Tracking the global generation and exports of e-waste. Do existing estimates add up?

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Abstract

The transport of discarded electronic and electrical appliances (e-waste) to developing regions has received considerable attention, but it is difficult to assess the significance of this issue without a quantitative understanding of the amounts involved. The main objective of this study is to track the global transport of e-wastes by compiling and constraining existing estimates of the amount of e-waste generated domestically in each country M_{GEN}, exported from countries belonging to the Organization for Economic Cooperation and Development (OECD) M_{EXP}, and imported in countries outside of the OECD M_{IMP}. Reference year is 2005 and all estimates are given with an uncertainty range. Estimates of M_{GEN} obtained by apportioning a global total of ~35,000 kt (range 20,000-50,000 kt) based on a nation's gross domestic product agree well with independent estimates of M_{GEN} for individual countries. Import estimates M_{IMP} to the countries believed to be the major recipients of e-waste exports from the OECD globally (China, India and five West African countries) suggests that ~5,000 kt (3,600 kt - 7,300 kt) may have been imported annually to these non-OECD countries alone, which represents ~23% (17% - 34%) of the amounts of e-waste generated domestically within the OECD. M_{EXP} for each OECD country is then estimated by applying this fraction of 23% to its M_{GEN}. By allocating each country's M_{GEN}, M_{IMP}, M_{EXP} and $M_{NET} = M_{GEN} + M_{IMP} – M_{EXP}$, we can map the global generation and flows of e-waste from OECD to non-OECD countries. While significant uncertainties remain, we note that estimated import into seven non-OECD countries alone are often at the higher end of estimates of exports from OECD countries.

1. Introduction

Waste Electrical and Electronic Equipment (WEEE) and e-waste are the two more frequently used terms for discarded devices and appliances that use electricity. According to Robinson,[1] e-waste refers to discarded electronic goods (e.g., computers, mobile telephones), whereas WEEE additionally includes non-electronic appliances (e.g., refrigerators, air conditioning units, washing machines). A clear-cut distinction between e-waste and WEEE is difficult, if nothing else because of the increasing use of electronics (e.g., microprocessors) in electrical equipment.[1] By 2005, the United Nations Environmental Program (UNEP) estimated that the volume of e-waste was anticipated to increase by a minimum of 3-5% per year, which is nearly three times faster than the growth of municipal waste.[2]

The trade and transport of used electrical and electronic equipment (UEEE) and/or e-waste from developed to developing regions has received considerable attention.e.g. [3, 4, 5] The debate is often fuelled by the duality of the potential economic and environmental benefits versus the potential risks to environmental and human health posed by discarded and exported EEE. Viewed in a positive light, it has been argued that the international trade and donations of used electronic equipment facilitates an opportunity to bridge the so-called “digital divide”, i.e. the disparity between the adoption of information and communications technology (ICT) in developed and developing regions.[6] Secondly, export of UEEE and e-waste to less affluent regions also represents a reallocation of resources as repairable equipment, spare parts, raw materials and valuable metals (e.g. Copper), which generate substantial post-consumption economic activity.[7,8, 9] Retrieval of metals from e-waste in developing regions may also be environmentally beneficial as it reduces the need for primary extraction of metals from mining ores[10], while reuse of second-hand and refurbished EEE in developing countries has the potential to extend the life-time of products by reducing the rate of turnover in comparison to developed countries.[4]

E-waste is among the most complex and persistent of any wastes generated, which makes environmentally sound management labour intensive and therefore expensive in countries with high labour costs. Environmental regulation and enforcement in developing countries with lower labour costs is often too weak to assure environmentally sound management of e-waste.[11] Informal dismantling and recycling activities, however, increase the propensity for environmental releases of many hazardous substances from EEE[1, 12, 13] (e.g., metals[14-16], halogenated flame retardants[17-19], polychlorinated biphenyls [20, 21]), relative to when the product is intact[4] or disposed in well managed waste streams.[10] The transboundary movement of e-waste may even represent a significant vector for the (long-range) transport of toxic contaminants embedded in these products, which thus far appears to have been largely ignored in studies of global emissions, fate and transport of contaminants.[21] For example, it has been estimated that the import of PBDEs via e-wastes into China exceeds domestic production of brominated flame retardants by a factor of 3.5.[22] Finally, informal dismantling and recycling activities, such as open combustion, may lead to *de novo* synthesis of toxic compounds, such as various halogenated dioxins[23, 24] and polycyclic aromatic hydrocarbons (PAHs)[25], adding to the toxic burden.[26] Overall, discarded EEE represent both potential value and toxic waste[27, 28] which, according to NGOs, has left poor informal recycling communities with “an untenable choice between poverty and poison”.[3]

