8-hydroxyquinoline, in Group 3, not classifiable as to carcinogenicity in humans. Excessive exposure to Cu results in adverse health effects including liver and kidney damage, anemia, immunotoxicity, and developmental toxicity. After ingestion of a copper sulfate solution, adverse health effects, like gastrointestinal distress, nausea, vomiting, and abdominal pain, were observed. Occupational exposure to Cu acts as an irritant of the respiratory tract (Agency for Toxic Substances and Disease Registry, 2004a).	1.3	1/NA (based on the bioavailable concentration) (UK Technical Advisory Group on the Water Framework Directive, 2012)

A: (Empa, 2009b; International Labour Organization, 2012)

B: Maximum contaminant level (United States Environmental Protection Agency, 2015c)

C: The acute and the chronic environmental quality standards (EU-standard), AA-EQS (annual average concentration) and MAC-EQS (maximum allowable concentration) represent chronic and acute environmental concentrations of chemical agents which affect water organisms significantly.

D: AA-EQS and MAC-EQS of cadmium are dependent on water hardness classes. Class 1: < 40 mg CaCO_3/L ; Class 2: 40 to 50 mg CaCO_3/L ; Class 3: 50 to 100 mg CaCO_3/L ; Class 4: 100 to 200 mg CaCO_3/L ;

Chemical	Examples of the occurrence of hazardous metals and metalloids in WEEE ^A	Health concerns (humans)	MCL ^B [mg/L]	Environmental quality standard (in surface water bodies) AA-EQS/MAC-EQS [$\mu\text{g/L}$] ^C
Indium (In)	Liquid crystal display screens, semiconductors, injection lasers, solar cells, photodiodes, and light emitting diodes (National Toxicology Program, 2001)	The IARC classifies indium and its compounds in group 2A, probably carcinogenic to humans (International Agency for Research on Cancer, 2015). The probably carcinogenic potential is deduced from animal studies. Exposure to indium compounds caused extraordinarily high incidences of malignant neoplasms of the lungs of rats and mice, increased incidences of pheochromocytomas in rats, and increased incidences of hepatocellular neoplasms in mice, even at very low test doses and short exposure periods (International Agency for Research on Cancer, 2006a).	-	26/NA (Ministry of the Environment Japan, 2014)
Lead (Pb)	Solder of printed circuit boards, glass panels and gaskets in computer monitors, cathode ray tube screens, and batteries. Lead-acid batteries used in vehicles (Blacksmith Institute and Green Cross, 2012)	The IARC classifies inorganic lead and its compounds in group 2A, probably carcinogenic to humans (International Agency for Research on Cancer, 2015). Inorganic lead, especially, causes damage to the central and peripheral nervous system, affects the blood system (increases blood pressure or anemia) and kidneys, and the brain development of children. The main target for lead toxicity is the nervous system (Agency for Toxic Substances and Disease Registry, 2007b; Osuagwu and Ikerionwu, 2010).	0.015	1.2 (based on the bioavailable concentration)/14 (European Parliament and Council of the European Union 2013)
Lithium (Li)	Lithium batteries and rechargeable batteries	No IARC classification (International Agency for Research on Cancer, 2015). Inorganic lithium compounds act as skin and eye irritants. Short-term exposure causes sneezing, coughing, and severe irritation of the respiratory system. After ingestion, mouth, trachea, and esophagus may be burned, or mental confusion, nausea, coma, and death result. Long-term exposure can affect the nervous system or it may affect the renal system (National Institute for Occupational Safety and Health, 1978). Moreover, there are assumptions that lithium exposure may affect the development of unborn children. Lithium is used therapeutically for the treatment of manic depression or bipolar disorders (Aral and Vecchio-Sadus, 2008; McKnight et al., 2012).	-	0.23/0.344 (adapted from a PNEC value) (European Chemicals Agency, 2015)
Mercury (Hg)	Relays, switches and printed circuit boards, fluorescent lamps, in some batteries, old thermometers	The IARC classifies mercury and inorganic mercury compounds in group 3, not classifiable as to its carcinogenicity to humans, and organic mercury compounds in group 2B, possibly carcinogenic to humans (International Agency for Research on Cancer, 2015). Mercury is known as a neurotoxin. Even at low doses it causes impairment of the nervous system. Typical symptoms of mercury poisoning are malfunction of peripheral visions, numbness in hands, feet, and around the mouth, extrapyramidal diseases and movement disorders, impairment in writing, of speech, hearing, and walking, mental degradation and kidney damage. Children, especially those born to mothers exposed to mercury, are highly vulnerable to mercury poisoning diseases e.g. ataxia, constriction of the visual field, congenital cerebral palsy, or mental retardation (Agency for Toxic Substances and Disease Registry, 1999).	0.002	NA/0.07 (biota standard of 20 $\mu\text{g/kg}$ wet weight) (European Parliament and Council of the European Union, 2013)
Nickel (Ni)	Rechargeable batteries, electron gun in cathode ray tubes	The IARC classifies metallic nickel and nickel alloys in group 2B, possibly carcinogenic to humans and nickel compounds in group 1, carcinogenic to humans (International Agency for Research on Cancer, 2015). Nickel and its compounds are known to cause allergic reactions by promoting contact dermatitis. Chronic exposure leads to lung fibrosis and cardiovascular and kidney diseases. Nickel compounds are known for their carcinogenic activity (Denkhaus and Salnikow, 2002).	-	4/34 (based on the concentration which is bioavailable) (European Parliament and Council of the European Union, 2013)

Chemical	Examples of the occurrence of hazardous metals and metalloids in WEEE ^A	Health concerns (humans)	MCL ^B [mg/L]	Environmental quality standard (in surface water bodies) AA-EQS/MAC-EQS [$\mu\text{g/L}$] ^C
Thallium (Tl)	Batteries, semiconductors, in scintillation counters, laser equipment, fiber glass, and photovoltaic cells	No IARC classification although it is suspected to be more toxic than Cd, Hg, and Pb. Today, few studies about its carcinogenic potential are available (Cheam, 2001). Because of its similarity in ionic charge and its ion radius to potassium, Tl(I), especially, can be absorbed and distributed easily throughout the entire body by mimicking potassium in its movement patterns and intracellular accumulation in mammals. In the body, it accumulates easily in bones, the renal medulla, and in the nervous system (Peter and Viraraghavan, 2005). Amounts of from 0.7 to 1.1 g of soluble Tl salts are determined to be the minimum lethal dose for an adult with a body weight of 70 kg (Moeschlin, 1980). Symptoms of acute Tl poisoning are alopecia, nausea, tachycardia, diarrhea, and impairments of the lungs, heart, and gastrointestinal system. Impairments of the nervous system are more likely to result from chronic exposure to Tl. However, there is a dearth of studies about the regular chronic uptake of low doses of Tl (Saddique and Peterson, 1983; Agency for Toxic Substances and Disease Registry, 2013; Frattini, 2005; Cvjetko et al., 2010).	0.002	0.013/0.8 (van Vlaardingen and Verbruggen, 2009)
Rare earth elements (REE)	Fluorescent layer (cathode ray tube screen), screens of mobile phones, tablets, and other electronic devices, catalysts, energy-efficient light bulbs, magnets (Hirano and Suzuki, 1996; Casado, 2013)	No IARC classification (International Agency for Research on Cancer, 2015). Information about the toxicity of REE is rare, therefore more research is required. REEs seem to be very persistent in the environment (Tang and Johannesson, 2006; Brioschi et al., 2013). They have a potential for accumulation in biota and humans (Tong et al., 2004; d'Aquino et al., 2009) and there is evidence for their chronic toxicity (Hirano and Suzuki, 1996). For instance, a link was observed between occupational REE exposure and the lung disease, pneumoconiosis (Sabbioni et al., 1982) and REE exposure was related with the formation of pulmonary fibrosis (McDonald et al., 1995). In refining REEs, radioactive waste is produced which may affect human and environmental health indirectly (El-Husaini and El-Hazek, 2005).	-	For fresh surface water the maximum permissible addition of REE ranges from 1.4 $\mu\text{g/L}$ for neodymium to 22 $\mu\text{g/L}$ for cerium (Sneller et al., 2000)
Zinc (Zn), (sulfide, chromates)	Plating material, interior of cathode ray tube screens, mixed with REE	No IARC classification (International Agency for Research on Cancer, 2015). Excessive short-term exposure to ingesting zinc can cause stomach cramps, nausea, and vomiting. Chronic ingestion of Zn can cause anemia, damage the pancreas, and decrease levels of high-density lipoprotein cholesterol (Agency for Toxic Substances and Disease Registry, 2005).	-	10.9/NA (UK Technical Advisory Group on the Water Framework Directive, 2012)

A: (Empa, 2009b; International Labour Organization, 2012)

B: Maximum contaminant level (United States Environmental Protection Agency, 2015c)

C: The acute and the chronic environmental quality standards (EU-standard), AA-EQS (annual average concentration) and MAC-EQS (maximum allowable concentration) represent chronic and acute environmental concentrations of chemical agents which affect water organisms significantly.

B) PAHs, dioxins, and furans

Polycyclic aromatic hydrocarbons (PAHs), such as: benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenzo[a,h]anthracene, dibenzo[a,l]pyrene, indeno[1,2,3-cd]pyrene, etc., polyhalogenated dibenzodioxins (PHDDs; for instance, polychlorinated dibenzodioxins, PCDDs), and polyhalogenated dibenzofurans (PHDFs) (for instance polychlorinated dibenzofurans, PCDFs) are the most toxic and carcinogenic compounds. They are produced by the incomplete combustion of organic matter and rudimentary WEEE processing or obsolete recycling methods (Yu et al., 2006b; Chan et al., 2007; Cui and Zhang, 2008; Sepúlveda et al., 2010; Blacksmith Institute and Green Cross, 2013).

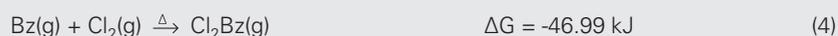
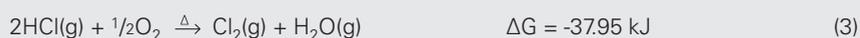
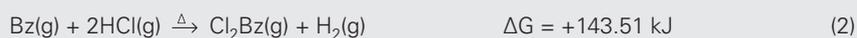
Use

PAHs, dioxins, and furans are not intentionally manufactured and they have no known commercial applications other than for research purposes (Empa, 2009b; International Agency for Research on Cancer, 2012a). These compounds are generally formed as unwanted by-products and they are subsequently released into the environment through the incomplete combustion of organic matter during residential/commercial biomass burning. This is a process that happens during cement production and other industrial combustion (production) processes, combustion of fossil fuels, and the incineration or open air burning of biomass (agricultural waste, deforestation, and wild fires), particularly if no soot particle filters are used. In 2007, it was estimated that the global annual atmospheric emission of 16 PAHs ranged from 331 to 818 Gg (as the interquartile range). In addition, it was shown that the proportion of emitted highly carcinogenic PAHs is higher in LAMICs (6.22%) than in HICs (5.73%) because of a lack of regulations and emission controls and the use of obsolete combustion methods (Shen et al., 2013).

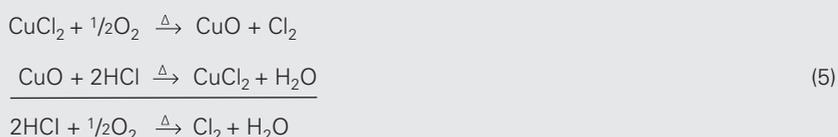
In terms of e-waste, the unregulated burning of polyvinyl-sheathed (or other related plastic coated) EEE, or the melting of halogenated polymer casings from electronic devices or coated wires to recycle plastics or to extract valuable metals, such as copper, are the most relevant processes involved in the formation of PAHs, PHDDs, and PHDF (Christmann et al., 1989; Söderström and Marklund, 2002; Wang et al., 2002; Liu et al., 2008; International Labour Organization, 2012). It is known that metals like Cu and Fe, which are contained in e-waste, act as catalysts for the formation of PHDDs and PHDFs as shown in equations 1 to 7. In 1996, it was calculated that about $13,100 \pm 2000$ kg/year of dioxins and furans were produced unintentionally and deposited from the atmosphere worldwide ($12,500 \pm 1399$ kg/year from terrestrial

deposition and 610 ± 1500 kg/year from oceanic deposition; Iida et al., 1974; Hagenmaier et al., 1987; Bruzy and Hites, 1996; Wang et al., 2002).

Through pyrolysis, PVC molecules cleave in HCl and organic molecules (aromatic rings; equation 1). These molecules could possibly react to form halogenated organic molecules (equation 2), though this reaction will not happen under normal conditions since it is thermodynamically inefficient (Gibbs free energy of formation: $\Delta G > 0 \rightarrow$ non-spontaneous, endergonic reaction). If HCl is converted to Cl_2 with a catalyst such as copper chloride, the formation of halogenated aromatic compounds (chlorobenzenes, dichlorobenzenes, chlorophenols, etc.) and, therefore, the possible formation of halogenated aromatic hydrocarbons, such as dioxins and furans, is favored (equation 3 and 4; $\Delta G < 0 \rightarrow$ spontaneous, exothermic reaction; Wang et al., 2002). As already mentioned, the formation of polyhalogenated dioxins and furans is induced if plastics, such as polyvinyl chlorides or other related polymers, are burned at low temperatures, when the presence of halogenated flame retardants can further induce the formation of halogenated dibenzodioxins and dibenzofurans (Wang et al., 2002; Weber and Kuch, 2003). In contrast, in the absence of metallic catalysts, PAHs are formed predominantly during e-waste incineration processes (Gullett et al., 1990; Wang et al., 2002).



Reaction 3 can be catalyzed by copper chloride, as presented in equation 5 (Hagenmaier et al., 1987).



where ΔG = Gibbs free energy of formation

Bz = Benzene

Cl_2 = Chlorine

Cl_2Bz = Dichlorobenzene

CuCl_2 = Copper chloride

CuO = Copper oxide

H_2 = Hydrogen

HCl = Hydrogen chloride

H_2O = Water

O_2 = Oxygen

PVC = Polyvinyl chloride

Environmental behavior and occurrence

There are over 100 different PAHs, about 75 different PCDDs, and 135 PCDFs with varying physicochemical properties between their homologue groups and their congeners. Of these, 2,3,7,8 tetrachlorodibenzodioxin (TCDD 2,3,4,7,8-pentachlorodibenzofuran (PeCDF), and the PAH, benzo[a]pyrene (B[a]P) are the ones of most concern (Table 9) from the environmental and human toxicological perspectives. Although PAHs, dioxins and their congeners, and the furans differ in their physicochemical properties, they have in common that they are generally all poorly soluble in water (water solubility: 2,3,7,8-TCDD = insoluble in water; 2,3,4,7,8-PCDF = 0,00024 mg/L; Benzo[a]pyrene = 0.00162 mg/L). They show high octanol-water coefficients (Log K_{ow} : 2,3,7,8-TCDD = 6.8; 2,3,4,7,8-PCDF = 6.9; benzo[a]pyrene = 6.35). They have a high affinity to be adsorbed from organic matter and to geo- and bioaccumulate in the environment and biota (Lohmann and Jones, 1998; International Agency for Research on Cancer, 2012a) and, therefore, they are all known as ubiquitous pollutants. In comparison to the metals and metalloids, the PAHs, dioxins, and furans formed are particularly environmentally distributed just by the air as the constituents of fumes or as molecules bound to fly ash, dust, and other organic particles. They are less likely to be distributed by water, mainly because they are formed and emitted during incomplete combustion processes and because of their partly semi-volatile and hydrophobic characteristics (Christmann et al., 1989; Lohmann and Jones, 1998; Söderström and Marklund, 2002; Chan et al., 2007). One exception is that during the extraction of metals at acid leaching sites, PCDD/Fs are significantly leached out into soils and released into the environment as well (Leung et al., 2007). For PAHs, dioxins, and furans, the atmospheric residence times range from several hours to several days before they undergo photolysis, or, more likely, they are degraded by OH-radicals or move to sediments through dry or wet deposition where they accumulate in the soils and biota (Lohmann and Jones, 1998; Lohmann et al., 1999).

As an example of the air pollution caused by these organic compounds, in ambient air in remote areas in HICs, concentrations of tetra- to octa-CDD/Fs homologues from 0.5 to 4 $\mu\text{g}/\text{m}^3$ are measured. In urban/industrial regions, concentrations of from 10 to 100 $\mu\text{g}/\text{m}^3$ were measured (Lohmann and Jones, 1998). In soils in industrial countries, such as the USA, Canada, Germany, South Korea, and Spain, PCDD/Fs concentrations of from 1.7 to 1080 $\mu\text{g}/\text{g}$ dry weight have been measured (Eljarrat et al., 2001; Hilscherova et al., 2003; Zheng et al., 2008a).

Elevated concentrations of PCDD/Fs in shredded e-waste, leaves of trees and shrubs, dust from workshop floors, and in soils in the vicinity of a large e-waste recycling facility in Taizhou, eastern China, indicate that e-waste processing and recycling facilities are significant input sources of compounds such as PCDDs, PCDFs, and other dioxin-like compounds originating from incomplete combustion processes, like PAHs (Shen et al., 2008; Ma et al., 2008). There, in shredder waste, PCDD/Fs concentrations ranged from 31 to 11,400 $\mu\text{g}/\text{g}$ dry weight and in tree and shrub leaves the concentrations ranged between 3460 and 9820 $\mu\text{g}/\text{g}$ dry weight. Workshop-floor dust and soils contained PCDD/Fs at concentrations of from 2560 to 148,000 and 854 to 10,200 $\mu\text{g}/\text{g}$ dry weight, respectively. Croplands in this region showed total PCDD/Fs concentrations up to 17 times higher than the arithmetic average, measured at reference sites. PAH levels in this region were up to 32 times higher when compared to the arithmetic average measured at control sites (Shen et al., 2008). Elevated levels of 2,3,7,8-TCDD and 1,2,3,7,8-PeCDF ranging from 1.98 to 4.95 $\mu\text{g}/\text{g}$ dry weight were found in hair samples of people living in the vicinity of an e-waste processing site near Guiyu, China, proving that indeed dioxin-like compounds have a potential for bioaccumulation (Luksemburg et al., 2002). In addition, in Jiangxi province, average concentrations of PCDD/Fs ranging from 41.5 to 133.8 $\mu\text{g}/\text{g}$ lipid were found in breast milk samples and from 177 to 843 $\mu\text{g}/\text{g}$ lipid were quantified in blood samples (Zheng et al., 2008a). For comparison, similar average total concentrations of PCDD/Fs of 125 and 299 $\mu\text{g}/\text{g}$ lipid were measured in breast milk and blood samples of pregnant women living in the vicinity of an industrialized area in Duisburg, Germany (Wittsiepe et al., 2007).

Toxicity

Besides their high potential for bioaccumulation, PAHs and PCDD/Fs are known for their toxic and carcinogenic potential. According to the IARC, PAHs such as dibenzo[a,h]anthracene and dibenzo[a,l]pyrene or benzo[b]fluoranthene and benzo[k]fluoranthene are classified as 2A, probably carcinogenic to humans or 2B, possibly carcinogenic to humans. The most hazardous PAH, benzo[a]pyrene, and the furan and dioxin 2,3,4,7,8-Pentachlorodibenzofuran (PeCDF) and 2,3,7,8 tetrachlorodibenzodioxin (TCDD) are classified according to the IARC in group 1, carcinogenic to humans as well (International Agency for Research on Cancer, 2015). The low MCLs of PAHs of 0.002 mg/L and of dioxins of 0.00000003 mg/L indicate that these compounds are posing a high risk to environmental and human health, whereas for TCDD it has to be considered that it is not soluble in water (MCLs and IARC classification are presented in Table 9). At present,

Although PAHs, dioxins and their congeners, and the furans differ in their physicochemical properties, they have in common that they are generally all poorly soluble in water.

no MCL for PCDFs has been determined (United States Environmental Protection Agency, 2009).

PCDD/Fs are known to cause adverse effects to human and animal health. For instance, in humans, excess risks for all types of cancer are associated with exposure to TCDD and PeCDF. Moreover, after the exposure to TCDD and dioxin-like compounds, changes in hormone levels were observed in humans and in animals. These changes result in increases in endocrine, reproductive and developmental defects, affecting the welfare and development of humans and other animals. High levels of TCDD exposure cause the skin disease referred to as chloracne (Kogevinas, 2001; International Agency for Research on Cancer, 2012a; Energy Justice Network, 2012).

The formation of different types of cancer, such as skin, lung, and bladder cancer, in human and animals has often been associated with exposure to PAHs as well (Boffetta et al., 1997). According to *in-vitro* and *in-vivo*

animal tests, PAHs, and especially benzo[a]pyrene, are known for eliciting carcinogenic, mutagenic and genotoxic effects (Huberman et al., 1976; Szmigielski et al., 1982; Grimmer et al., 1991; Goldstein et al., 1998; Miller and Ramos, 2001).

From the environmental toxicological point of view, the AA-EQS and the MAC-EQS of B[a]P, the most hazardous PAH, are 0.00017 and 0.27 µg/L (Table 9). These indicate that even low chronic and acute exposure to this compound poses a high risk to aquatic organisms and aquatic ecosystems. For PCDD and other dioxin-like compounds no AA-EQS and MAC-EQS were available. Nevertheless, the determined EQS of these compounds, which should not be exceeded in biota to avoid poisoning water surface organisms, is 0.0065 µg/kg TEQ (toxic equivalents according to the World Health Organization 2005 Toxic Equivalence Factors; European Parliament and Council of the European Union, 2013).

Besides their high potential for bioaccumulation PAHs, PCDD/Fs are known for their toxic and carcinogenic potential.