Numerous studies and reviews on e-waste are largely restricted to reporting scattered data on e-waste generation, exports and/or imports, with very few attempts to critically assess whether export and import estimates are reasonable and consistent. As a result, our quantitative understanding of transboundary movements of e-waste remains limited.[29] A notable exception is the study by Lepawsky and McNabb[28] who explored data from the COMTRADE database on licit trade of waste batteries and accumulators between 2001 and 2006. A key finding was that the global trade is not merely about exports of wastes from developed to developing regions, but that a significant part of the trade occurs intra-regionally. However, the authors recognized that their study merely addressed a single licit trade data category, which is neither representative of illicit transports nor other categories of e-waste. More recently, Zoeteman et al.[30] developed a tentative global inventory, including export-import matrices (or "source-receptor relationships") for four out of ten e-waste categories as defined by the European WEEE Directive.[31] While this represents a valuable step forward, their budget was restricted to defined regions rather than individual countries and contained limited attempts to evaluate the uncertainty of the resulting estimates.

The main objective of this study is to present a consistent mass balance of the global generation and movement of e-waste from OECD to non-OECD countries based on the compilation and analysis of existing data. We will restrict our analysis to data reflecting the middle of the last decade (reference year 2005) because of the enhanced availability of data in recent years, and focus on the uncertainties in the resulting mass balance. We believe that this quantitative approach will facilitate identification of some of the more critical knowledge gaps and offer a more nuanced perspective on the transboundary flows of e-waste to developing regions.

2 Methods

2.1 E-waste and WEEE

Due to the lack of a universal definition of e-waste and WEEE, we will consider (total) e-waste or WEEE as the sum of the ten categories reflected in the European WEEE Directive unless specified otherwise. Table S1 in the Supporting Information lists these ten categories and examples of equipment and products within each. These data may also serve as a reference to get an approximate idea about total tonnage of e-waste that could be anticipated whenever the scope of studies referred to is restricted to one or a few categories of e-waste alone.

2.2 Mass balance

The main objective was three-fold: (i) to estimate the amount of e-waste generated by countries for the reference year 2005 (2.2.1), (ii) to estimate the amount exported from OECD to non-OECD countries (2.2.2), and (iii) to map the global generation and movement of e-waste (2.2.3). The chosen static mass balance (or mass flow) approach was deliberately simple to facilitate transparency and comparability with available independent data.

The net amount (M_{NET} in kt) of e-waste (with imports and exports as gain and loss terms, respectively) processed annually in any given country is calculated as

$M_{NET} = M_{GEN} + M_{IMP} - M_{EXP}$ [Equation 1]

where M_{GEN} is the amount of e-waste generated domestically by its own population, M_{IMP} and M_{EXP} are the amounts of e-waste imported to and exported from the country. As we are interested in quantifying the amounts of e-waste exported to developing regions, we only quantify transports between OECD and non-OECD countries while transboundary movement of e-waste within a given region is ignored. To the best of our knowledge, there is no significant export of e-waste from non-OECD to OECD. In other words, M_{IMP} is considered to be zero for OECD countries and M_{EXP} to be zero for non-OECD countries. Accordingly, Equation 1 simplifies to $M_{NET} = M_{GEN} - M_{EXP}$ for OECD countries while $M_{NET} = M_{GEN} + M_{IMP}$ for those non-OECD countries which are implicated as recipients of e-wastes from OECD. Furthermore, we do not aim to distinguish between licit and illicit flows of e-waste, but focus on the quantities alone.