Table 9: PAHs and other hazardous compounds formed and released in the burning of EEE and their risks to human health and aquatic systems (Empa, 2009b; International Labour Organization, 2012)

Chemical	Formation and occurrence of hazardous PAHs and halogenated hydrocarbons in WEEE ^A	Health concerns (humans)	MCL ^B [mg/L]	Environmental quality standard (in surface water bodies) AA-EQS/MAC-EQS [µg/L] ^C
Polycyclic aromatic hydrocarbons (PAH) (benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenzo[a,h]anthracene, dibenzo[a,l]pyrene, indeno[1,2,3-cd]pyrene, etc.)	By-products of incomplete combustion of organic matter and polyvinyl chloride (Wang et al., 2002).	According to the IARC, PAHs such as dibenzo[a,h]anthracene and dibenzo[a,l]pyrene or benzo[b]fluoranthene and benzo[k]fluoranthene are classified in group 2A, probably carcinogenic to humans or group 2B, possibly carcinogenic to humans. The most hazardous PAH, benzo[a]pyrene is even listed in class 1, carcinogenic to humans, posing a risk to environmental health (International Agency for Research on Cancer, 2015). The formation of different types of cancer, such as skin, lung, and bladder cancer in humans have often been associated with the exposure to PAHs (Boffetta et al., 1997). According to <i>in-vitro</i> and <i>in-vivo</i> animal tests, PAHs, especially benzo[a]pyrene, are known for their carcinogenic, mutagenic, and their genotoxic effects (Huberman et al., 1976; Szmigielski et al., 1982; Grimmer et al., 1991; Goldstein et al., 1998; Miller and Ramos, 2001).	0.0002	0.00017/0.27 for B[a]P (European Parliament and Council of the European Union, 2013)
Note: the formation of polybrominated dibenzodioxins and dibenzofurans is possible as well if brominated hydrocarbons are burned PCDD/PCDF polychlorinated dibenzodioxins and dibenzofurans	PCDD and PCDF are unwanted by-products of incineration, uncontrolled burning and certain industrial processes. The open burning of plastic (polyvinyl chloride) sheathed copper wires to recover copper is one of the main reason for the formation of PCDDs and PCDFs (Christmann et al., 1989; Söderström and Marklund, 2002; Liu et al., 2008; Robinson, 2009). There is an observed link between the formation of PCDDs and PCDFs (Söderström and Marklund, 2002; Weber and Kuch, 2003).	2,3,4,7,8-Pentachlorodibenzofuran (PeCDF) and 2,3,7,8-tetrachlorodibenzodioxin (TCDD) are classified according to IARC in group 1, carcinogenic to humans (International Agency for Research on Cancer, 2015). These compounds are known to cause adverse effects to human and animal health. In humans, excess risks for all types of cancer are associated with exposure to TCDD and PeCDF. Moreover, after exposure to TCDD and dioxin-like compounds, changes in hormone levels were observed in humans and in animals. These increases in endocrine, reproductive, and developmental defects are of the highest concern. High levels of TCDD exposure cause the skin disease referred to as chloracne (Kogevinas, 2001; International Agency for Research on Cancer, 2012a; Energy Justice Network, 2012).	0.00000003 for dioxin	No AA-EQS/MAC-EQS available. However, EQS of maximal tolerable concentrations of dioxin-like compounds in biota of 0.0065 µg/kg TEQ (toxic equivalents according to the World Health Organization 2005 Toxic Equivalence Factors) are determined (European Parliament and Council of the European Union, 2013).

A: (Empa, 2009b; International Labour Organization, 2012)

B: Maximum contaminant level (United States Environmental Protection Agency, 2015c)

C: The acute and the chronic environmental quality standards (EU-standard), AA-EQS (annual average concentration) and MAC-EQS (maximum allowable concentration) represent chronic and acute environmental concentrations of chemical agents which affect water organisms significantly.

C) Flame retardants and other halogenated hydrocarbons.

Chlorofluorocarbons (CFCs), perfluorooctane sulfonates (PFOS), polychlorinated (or brominated) diphenyl ethers (PCDEs/PBDEs), polychlorinated (or brominated) biphenyls (PCBs, PBBs), polyvinyl chloride (PVC), and tetrabromobisphenol-A (TBBPA) are the most hazardous flame retardants and halogenated hydrocarbons that are contained in e-waste (Empa, 2009b; International Labour Organization, 2012).

Use

Polychlorinated biphenyls (PCBs) were mainly produced and used in the period 1929-1977 as electrical insulating fluids in transformers and capacitors and as hydraulic, heat transfer, and lubricating fluids in machinery. Furthermore, in combination with other agents, they were added to plastics as plasticizers and fire retardants. They were contained also in products such as caulks, adhesives, and carbonless copy paper (Erickson and Kaley, 2011). All in all, between 1929 and 1984, between 1.3 and 1.7 million tonne of PCBs were produced (Breivik et al., 2007; Stockholm Convention, 2008). Today, equipment and machinery which contain PCBs are still in use, obsolete equipment is stockpiled, and PCB wastes are not yet managed in an environmentally sound manner. According to the Stockholm Convention it is intended to securely remove all PCB stocks by 2028 (Stockholm Convention, 2008). Moreover, there is evidence that PCBs can be produced as by-products and afterwards released into the environment during industrial or waste combustion processes as well (Müller and Dongmann, 1998; Ishikawa et al., 2007; Li et al., 2009).

Polychlorinated diphenyl ethers (PCDEs) were used as dielectric insulating fluids or as hydraulic and heat transfer fluids, lubricants, plasticizers, and flame retardants. PCDEs were applied as fungicides, slimicides, and wood preservatives (Koistinen, 2000; Domingo, 2006).

The brominated hydrocarbons, PBB, PBDE, and tetrabromobisphenol A (TBBPA), are primarily used as fire retardants in plastics, as thermoplastic components, or cable insulation, and they are contained in the plastic housings of EEE, printed circuit boards, etc. (International Labour Organization, 2012). TBBPA is used as reactive flame retardant (chemically bonded into the polymeric material, not volatile) or as an additive flame retardant in plastics (volatile). Often, TBBPA additives were used as flame retardants in acrylonitrile-butadiene-styrene and phenolic resins or as an intermediate in the production of other additive flame retardants (Institute for Health and Consumer

Protection - European Chemicals Bureau, 2006). Today, TBBPA additives are the most widely used in the extensively produced and not yet regulated brominated flame retardants (He et al., 2010).

Polyvinyl chlorides (PVCs) are used ubiquitously – they are one of the most widely used plastics worldwide. They are contained in all kind of packaging and sheathing material (for food, EEE, and other kind of goods), plastic bottles, credit cards, and audio records. In the construction industry, PVCs are used as imitation leather or in window frames, cables, pipes, floorings, wallpapers, and window blinds (Greenpeace, 2005). As already mentioned, the inappropriate production, disposal, and incineration of PVCs can lead to the emission of highly carcinogenic, persistent organic pollutants (POPs), such as dioxins, furans, PAHs, and halogenated biphenyls. Therefore, environmentally unsound production, disposal, and incineration can affect human and environmental health indirectly (Müller and Dongmann, 1998; Shen et al., 2008; Ma et al., 2008).

The use of chlorofluorocarbons (CFCs) decreased when it was found that the release of these resulted in depletion of the stratospheric ozone layer, which may result in an increase of biologically harmful solar ultraviolet radiation (Newman et al., 2009). It was also determined that CFCs act as potent greenhouse gases (GHGs; Hansen et al., 1989). Because of these negative effects, the use of CFCs was banned on global scale through the Montreal Protocol on substances that deplete the ozone, which was negotiated in 1987 (Newman et al., 2009; Environmental News Network, 2012). Nevertheless, before they were banned, CFCs were used as cooling agents in refrigerators, freezers, air conditioners, and in cooling units in general. They were also contained in insulation foam (Newman et al., 2009).

Perfluorooctane sulfonate (PFOS) is used in the photographic industry and in photolithography. It is contained in semiconductors, photo-resistant-, and anti-reflective coatings. Furthermore, it is a component of EEE, firefighting foam, hydraulic fluids, and textiles. Today, the production and application of PFOS is restricted according to the requirements of the Stockholm Convention and there are initiatives for a voluntary phasing out of PFOS production from several chemical production facilities (Swedish Chemicals Inspectorate and Swedish Environmental Protection Agency, 2004; United Nations Environment Programme, 2013d).

Environmental behavior and occurrence

Most of these halogenated compounds, especially PCBs, PCDEs, PBBs, PBDEs, and PFOS, are fulfilling the per-

Polyvinyl chlorides (PVCs) are one of the most widely used plastics worldwide.

Inappropriate production, disposal, and incineration of PVCs can lead to the emission of highly carcinogenic, persistent organic pollutants (POPs), such as dioxins, furans, PAHs, and halogenated biphenyls.

sistent, bioaccumulation, and toxicity (PBT) criteria of the Stockholm Convention. All of these compounds are known to have long environmental residence times and they remain unchanged in the environment for extended periods of time. They are ubiquitous pollutants found in soil, water, and, notably, the air being distributed throughout the environment by natural processes. In addition, these compounds are known for their bioaccumulative potential. Thus, they are accumulating in the fatty tissue of living organisms and humans and they are enriched throughout the food chain. Given their high toxicity, they are affecting humans and wildlife. Because of their characteristics, their production and use is restricted or even banned worldwide within the scope of the Stockholm Convention (United Nations Environment Programme, 2013d).

Nevertheless, although the Stockholm Convention has been implemented, elevated concentrations of those halogenated compounds still can be found in the environment. For instance, in the breast milk of women living in the vicinity of an e-waste recycling site in Bui Dau, Vietnam, increased concentrations of 20-250 ng/g lipid weight of PBDE and its congeners were measured, indicating their potential for bioaccumulation. In comparison, the breast milk of Swedish women showed lower mean concentrations of 4 ng PBDE/g lipid weight while the maximum concentrations were 28.2 ng PBDE/lipid weight (Lind et al., 2003). In addition, in soil and sediment samples next to an open e-waste disposal and recycling site in Guiyu Guangdong, China, elevated PBDE concentrations ranging from 0.26 to 824 ng/g dry weight were detected (Wang et al., 2005). In this region, a monthly average PBDE concentration of 16.8 ng/m³ was measured in particles with aerodynamic diameters smaller than 2.5 µm (PM_{2.5}). These particles were detected in the air in the vicinity of a site with high e-waste burning activities (Wong et al., 2007c). This concentration exceeds the industrial EPA air screening level of 1.4 ng/m³ (United States Environmental Protection Agency, 2014b). As a comparison, in Europe, background levels of PBDE in soils range between 0.065 to 12 ng/g dry weight (Hassanin et al., 2004).

PCB concentrations measured in soils at the open burning sites of e-waste recycling facilities in Guiyu were up to 458 µg/kg (Wong et al., 2007c). In comparison, the maximum measured environmental concentration of PCBs in five European cities (Glasgow, Torino, Aveiro, Ljubljana, and Uppsala) was 172 µg/kg dry weight (Cachada et al., 2009).

TBBPA concentrations of 25.2 ± 2.7 ng/g were determined in soil samples from China (Yu et al., 2008). In Spanish soils from an industrial region, comparable TBBPA concentrations were measured ranging between 3.4 and 32.2 ng/g dry weight (Sánchez-Brunete et al., 2009). Elevated median TBBPA concentrations ranging between 28 to 173 ng/g lipid weight were found in the muscles of six individual bird species that had been fed with food originating from an e-waste recycling region in Qingyuan, South China (He et al., 2010). In this region, TBBPA mean concentrations of 68 ng/L were found in water, 295 ng/g dry weight in soil samples, and 8917 ng/g dry weight in plant leaf samples. These results show that TBBPA has the potential to accumulate primarily in soil plants and wildlife. Maybe it would be appropriate to add this highly bioaccumulative product to the list of the restricted or banned brominated flame retardants along with PBB and PBDE. A summary of the fields of applications of these halogenated hydrocarbons is presented in Table 10.

Toxicity

The polyhalogenated biphenyls and diphenyl ethers are known for their high toxicity and their carcinogenic potential. The IARC lists PCBs in group 1, carcinogenic to humans, and PBBs are included in group 2A, probably carcinogenic to humans. PCDE and PBDE have not been classified by the IARC but might be comparably toxic to humans due to their structural similarity to PCBs and PBBs, respectively (International Agency for Research on Cancer, 2015). Exposure to PCBs causes impairment of the immune system because of their immune-suppressive effects. After uptake of, or direct contact with PCBs, they can cause damage to the liver, the skin – in form of chloracne – and the reproductive system by affecting the thyroid gland. In addition, there is evidence that exposure to PCB promotes the formation of several types of cancer (Agency for Toxic Substances and Disease Registry, 2000; Stockholm Convention, 2008).

Because of a lack of epidemiological studies, it is still not possible to find a significant correlation between exposure to PBB and the formation of human cancer, though results from animal tests showed effects similar to those of PCBs. Exposure to PBBs caused the formation of different types of cancers in rats and mice. In other animal tests, skin diseases, such as chloracne, impairments to the central nervous system, the liver, kidney, thyroid glands function, and the reproduction system were observed as well (Agency for Toxic Substances and Disease Registry, 2004b; National Toxicology Program, 2014c).

PVCs and other polyvinyl based compounds were, according to the IARC, listed in group 3, not classifiable as to

Exposure to PCBs causes impairment of the immune system because of their immune-suppressive effects.

its carcinogenicity to humans (International Agency for Research on Cancer, 2015). Nevertheless, it has to be considered that during the production, recycling, and incineration of PVCs, hazardous compounds, such as PAHs, dioxins, furans, halogenated biphenyls, and polychlorinated diphenyl ethers, can be produced and released into the environment (Gullett et al., 1990; Wang et al., 2002; 2005).

CFCs, PFOS, and TBBPA are not classified according to the IARC (International Agency for Research on Cancer, 2015). From the environmental and human health perspectives, CFCs are destroying the stratospheric ozone layer, which consequently results in an increase of biologically harmful and aggressive solar ultraviolet radiation (Newman et al., 2009). At high concentrations, CFCs can be transformed to even more toxic gases, such as chlorine and phosgene (New Hampshire Department of Environmental Services, 2010). Furthermore, CFCs are acting as potent GHGs (Hansen et al., 1989). For humans, the inhalation of large volumes of CFCs affects the nervous system with symptoms of alcohol-like intoxication, reduced coordination, light-headedness, headaches, tremors and convulsion, and even cardiac arrhythmia. Dermal contact can lead to skin damage referred to as frost bite (New Hampshire Department of Environmental Services, 2010).

PFOS meet the requirements of the PBT criteria of the Stockholm Convention. From a human health perspective, information about the health risks from exposure to PFOS is still lacking. Nevertheless, according to several epidemiological studies, exposure to PFOS was assumed to be linked with the formation of bladder cancer (Organisation for Economic Co-operation and Development, 2015). According to animals tests, it has been shown that exposure to PFOS is highly toxic and that these compounds have a high affinity for bioaccumulation. In two mammalian species, rats and monkeys, sub-chronic exposure to PFOS resulted in hepatotoxicity and mortality. In addition, the exposure of mammals to PFOS was

associated with causing impairments in reproduction as well. The half-life times in rats is 100 days, in monkeys it is 200 days, and in humans it can be 1 year (Luebker et al., 2002; Seacat et al., 2002; 2003; Inoue et al., 2004; Organisation for Economic Co-operation and Development, 2015).

According to the risk assessment report of the Institute for Health and Consumer Protection's and the European Chemicals Bureau, TBBPA is not currently classified for environmental or human health effects (Institute for Health and Consumer Protection – European Chemicals Bureau, 2006). From the data available, TBBPA is not known as a skin, eye, or respiratory tract irritant. From animal tests with rats, no evidence was found that exposure to TBBPA caused adverse effects to the endocrine and the reproduction systems. Information about the carcinogenic potential of TBBPA has not been found yet (Institute for Health and Consumer Protection – European Chemicals Bureau, 2006). Nevertheless, rudimentary plastic recycling and the low-temperature burning processes for plastics containing TBBPA and other brominated or chlorinated flame retardants can lead to the formation and emission of hazardous polybrominated dibenzodioxins and polybrominated dibenzofurans or PCDDs and PCDFs, respectively (Thies et al., 1990; Empa, 2009b).

For the halogenated hydrocarbons considered in this report, an MCL standard level for PCB compounds in drinking water of 0.0005 mg/L and of 0.00000003 mg/L for dioxins were determined. For the other compounds no MCL is available yet (Table 9 and Table 10; United States Environmental Protection Agency, 2015c).

For all the previously mentioned flame retardants and halogenated hydrocarbons just as for PFOS/Fs, the chronic environmental quality standard (AA-EQS) of 0.00065 µg/L has been proposed. For PBDE, the proposed acute environmental quality standards (MAC-EQS) was 0.14 and for PFOS, 36 µg/L (European Parliament and Council of the European Union, 2013).

Table 10: Flame retardants and halogenated hydrocarbons occurring in WEEE and their risks to humans and aquatic systems (Empa, 2009b; International Labour Organization, 2012)

Chemical	Formation and occurrence of hazardous PAHs and halogenated hydrocarbons in WEEE ^A	Health concerns (humans)	MCL ^B [mg/L]	Environmental quality standard (in surface water bodies) AA-EQS/MAC-EQS [$\mu\text{g/L}$] ^C
chlorofluorocarbon (CFC)	Contained in old refrigerators and freezers, cooling units, and insulation foam. The use of CFC is decreasing because of global bans and restrictions (Montreal Protocol on substances that deplete the ozone which was negotiated in 1987; Newman et al., 2009; Environmental News Network, 2012).	Not classified according to the IARC (International Agency for Research on Cancer, 2015). CFC uptake – inhaling high concentrations – affects the central nervous system with symptoms of alcohol-like intoxication, reduced coordination, light-headedness, headaches, tremors, and convulsions. High concentrations can lead to cardiac arrhythmia. Skin contact with CFCs can cause frost bite. The exposure of CFCs to high temperatures can cause the formation of more toxic gases, such as chlorine and phosgene (New Hampshire Department of Environmental Services, 2010). In addition, CFCs are known to destroy the ozone layer, which results in an increase of biologically harmful solar ultraviolet radiation (Newman et al., 2009) and CFCs act as potent GHGs as well (Hansen et al., 1989).	–	–
polychlorinated biphenyls and polychlorinated diphenyl ethers (PCB/PCDE)	From 1929 to 1977, PCBs were commercially used as insulation material or as dielectric insulating fluids in older electronic products, transformers, and capacitors. They were contained in inks and plastic (International Agency for Research on Cancer, 2012a). PCDEs were used as fire retardants in plastics (thermoplastic components, cable insulation) or as dielectric insulating fluids, hydraulic and heat transfer fluids, and lubricants and plasticizers. PCDEs were contained as impurities in chlorophenol-based compounds such as fungicides, slimicides, wood preservatives, etc. (Koistinen, 2000; Domingo, 2006).	PCBs are classified in group 1, carcinogenic to humans (International Agency for Research on Cancer, 2015). PCB exposure causes damage to the immune system (immuno-suppressive effects), liver, skin (chloracne), reproductive system, gastrointestinal and respiratory tract, and thyroid gland, and promotes the formation of cancer (Agency for Toxic Substances and Disease Registry, 2000; Stockholm Convention, 2008). PCDEs have not been classified by the IARC but might be comparably toxic to humans due to their structural similarity to PCBs (International Agency for Research on Cancer, 2015).	0.0005 (PCBs)	–
polybrominated diphenyls and polybrominated diphenyl ethers (PBB/PBDE)	PBB and PBDEs are used as fire retardants in plastics (thermoplastic components, cable insulation). They are contained in the plastic housings of EEE, printed circuit boards, etc.	According to the IARC the PBBs are classified as group 2A, probably carcinogenic to humans. Similar to the effects of PCB (see above). According to animal tests PBBs are known to cause different types of cancer in rats and mice, although because of a lack of epidemiological studies it is still not possible to find a significant correlation between the exposure to PBB and the formation of human cancer (Agency for Toxic Substances and Disease Registry, 2004b; National Toxicology Program, 2014c). During animal tests and unintentional exposure to PBBs, the formation of chloracne or other forms of skin irritation were observed. Significant evidence of damage to the central nervous system, liver, kidneys, thyroid gland function, and reproduction system is available from animal studies (Agency for Toxic Substances and Disease Registry, 2004b). PBDEs have not been classified by the IARC but might be comparably toxic to humans due to their structural similarity to PBBs (International Agency for Research on Cancer, 2015).	–	NA/0.14 for PBDE (biota EQS 0.0085 $\mu\text{g/kg}$ wet weight) (European Parliament and Council of the European Union, 2013)
perfluor octane sulfonate (PFOS)	Used in the photographic industry and in photolithography. PFOS are also contained in semiconductors and photo-resistant and anti-reflective coatings. Now, PFOS production is being voluntarily phased out (Swedish Chemicals Inspectorate and Swedish Environmental Protection Agency, 2004).	No IARC classification (International Agency for Research on Cancer, 2015). According to several animal tests it has been demonstrated that PFOSs are highly toxic and that they have a high potential for bioaccumulation. The half-life times in rats, monkeys and in humans are 100 days, 200 days or 1 year respectively. In both species, rats and monkeys, sub-chronic exposure to PFOS results in hepatotoxicity and mortality. Impairments in the reproductive systems of mammals was linked to exposure to PFOS (Luebker et al., 2002; Seacat et al., 2002; 2003; Inoue et al., 2004; Organisation for Economic Co-operation and Development, 2015). From a human toxicological point of view, adequate information about the health risk from exposure to PFOS is not available. However, according to some epidemiologic studies, exposure to PFOS was linked to the formation of bladder cancer (Organisation for Economic Co-operation and Development, 2015).	–	0.00065/36 (European Parliament and Council of the European Union, 2013)

A: (Empa, 2009b; International Labour Organization, 2012)

B: Maximum contaminant level (United States Environmental Protection Agency, 2015c)

C: The acute and the chronic environmental quality standards (EU-standard), AA-EQS (annual average concentration) and MAC-EQS (maximum allowable concentration) represent chronic and acute environmental concentrations of chemical agents which affect water organisms significantly.

Chemical	Formation and occurrence of hazardous PAHs and halogenated hydrocarbons in WEEE ^A	Health concerns (humans)	MCL ^B [mg/L]	Environmental quality standard (in surface water bodies) AA-EQS/MAC-EQS [$\mu\text{g/L}$] ^C
polyvinyl chloride (PVC)	PVC is used as cable insulation, computer housing or as housing material of other EEE because of its fire-retardant properties.	According to the IARC, PVCs are classified as group 3, not classifiable as to its carcinogenicity to humans (International Agency for Research on Cancer, 2015). The burning of PVCs can cause the formation of hazardous and highly carcinogenic substances, such as PAHs, PCDD and PCDFs, and other dioxin-like compounds (Gullett et al., 1990; Wang et al., 2002; 2005).	–	–
tetrabromobisphenol A (TBBPA)	TBBPAs are used as flame retardants in plastics (thermoplastic components, cable insulation). For example, TBBPA is most widely used in printed wiring boards and casings of electronic devices. It is used as a reactive flame retardant in epoxy and polycarbonate resins, or as an additive flame retardant in acrylonitrile-butadiene-styrene (ABS) resins and phenolic resins. TBBPAs are used as intermediates to produce other flame retardants as well. (Institute for Health and Consumer Protection - European Chemicals Bureau, 2006).	No IARC classification (International Agency for Research on Cancer, 2015). TBBPA is not currently classified for environmental or human health effects (Institute for Health and Consumer Protection - European Chemicals Bureau, 2006). TBBPA is not known as a skin, eye, or respiratory tract irritant and according to animal tests with rats, no evidences were found that exposure to TBBPA caused adverse effects to the endocrine and the reproductive systems. Information about the carcinogenic potential of TBBPA has not been found yet (Institute for Health and Consumer Protection - European Chemicals Bureau, 2006). Nevertheless, rudimentary plastic recycling and low-temperature burning processes of plastics containing TBBPA and other brominated flame retardants leads to the formation and emission of hazardous polybrominated-dibenzodioxins and polybrominated-dibenzofurans (Thies et al., 1990; Empa, 2009b).	–	–

A: (Empa, 2009b; International Labour Organization, 2012)

B: Maximum contaminant level (United States Environmental Protection Agency, 2015c)

C: The acute and the chronic environmental quality standards (EU-standard), AA-EQS (annual average concentration) and MAC-EQS (maximum allowable concentration) represent chronic and acute environmental concentrations of chemical agents which affect water organisms significantly.

Input pathways of e-waste pollutants

Generally, for e-waste pollutants there are two possible main input pathways by which they can enter the environment. If e-waste is disposed of inappropriately, soluble toxicants, such as several heavy metals (for instance Pb and Sb) can be leached from e-waste landfills especially after stronger rain events. They then remain in the soil or they can be further transported via surface runoff into rivers or they can drain into groundwater aquifers (Robinson, 2009). However, the main entry of e-waste pollutants happens through inappropriate recycling and e-waste processing practices. For example, open burning or incineration of e-waste can lead to the formation and emission of highly toxic compounds into the atmosphere. These can be distributed by air and become sediments in soils and surface waters via dry or wet deposition. This seems to be especially the case in LAMICs where, often, exhaust fumes are not controlled or filtered and regulations are lacking (Stewart and Lemieux, 2003; Leung et al., 2008; International Labour Organization, 2012). Additionally, precious and other valuable metals are leached from e-waste using strong acids. These highly toxic agents can leak from their containers and pollute water systems and soils (Robinson, 2009).

Production and pollution trends of hazardous compounds associated with e-waste

Data availability

Data about e-waste production and particularly data about the transboundary movements of WEEE is difficult to assess. Mainly this is because of the illegal or hidden export of e-waste from OECD countries to non-OECD countries to save on the expenses of e-waste disposal, recycling, and labor costs. For instance, there is evidence from the US EPA that sending WEEE for disposal and/or recycling in Asia would cost one-tenth of the expense to process the materials in the USA (International Labour Organization, 2012). With the currently available data on the production of EEE, the modelling of WEEE generation and its transboundary movements are not possible. This is especially so since such data is more likely to be available in higher-income countries than it is in LAMICs and data about the average lifespan and innovation cycles of individual items of EEE varies from region to region. (In higher-income countries the innovation cycles for and the lifespans of EEE are shorter than those in LAMICs. In these countries, older equipment is used for longer periods of time; Robinson, 2009).

In general, it can be assumed that information about the output figures for EEE and the generation of WEEE alone are not satisfactory to assess the extent of the environmental burden caused by the inappropriate disposal of EEE. It is necessary to get more details about the trade patterns of obsolete EEE because these are largely still not transparent and comprehensible.

Future trends and hot spots

Although the amount of available data about e-waste is rare, several research groups and NGOs are trying to shed light on the output figures for EEE or to get information about the amounts of WEEE generated. These researchers are trying to determine their mass fluxes and gain information about the futures of obsolete and inoperable EEE from a global perspective. They are also trying to assess the negative impacts on environmental and human health caused by the inappropriate disposals and recycling of WEEE (Widmer et al., 2005; United Nations Environment Programme, 2006a; Robinson, 2009; Empa, 2009e; Skinner et al., 2010; Mundl, 2010; International Labour Organization, 2012; Silicon Valley Toxics Coalition, 2014; United Nations Environment Programme, 2014).

Where the illegal export of WEEE is concerned, known and suspected routes of e-waste dumping are presented in Figure 25 and Figure 26 (Lewis, 2010, 2011; International Labour Organization, 2012; Silicon Valley Toxics Coalition, 2014). Australia, Japan, Korea, North America, and Western Europe are suspected of being the main exporter of e-waste to LAMICs.

Known targets for illegal e-waste disposal seem to be Brazil, China, Ghana, India, Nigeria, Mexico, Pakistan, Singapore, and Thailand. Other suspected destinations for obsolete and inoperable EEE are Argentina, Benin, Chile, Egypt, Eastern Europe, Haiti, Indonesia, Ivory Coast, Kenya, Malaysia, Philippines, Russia, Senegal, Tanzania, Ukraine, United Arab Emirates, Venezuela, and Vietnam. Unfortunately at present, there is no system for tracking legal or illegal exports of WEEE. Therefore, no direct quantitative data on the exported volumes of e-waste could be found and not every destination for exported and dumped e-waste could be located (Lewis, 2011). Nevertheless, there is evidence that China is one of the main destinations for e-waste. Experts suspect that upto 70% of exported WEEE is probably sent to China – primarily to southeast China near Beijing, the Yangtze River Delta, and the Pearl River Delta (Tong and Wang, 2004; Bodeen, 2007).

It can be assumed that there is a positive correlation between the demand and availability of PCs and other potential e-waste items and the gross domestic product of a country. Therefore, at this time, the regions with the highest GDPs, such as Western Europe, the United States and Australasia, are the most likely e-waste producers. During the next 10 years, regions with high economic growth, such as China, Eastern Europe, and Latin America will catch up with or even exceed the e-waste generation of the former (Robinson, 2009). Thus, besides the loads of e-waste that are illegally exported to LAMICs for disposal or recycling, the additional domestic generation of e-waste will further increase the environmental burden caused by



Figure 25: Known sources of e-waste and its known and suspected shipping routes (International Labour Organization, 2012; Lewis, 2011; Silicon Valley Toxics Coalition, 2014).

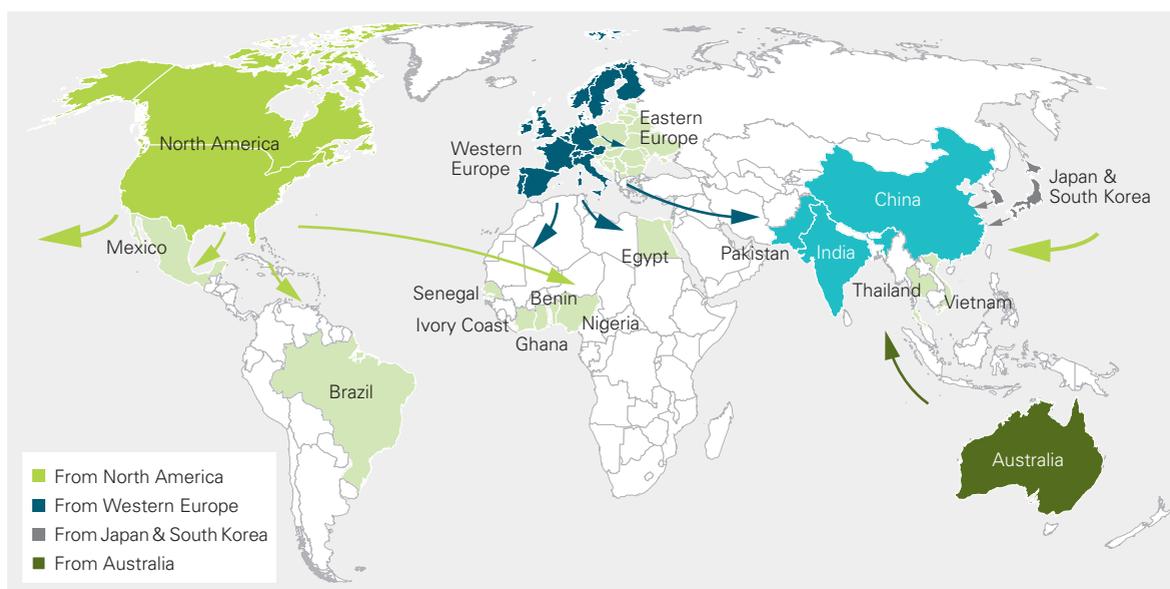


Figure 26: Export of e-waste from HICs to LAMICs (Lewis, 2010; International Labour Organization, 2012)

e-waste pollutants in LAMICs experiencing an economic boom. In general, the recent global production (data from 2006 and 2009) of WEEE is suspected to range between 20 and 50 million tonne (United Nations Environment Programme, 2006a; Robinson, 2009; Schluep et al., 2009). In 2014/15 it is estimated that between 40 and 70 million tonne of WEEE might be generated (Jain, 2008).

Issues of special concern

Contaminants in the e-waste processing region of Guiyu, Guangdong Province, China

During the last decades, the people in Guiyu have changed over from a traditionally rice-growing community to an e-waste recycling and processing center (Leung et al., 2006). Today, Guiyu, with its surrounding towns in Guangdong Province, probably has become one of the largest e-waste disposal and recycling sites in the world, receiving large amounts of e-waste from domestic and international sources (Wong et al., 2007a; Greenpeace, 2009). The major recycling and processing activities in this region are toner sweeping, dismantling of EEE, recovering copper from wires and EEE, chipping and melting plastic, heating printed circuit boards over honeycombed coal blocks, and to recover gold and other valuable metals by using strong acids (cyanides, sulfuric acid, and hydrochloric acid; Puckett et al., 2002; Leung et al., 2006). The redundant e-waste is often dumped and openly burned without any controls or precautions, leaving behind an environmental burden of high severity. For instance, according to the disposal and processing of e-waste, POPs

(like PAHs, dioxins, and furans) and halogenated hydrocarbons (like PCDE/PBDEs, PCB, and PBB) or inorganic pollutants (like heavy metals such as Cd, Cu, Ni, Pb and Zn) can be released in the environment, affecting environmental and human health.

For example, the sediments of a duck pond in the vicinity of an e-waste dumping and open burning site showed elevated total PAH concentrations (of the 16 PAHs banned by the US EPA) of up to 514 µg/kg. In rivers in Guiyu, the concentrations of seven carcinogenic PAHs were from two to eight times higher (28-111 µg/kg) and in duck ponds from seven to nine times higher (94-122 µg/kg) than the concentrations found in the reservoir (13.2 µg/kg). In this region, soil samples from a printer roller dump site had total PAH concentrations of up to 593 µg/kg. These values are comparable with those found at another large-scale e-waste recycling site in Taizhou, China, where total PAH concentrations ranged from 488 to 764 µg/kg dry weight (Tang et al., 2010). Currently, global guidelines and limit values for PAHs have not been established. However, although these values do not exceed the soil criteria for PAH concentrations of the 'Dutch list' (Environmental Protection Department of Hong Kong, 2004) – 1000 µg/kg, which implies that the soil is contaminated – the elevated PAH concentrations in Guiyu are of high environmental concern. This is especially so since the pollution from e-waste and the informal businesses is increasing and PAHs are known to accumulate via the food chain, be persistent, and highly toxic even at low concentrations (Environmental Protection Department of Hong Kong, 2004). In addition, sediments from the Lianjiang River (Guiyu, China) show that this river is contaminated by PCB and its congeners. Total PCB concentrations of up to

743 $\mu\text{g}/\text{kg}$ were measured. This exceeds the Canadian Environmental Quality Guideline of 277 $\mu\text{g}/\text{kg}$ (Leung et al., 2006). A high concentration of total mono-hepta PBDEs of 1140 $\mu\text{g}/\text{kg}$ was found in soil samples at an informal dumping site for burned plastic in Guiyu, while in similar samples from a printer roller dumping site in the same area, the concentration was found to be 1169 $\mu\text{g}/\text{kg}$. Serious levels of contamination with PCDD/F and PBDEs were found in surface samples from the e-waste recycling area in Taizhou, China, as well. At this site, PBDE concentrations ranged from 27.9 to 3128.4 $\mu\text{g}/\text{kg}$ and PCDD/Fs concentrations from 218.3 to 3122.2 $\mu\text{g}/\text{kg}$ (Tang et al., 2014). Besides the organic pollutants, e-waste processing and recycling is often associated with the release of inorganic contaminants. For instance, sediments of the Lianjiang River were considerably contaminated with Cd (mean value 4.09 ± 3.92 mg/kg), Cu (1070 ± 1210 mg/kg), Ni (181 ± 156 mg/kg), Pb (230 ± 169 mg/kg), and Zn (324 ± 143 mg/kg; Wong et al., 2007b).

Currently, there is a dearth of detailed information about the consequences of chronic e-waste pollutants to environmental health and their environmental risks, especially in LAMICs. That is the main reason why it is difficult to give information about the severity of the pollution caused by informal e-waste activities. Nevertheless, as shown before, from the several environmental samples collected from e-waste disposal and processing sites, there is evidence concerning the concentrations of highly toxic POPs or inorganics (heavy metals and metalloids). This despite the (intended or unintended) production, use, import, and export of POPs has been banned or restricted globally since the Stockholm Convention came into force in 2004. These POPs are controlled by the Stockholm Convention to reduce their entry into environmental systems and to mitigate their impacts on environmental and human health (Leung et al., 2006). For instance, POPs, such as halogenated hydrocarbons, PCBs, PCDD/Fs, and PCDE and PBDE, are associated with such adverse health effects as impairment of the reproduction systems of humans and wildlife while acting as endocrine disruptors and in the formation of several forms of cancer (Table 10). They are known to bioaccumulate throughout the food chain or to remain and accumulate in soil or sediments (Leung et al., 2006). In addition, the release of heavy metals is affecting environmental and human health, the nervous systems, the mental development, the respiratory tracts, and the digestive tracts of wildlife and people (Leung et al., 2006).

Health consequences of disposal, dismantling, and recycling activities of WEEEs

A systematic review of epidemiological studies of the health consequences of ingesting the chemicals released by e-waste disposal and/or e-waste processing activities shows that human exposure to e-waste is significantly associated with impairments in reproduction, neurodevelopment, and mental health. In addition, toxicants released during e-waste disposal and processing are known to increase the incidence of cancerous diseases by causing DNA damage, chromosomal aberrations, and changes in gene expression (Zhao et al., 2009; Grant et al., 2013).

Grant et al. (2013) studied the health consequences of WEEE recycling and processing in southeast China, mainly in Guiyu and Taizhou. By reviewing the epidemiological studies they showed the positive correlation between exposure to e-waste and the negative impacts on human health.

Their review revealed that halogenated hydrocarbons, such as PBDEs, PCDDs, PCDFs, and PCBs, which are released during e-waste processing, caused variations in thyroid-stimulating hormone levels (Ju et al., 2008; Yuan et al., 2008; Wang et al., 2010; Zhang et al., 2010; Han et al., 2011; Grant et al., 2013). In the vicinity of an e-waste dismantling site in Guiyu, China, the lung function of school children (8 to 9 years of age) was affected. They showed lower forced vital capacity (FVC = the amount of air that can be forcibly exhaled from the lungs after taking a deep breath). These impairments in lung function are linked with the exposure to and the uptake of heavy metals, such as Cr, Mn, and Ni, which are emitted by the e-waste processing sector. The uptake of heavy metals was proven by the elevated blood levels of Mn of 374.92 nmol/L and of Ni of 5.3 mg/L: control samples contained 271.18 nmol/L of Mn and 3 mg/L of Ni (Zheng et al., 2013). In these regions with their high informal e-waste processing activities, reproductive health was affected as well. For instance, the exposure to e-waste was often accompanied by considerable increases in spontaneous abortions (Wu et al., 2012b), stillbirths (Guo et al., 2012; Xu et al., 2012), premature births reduced birth weights (Guo et al., 2012; Wu et al., 2012b; Xu et al., 2012), and reduced birth length (Wu et al., 2011b, 2012b; Grant et al., 2013). Other studies showed that increased lead levels could be found in the cord blood and meconium of neonates if their parents, and especially their mothers, were involved in e-waste recycling activities or if they lived in the vicinity of e-waste processing sites before and during their pregnancy (Li et al., 2008d; Liu et al., 2011). The elevated lead concentrations and probably the addi-

Exposure to e-waste was often accompanied by considerable increases in spontaneous abortions, stillbirths, premature births, reduced birth weights, and reduced birth length.

tional exposure to other contaminants released from e-waste processing resulted in impairment of the children's mental development. From neonatal behavioral neurological examinations, the Guiyu newborns with the higher lead concentrations showed abnormalities in temperament scores and low neonatal behavioral neurological assessment scores (Li et al., 2008d; Liu et al., 2011; Grant et al., 2013). E-waste and its pollutants are known to cause genetic mutations and cytogenetic damage. For instance, mothers involved in e-waste recycling had elevated Cr levels (median 94 µg/L) in umbilical cord blood. The exposure to Cr, in combination with other pollutants from the e-waste recycling, were correlated with DNA damage (Li et al., 2008c). In Jinghai, China, workers involved in e-waste processing had increased chromosomal aberration levels 20 times higher than those who were not working in the same sector (Liu et al., 2009). More evidence that pollutants from the e-waste sector can cause damage to DNA are mentioned in the comprehensive epidemiological study of Grant et al. (2013).

In conclusion, there is a lot of evidence that pollutants from e-waste are indeed a health risk for workers involved in e-waste businesses and for their families if they are living in the vicinity of e-waste processing and dumping sites.

Lack of implementation of policies and regulations

In Delhi, the Indian capital, the informal e-waste recycling sector has a high employment potential with an increasing trend. Especially for the urban poor, informal e-waste businesses are a preferred opportunity to make a profit (Sinha-Khetriwal et al., 2005; International Labour Organization, 2012). Delhi is a favored site for informal e-waste collection and processing (Sinha-Khetriwal et al., 2005; International Labour Organization, 2012) given:

- The good infrastructure
- Its position as a nodal point in trade
- India's strong economics
- The increase in domestic e-waste production
- The additional loads of e-waste from shipments from HICs which are the major sources of e-waste.

It is estimated that in 2005 in India, between 146,180 and 360,000 tonne of WEEE was generated domestically and it is estimated that 800,000 tonne of e-waste will be produced in India by 2012 (Zoeteman et al., 2010; Wath et al., 2011). In addition, in 2005 up to 850,000 tonne of WEEE

might have been imported into India for disposal and further processing (more recent data have not been found; Zoeteman et al., 2010; Breivik et al., 2014). It has to be considered that given the high complexity of the WEEE production, trade, and processing businesses, the high levels of informal and illegal e-waste transportation and disposal activities, and the increasing trend in global WEEE generation, these numbers may well be significantly underestimated.

However, with the help of stricter governmental regulations in Delhi, a crackdown on informal e-waste businesses has been initiated. There, the effort was made to reduce the number of informal e-waste businesses, to improve safety, and to mitigate the impacts on human and environmental health, which are associated with informal e-waste processing activities (Skinner et al., 2010). Nevertheless, instead of stopping the informal businesses, these were just trans-located to satellite towns, such as Saharanpur and Meerut, while the e-waste trade in the city continues (Waste Management World, 2011).

Figure 27 shows the possible formal, semi-formal, and informal paths of the e-waste trade within India. In addition, the graphic shows that while e-waste can originate from domestic e-waste production sources, such as private consumers, government institutions, industrial consumers, or manufactures, the largest amount of e-waste is imported from HICs. Furthermore, it can be seen that the different formal, semi-formal, and informal stakeholders involved in the trade and processing of e-waste are interlinked (Skinner et al., 2010). First (green path), the e-waste arising from formal sources is given to friends, donated to institutions or sold to responsible formal dismantlers/recyclers. Second (blue path), primarily for economic reasons, most semi-formal stakeholders act as a link between the formal and informal e-waste businesses by sending e-waste to informal dismantlers and recyclers. Third, the informal sector (orange path) is dismantling and processing e-waste or they are even involved in the informal extraction of valuable materials from e-waste (Jain, 2009; Skinner et al., 2010). It must be recognized that Figure 27 shows a simplified path of e-waste trades. In practice, the flow of e-waste is much more complex and more elusive, which makes it difficult to enact effective regulations and policies (Skinner et al., 2010). As described in the section **E-waste pollutants of environmental concern** (p.106), informal e-waste recycling is mostly responsible for causing severe problems to environmental and human health.

Best practices

The illegal trade on e-waste and the informal e-waste recycling businesses are significant cross-cutting issues on a global scale. Of all countries, the LAMICs are those with the highest e-waste burdens (Skinner et al., 2010; Lewis, 2010, 2011; International Labour Organization, 2012; Silicon Valley Toxics Coalition, 2014).

To mitigate the entry of highly toxic pollutants into the environment through e-waste disposal and processing initiatives, significant efforts are required to implement best practices for e-waste treatment. The introduction of sound management practices for e-waste businesses are required at local and international levels. To facilitate implementation of best practices and sound waste management, collaboration and communications between stakeholders from the electrical and electronic industry, governments, customs authorities, regulatory and environmental agencies, intergovernmental or non-governmental organizations and local authorities need to be strengthened. In addition, purchasers of EEE and civil society, in general, can support the production of greener and more sustainable EEE by purchasing electronic products with less toxic compounds or which do not contain recycled material from informal e-waste businesses. Alternatively, they can support internationally or locally certified e-waste campaigns (for instance the WorldLoop's e-Resource Certificate Programme (WorldLoop, 2013) or the Swiss e-waste program (Empa, 2009e) to promote the controlled and safe collection, processing, and recycling of e-waste (International Labour Organization, 2012). Details of already implemented and theoretical best practices for a more environmentally-friendly trade and processing of e-waste follow.

Implemented examples

Increased data transparency through the (Step) initiative

Solving the e-waste problem (Step) is an international initiative that was established in late 2004. To date, Step has over 60 members representing manufacturers, recyclers, academics, and government and non-governmental organizations committed to solving the increasing e-waste problem (Step Initiative, 2016a). The main objectives of this initiative are to (Step Initiative, 2014):

- conduct and share scientific research
- set strategies and goals to overcome the e-waste problem

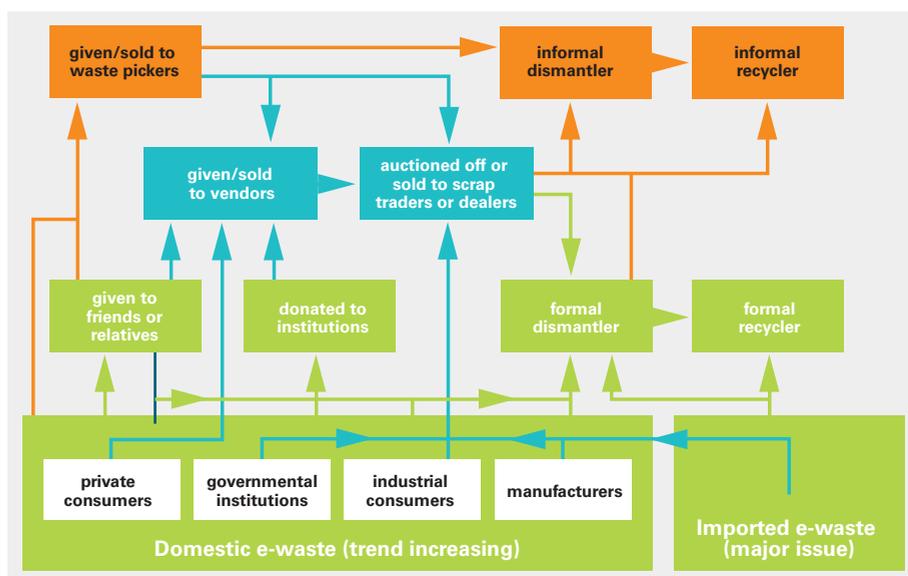


Figure 27: The formal (green), semi-formal (blue), and informal (orange) paths of e-waste flows within India (Skinner et al., 2010)

- provide training on e-waste issues
- communicate and raise awareness

To fulfill their aims, the members of the Step initiative they have to comply with five principles:

1. Their work is founded on scientific assessments and integrates a comprehensive view of the social, economic, and environmental aspects of e-waste
2. They conduct research on the entire life cycle of EEE by considering their global supply, processes and material flows
3. Their research and pilot projects are feasible approaches to the problems caused by e-waste
4. They reject all illegal activities related to e-waste, including illegal exports (shipments) and reuse and recycling practices that affect environmental and human health
5. They are eager to promote safe, eco-, and energy-efficient reuse and recycling practices on a global scale in a socially responsible manner

Their five core theme areas, which are described in more detail on the homepage of the Step initiative, are (Step Initiative, 2016b):

- Policy to analyze existing approaches and e-waste policies
- Redesign of EEE to promote design for better reuse, repair, refurbishment, and recycling
- Reuse to develop replicable, sustainable, and globally consistent reuse systems for EEE
- Recycle to enhance global recycling infrastructures
- Capacity-building to increase awareness of the growing e-waste problem.

For instance, in respect of their commitments to mitigate the e-waste problem, the Step initiative is compiling a world map with data about EEE that is put on the

market. It also provides information on the WEEE that is generated domestically in each country in kg/inhabitant or in total kilotonne (Figure 28), although, in general, the e-waste problem is hard to capture, mainly because of a lack of comprehensive data. These data are available to the public and they are helping to localize hot spots with e-waste problems. They are used internally and externally to find locations that generate large volumes of e-waste and where disassembling and processing programs for e-waste, or new state-of-the-art WEEE recycling facilities could be started. However, the amounts of WEEE that are exported illegally are not considered in the Step calculations, which may cause an underestimation of the amounts of e-waste accumulated and their associated environmental risks, mainly in LAMICs. During Step’s editing of the data it has defined EEE and WEEE according to the EU Waste Electrical and Electronic Equip-

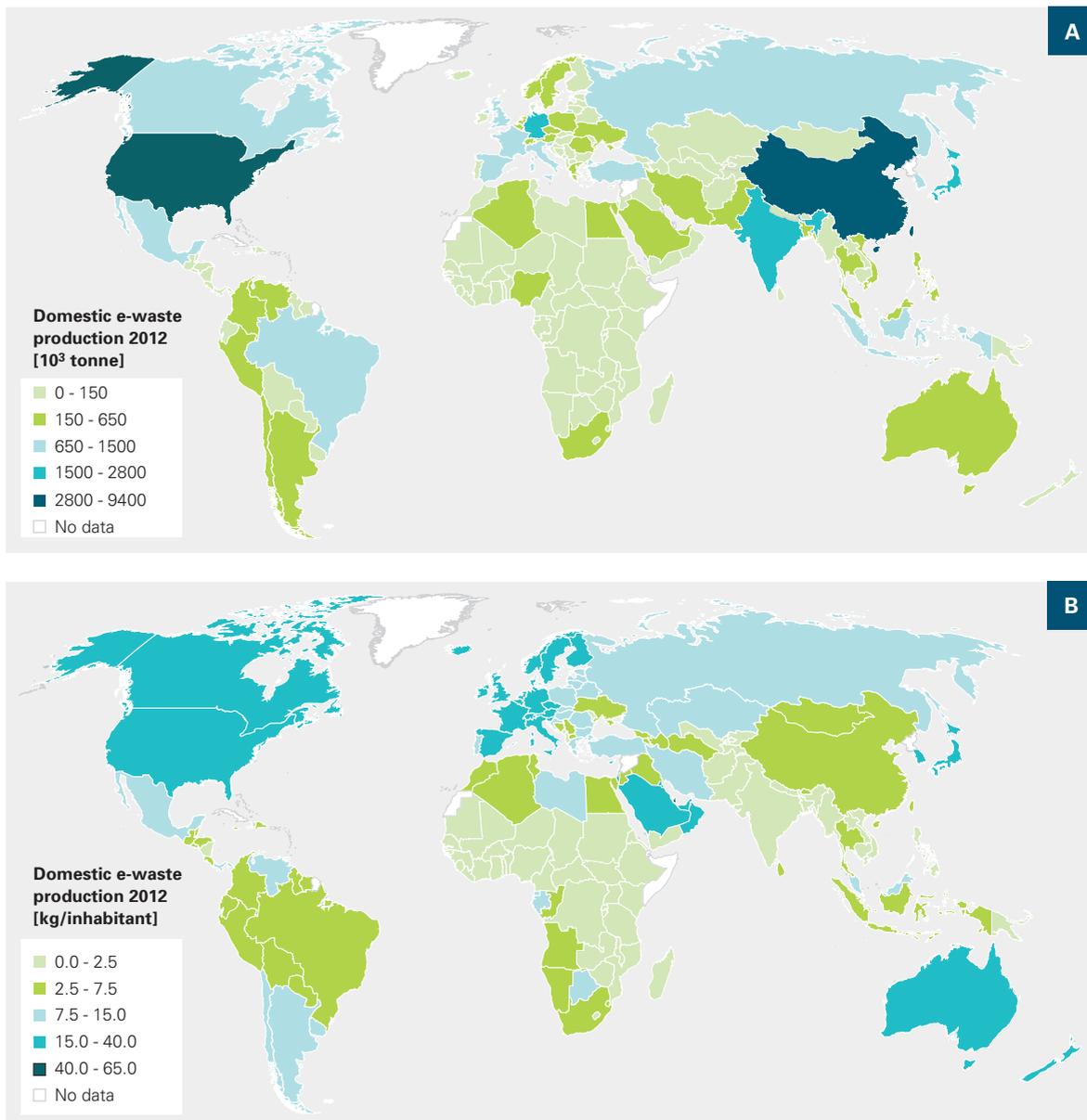


Figure 28: World map with domestic e-waste production in 10³ tonne (A) and in kg/inhabitant (B) for 2012 (Step Initiative, 2015).

ment Directive categories and products. Nevertheless, although there may be some uncertainties, its world map of e-waste production is unique and is the first data base to provide such comprehensive and international data, thus increasing the transparency of e-waste data (Step Initiative, 2015).

E-waste assessment methodology and implementation of dismantling programs

Since the 1990s, Switzerland was one of the first countries in the world to introduce a national e-waste management system. The Swiss Federal Laboratories for Materials Science and Technology (Empa) has established a good reputation for assessing the serious health, socioeconomic, and environmental problems caused by inappropriate e-waste disposal and rudimentary recycling practices. It has also developed solutions to mitigate these issues by finding and implementing an effective individualized e-waste management system. Since 2003, Empa, which has acted as one of the technical control bodies of the Swiss e-waste management system, is using and adapting the knowledge gained in Switzerland to the needs of LAMICs. Empa has taken part in several e-waste projects in Africa, Asia, and Latin and South America where they are trying to improve the living conditions of local residents, by helping to better manage e-waste streams and protect resources. The projects seek to improve the economic situation in general and to reduce the health risks to humans and the environment (Empa, 2009c).

For instance, after a detailed e-waste country assessment in South Africa, an e-waste processing facility was implemented in Cape Town. From February to November 2008, this facility was able to process around 60 tonne of WEEE, generated an income about USD14,000, and provided direct employment for 19 people (Empa, 2009d). Other projects on sound e-waste management where Empa has been engaged are described on the Empa (2009c) e-waste guide web page. Their latest projects were conducted in Brazil, China, Columbia, Kenya, Morocco, Peru, Senegal, South Africa, and Uganda.

From their extensive experience, Schluep et al. (2012) explain that pure technical implementation alone is often insufficient to enable sound e-waste management. This is the case, particularly, in LAMICs where legal and institutional frameworks and infrastructure are lacking and, therefore, e-waste management requires a comprehensive and well-structured approach. In order to understand the prevalent framework of conditions, the current e-waste regulations and legislations need to be compiled and an assessment made of stakeholders, mass flow, and the environmental and socioeconomic impacts. This requires

a country-specific e-waste assessment to be conducted. Along these lines, Schluep et al. (2012) have published a publicly available report, that explains their methodology of e-waste assessment. This report can be used as a reference for organizations that are interested in e-waste assessment projects enabling sound e-waste management. The report about their e-waste assessment methodology shows how to get results about the legal framework conditions, how to understand stakeholder interactions, the mass-flows of WEEE, and how to identify WEEE hotspots. This information will provide a comprehensive overview of the e-waste situation in a specific region for the relevant stakeholders. It will help to evaluate the potentials for employment or for possible improvements in the living condition of local people who are engaged in the e-waste business. The assessment of mass flow and other economic data are helpful when implementing appropriate business models for e-waste collection, processing, and recycling activities. In summary, their e-waste assessment methodology provides all the relevant information required for implementing a region-dependent e-waste management system (Schluep et al., 2012).

Besides Empa, other international organizations, such as the United Nations Industrial Development Organization (UNIDO), the United Nations Environment Programme (UNEP), the Basel Convention, the StEP Initiative, the Partnership for Action on Computing Equipment, the Swiss e-waste program, and Hewlett-Packard, are pursuing similar goals and they all apply the e-waste assessment methodologies of Empa and SOFIES SA (Schluep et al., 2012).

Improvements in WEEE collection and recycling practices

Improvements in WEEE collection and recycling practices are urgently needed. The LIFE + WEEE Label of Excellence (WEEELABEX) EU project was initiated to protect the environment by promoting sound e-waste trading and recycling practices in Europe. This project comprises the enactment of European standards with respect to WEEE collection, handling, storage, recycling, and disposal in compliance with EU health, safety, and environmental legislation. According to these standards, monitoring programs of processing companies will be started. The monitoring will be conducted by auditors, who are trained by the WEEELABEX office to ensure consistent monitoring approaches and that the same sets of standards are used for auditing. If the parties and companies involved in WEEE operations comply with the implemented standards of the WEEELABEX initiative they are awarded the project targeted conformity verification, referred to as

the WEEE label of excellence (WEEELABEX, 2013). With the help of this project, consistent and new standards for WEEE collection, storage, and processing, which are already becoming international benchmarks, were successfully developed within the EU. So far, about 30 companies have been awarded the WEEELABEX conformity verification. More detailed information about this initiative are available on the webpage www.weelabex.org/.

Development and implementation of greener technologies

The development and implementation of greener technologies leads to a reduction in the volume of WEEE produced. For instance, use of the EPEAT® global rating system, managed by the non-profit organization Green Electronics Council, Portland, Oregon, USA, helps purchasers (businesses, schools, hotels, hospitals, and governments), manufacturers, and others track down and offer environmentally preferable EEEs (Green Electronics Council, 2015). EPEAT® registered electronics meet strict environmental criteria. For instance, EPEAT® registered products use less environmentally sensitive materials in their manufacture, are designed for an increased lifecycle, consume less energy, and disposal of their WEEE products is managed soundly.

The Fairphone enterprise is another example how greener EEE can be supplied for end-users. Fairphone was started in 2010 as a project of the Waag Society, Action Aid, and Schrijf-Schrijf to increase awareness about minerals and the conflicts that are associated with the mining of these minerals in the Democratic Republic of Congo. Given the omnipresence of mobile phones, Fairphone is focusing on producing mobile phones that are designed to have a longer life and increased reparability. The source material originates from local economies and conflict-free mining sites and not from mining sites controlled by armed militias. In addition, properly recycled material is used in the production of the mobile phones. Furthermore, Fairphone guarantees that during production, the employees worked under fair and safe working conditions. Currently, they have 31 employees and they have sold about 50 thousand Fairphones (Fairphone, 2015).

Theoretical examples

Strengthening the regulatory framework and introducing attractive incentives

As described in the section **Lack of implementation of policies and regulations** (p. 122), implementing regulations alone is not sufficiently effective to improve occupational safety and to reduce the impacts on environmental

and human health. The example of the informal e-waste businesses in Delhi showed that strengthening regulations and prohibitions alone are not solving the e-waste problem. In the Delhi case, the informal businesses simply shifted from the city center to remote places and the informal e-waste recyclers continued their work using harmful and rudimentary recycling methods (Sinha-Khetriwal et al., 2005; Sinha et al., 2010; International Labour Organization, 2012). As long as informal e-waste businesses provide profit-yielding employment for many people in poverty, the informal activities will continue although such businesses are dangerous and life threatening ones. This is especially so when there are no attractive incentives available that promote and support formal e-waste recycling activities. People who are involved in e-waste businesses should be informed and further educated about the perils of working with e-waste and its impact on environmental and human health. Efforts are needed to mitigate occupational accidents and health risks by raising people's awareness about their work with hazardous compounds. Incentives need to be provided that will urge them to seek safer and healthier working conditions (Wang et al., 2011).

In general in LAMICs, it is necessary to raise awareness of the environmental and human health risks in businesses where hazardous chemicals are involved, such as informal e-waste dismantling and processing activities. It is equally necessary to enable the environmentally sound management of waste and chemicals and to guarantee improvements in occupational and environmental health. In addition, guidance and training for informal e-waste business to become more formal or to cooperate and integrate into the formal sector are important (just as it is the case for informal and small scale mining businesses described in the section **Theoretical examples** (p. 100). However, this will be challenging, especially as it is mostly uneducated people with low literacy levels, living in extreme poverty who are involved in informal e-waste processing and recycling businesses (Nimpuno et al., 2011; International Labour Organization, 2012; Rockson et al., 2013). Actually, there is evidence that informal e-waste recycling activities, although using rudimentary methods, are economically advantageous businesses and even out-compete formal recycling businesses mainly because of the lower costs of complying with the legislation and the possibility to externalize environmental costs. In comparison, recyclers of the formal e-waste sector have increased operating costs since they are paying contributions for the treatment of the wastewater they produce (Skinner et al., 2010).

Introducing financial incentives, such as funding the best recycling practices or giving grants for the sound management of wastewater effluents and the disposal of WEEE, could be a very effective method to reduce the use of informal e-waste processing and recycling practices for domestic e-waste and imported e-waste from HICs (Williams et al., 2008). Another possibility would be to provide financial incentives for transferring hazardous WEEE, which cannot be easily and safely disassembled and processed by informal businesses, to formal state-of-the-art businesses or, even better, to certificated end-processors using sound and controlled processing methods for e-waste. If the capacities for sustainable and sound e-waste processing techniques are available, such an integration of formal e-waste businesses at the international or national level would help to mitigate occupational and environmental health risks (Williams et al., 2008; International Labour Organization, 2012).

Better production processes through extended producer responsibility (EPR) and the green production of EEE

Eliminating informal e-waste businesses and the illegal trade in WEEE, and establishing and launching state-of-the-art e-waste processing facilities alone are not sufficient to mitigate the environmental and human health risks from e-waste pollutants. Mitigating these risks needs additional steps taken by the EEE production industry. For instance, during production, the use of highly toxic chemicals could be reduced or limited voluntarily, by governmental restrictions, or by finding substitutes that are less hazardous and easier to extract and recycle (International Labour Organization, 2012).

One approach in this direction is the Restriction on the use of certain hazardous substances (RoHS) Directive enacted in 2002 and modified in 2011 (European Parliament and Council of the European Union, 2011). This bans or restricts hazardous material in EEE for all products brought to market in Europe. For instance, according to the RoHS Directive, the use of metals and substances such as Pb, Hg, Cd, Cr(VI), polybrominated biphenyls (PBBs), and polybrominated diphenyl ethers (PBDE) are restricted in the casing of EEE and printed circuit boards. Nevertheless, despite the introduction of the RoHS Directive, the generation and release of highly toxic and carcinogenic pollutants, such as dioxins and furans, cannot be prevented (Williams et al., 2008). Electrical and electronic products produced in LAMICs, which contain recycled material from informal e-waste businesses, or obsolete and secondhand EEE from HICs being reused in LAMICs, still may contain higher amounts of hazardous compounds, possibly because of the lack of

controls and regulations in these countries (Weidenhammer and Clement, 2007; Chi et al., 2011; International Labour Organization, 2012). On a global scale, more efforts are necessary to reduce or abolish the use of highly toxic compounds like halogenated flame retardants and heavy metals such as cadmium and mercury. In future, more focus is needed to reduce the amounts of hazardous toxicants and compounds that are used in producing EEE. The production of easy-to-disassemble and recycle EEE needs to be promoted to mitigate occupational risks and to close gaps in the material flow system to avoid the release of highly toxic substances into the environment (International Labour Organization, 2012).

Furthermore, increased responsibility needs to be placed on the EEE production industry. Firstly, in the direction of sound waste management by the industry having to pay fees for the disposal and recycling of the products or wastes generated during their production. This would provide an incentive to produce EEE which contains less hazardous compounds and which is easier to recycle. Secondly, there should be increased responsibility for the EEE production sector for recycling materials in EEE at the end of the equipment's useful life. The manufacturers can reduce the amounts of virgin (primary) metals taken from the mining sector by initiating take-back and collection programs for WEEE. They can achieve this by setting up trade agreements with formal state-of-the-art facilities that implement an efficient, sustainable, and environmentally-friendly recycling of WEEE. Such waste related policies and initiatives are based on the EPR principles, which shift the responsibility from municipalities to producers by compelling producers to take financial responsibility for the disposal and recycling of their WEEE (Yu et al., 2006a). Additionally, closing gaps in the material flow cycle by improving the recycling of WEEE and by incorporating less hazardous compounds, secondary metals, or less scarce metals can lead to a mitigation of the exposure to chemical pollutants from both the e-waste processing and mining sectors.

In summary, the introduction of the RoHS Directive may help to reduce the amount of hazardous pollutants and consequently the impacts of WEEE on environmental and human health even before the WEEE is traded and disposed of inappropriately into the environment or during its recycling. Until now, this approach has been enacted only within Europe and no international directives and legislation with this focus have been developed yet. In general, the EPR approaches are supporting sound waste management of WEEE and they give incentives to reduce the amounts of WEEE produced and traded by the EEE industry. In conclusion, the regulations and approa-

ches of the RoHS Directive and the initiatives based on the EPR principles are promoting the production of 'greener' – more sustainable and eco-friendly – EEE products. They also promote the sound disposal and management of WEEE, but further agreements and approaches at the international level are required to enforce the greener production and disposal of EEE globally.

Green production of EEE and increased data transparency

Over the last years with the continuous development of technology, the life span of EEE has been showing a generally decreasing trend. This, along with the growing population and increasing living standards has resulted in a global increase in WEEE. For instance, the life span of a PC decreased from 4.5 to 2 years during the period 1992 to 2005 (Culver, 2005; Widmer et al., 2005).

Today, in the period of excessive informal e-waste processing and recycling and the resulting occupational and environmental health risks, the production of greener and more environmentally friendly EEE is needed to mitigate the negative impacts associated especially with these e-waste businesses (International Labour Organization, 2012). There are several criteria which have to be fulfilled to design green EEE. For example, the products should be carbon neutral and the GHG production should be as low as possible. They should be easy to dismantle, easy to repair and recycle, and their durability (lifespan) should be maximized. The use of toxic compounds and primary materials (e.g. metals and plastics) should be minimized or abandoned. In addition, efforts are needed to find solutions and technologies that go beyond our current dominant technologies. Production should actively engage the aims of local communities as well as those of the stakeholders, and the reuse of EEE should be fostered. Ultimately, initiatives for taking back obsolete equipment, for sound approaches to the management of e-waste, and appropriate state-of-the-art recycling technologies should be included to close the life cycle of EEE. Such initiatives would help to prevent the negative impacts associated with disposal and recycling practices for the end-of-life products of the EEE sector – much like a cradle to the grave principle (Greenpeace, 2011).

Fortunately, because of several environmental conventions, such as the Stockholm and the Basel Conventions (United Nations Environment Programme, 2013d; 2014) and the Strategic Approach to International Chemicals Management (United Nations Environment Programme, 2006b), the production industry is being put under pressure to improve its performance and provide and promote greener and more sustainable end-products to consu-

mers (Greenpeace, 2011). Along these lines, Greenpeace has published a 'Guide to Greener Electronics' which includes the ranking of 15 companies according to their energy efficiency, the sustainability of their operations, and their compliance with several additional criteria for the production of greener EEE. These additional criteria include whether they give information regarding:

- Their GHG production and if they have specific plans to reduce the emission of GHGs
- If they use clean energy and if their operations have a high product energy efficiency
- If they avoid hazardous substances during their production
- If they use recycled plastics
- If their products have a sustainable product life cycle (high durability, easily repaired).
- If they try to reduce energy consumption throughout the supply chain
- If they follow specific policies and practices for sustainably sourcing paper fibers and using conflict-free minerals
- If they implement effective voluntary take-back initiatives of WEEE.

Greenpeace determined that, of the companies tested, Hewlett-Packard (HP) best meets the criteria for greener electronics – the company scored 5.9 points out of 10. However, HP was awarded a very low number of points for their clean energy policy, for their product life cycle, and for the use of recycled plastic. HP is followed by Dell (5.1 points), Nokia (4.9 points), and Apple (4.6 points). These results show that although some efforts, initiatives, and improvements in production and in the provision of green technologies have been taken, further steps towards the production of sustainable and environmentally friendly EEE are required. In addition, data about energy consumption, product life cycle, and production, in general, are not transparent and difficult for the consumer to assess. Such data need to be more transparent and make it easier for the consumers to make decisions as to whether they are willing to support the development of green technologies or not.

At present, the main focus in the field of green technology is on reducing the use of hazardous compounds, not on

improving the efficiency of the product life cycle or other aspects, such as ease of disassembly or facilitating the recycling of EEE. The reason why green technologies are described in this chapter with the theoretical examples of good practices is that the practices used by the main companies are still not satisfactory (Greenpeace, 2011).

One innovative idea for end-products that are easy to assemble and upgrade is the Bloom laptop which has been developed by a group of students from Stanford University and Aalto University of Finland. This laptop can be disassembled by hand easily, individual parts can be easily replaced and upgraded, and any broken elements can be exchanged easily by the consumer alone (Bhobe et al., 2010; International Labour Organization, 2012). Another idea is the vision of the mobile phone of the independent organization Phonebloks. Their idea is to design a mobile phone encouraging the development and production of EEE that produces less electronic waste, is easy to upgrade, is recyclable, and has, therefore, an increased life span (Phonebloks, 2016). Their phones will consist of individual blocks with different functions e.g. different cameras, processors, displays, and so on. The idea is that consumers can design their own phones according to their own wishes and needs. In addition, Phonebloks want to provide a technology where consumers can upgrade or repair their phone by themselves by replacing just individual parts (blocks) instead of buying a completely new phone. This reduces the amount of e-waste produced and considerably increases the life span of these phones. While these are innovative ideas and there is some interest in these products by electronic companies, these products are not likely to be adopted soon (Bhobe et al., 2010; Phonebloks, 2016).