2.2.1 Domestic generation

It is difficult to rationalize export and import estimates if not considered within the wider context of the amounts of e-waste generated both domestically and globally. The first task was to estimate the annual generation of e-waste by country in 2005. One way to do this would be to compile historical data compiled by individual countries and jurisdictions through a bottom-up approach. However, compiling a global inventory of the annually generated amounts of e-waste from national data is difficult because, typically, data from different countries and jurisdictions are not coherently defined. For example, most studies carried out in North America tend to restrict the scope of e-waste to electronics alone while, in Europe, e-waste comprises both electrical and electronic equipment as reflected in the EU WEEE Directive.[31, 32] In many countries estimates of the historical generation of e-waste are also often not available or incomplete.[33]

Instead, we have chosen a top-down approach, whereby an estimate for the global generation of e-waste is distributed among countries using surrogate data, to ensure a comparable and consistent scenario. Our point of departure is the frequently cited estimate by UNEP from 2005 which states that *every year, 20 to 50 million tonnes of electrical and electronic equipment waste ("e-waste") are generated world-wide*.[2] We explore the average of this estimate (35,000 kt per year) as our default for the globally generated amount of e-waste, with 20,000 and 50,000 kt per year as our lower and upper bound estimates, respectively. We note that this estimate is not universally accepted as Robinson[1] suggested that the global e-waste production is at the lower end of this range.

In order to distribute the global estimate to individual nations, we took advantage of the often tight relationship observed between the generation of e-waste and key economic indicators, such as gross domestic product (GDP)[1, 34] which has given rise to the notion that e-waste is the "*effluent by the affluent*".[3] The tight relationship is exemplified in Figure S1, which plots the total number of cell phone subscriptions as a function of Gross Domestic Product (GDP), weighted for Purchasing Power Parity (PPP), based on statistical data for the year 2005.[35] GDP (PPP) as of 2005 was used as a proxy for distributing the UNEP estimate by country.

2.2.2 Imports and exports

A lack of reliable and relevant activity data, rooted in the often illicit nature of transboundary waste flows, makes it virtually impossible to accurately quantify the amount of e-waste exported from the OECD.[1] Such lack of knowledge may lead to significant underestimates of actual e-waste exports, and of illegal exports in particular, if one chooses a forward approach. An inverse approach was therefore selected, where data on national imports of e-waste to non-OECD countries (M_{IMP}) are collected and analyzed first. In the specific case of China for which more detailed data are available, the national estimate is derived from constraining data on amounts treated in major e-waste areas along with data on the number of workers involved in these regions and for China as a whole. The national import data are in turn compared with data or estimates on e-waste exports for OECD countries. In the latter case, export estimates (M_{EXP}) are typically derived as

$$M_{EXP} = M_{GEN} * f_{COL} * f_{EXP} \quad \text{[Equation 2]}$$

where f_{COL} is the fraction of the annual amount of e-waste generated which is collected for recycling, while f_{EXP} refers to the fraction collected for recycling which is exported to non-OECD countries rather than handled domestically. Data on f_{COL} and f_{EXP} were compiled from the literature. The fraction f_{COL} is a key consideration and can vary substantially among different categories of e-waste, as initiatives to promote collection and recycling are implemented over time.

2.2.3 Uncertainties and limitations

While our mass balance approach is deliberately simplistic, reflecting the lack of more accurate and reliable data, it has the advantage of generating estimates for M_{GEN}, M_{IMP} and M_{EXP} that can be compared with independent estimates from the literature. Our overall approach was designed to facilitate an evaluation of the consistency of estimates for M_{GEN}, M_{EXP} and M_{IMP}. Uncertainties in our top-down estimates of M_{GEN} can be evaluated through comparison with independently derived estimates of M_{GEN}, while independently derived estimates of M_{IMP} and M_{EXP} can be compared against each other. Whenever feasible, we present our own estimates as numerical ranges with default, maximum and minimum values, rather than as discrete and definitive numbers. The resulting estimates are all included in the SI to facilitate transparency and additional scrutiny.

As this study merely attempts to develop and discuss a static budget for the generation and transboundary movements of e-waste for the reference year 2005, it implies that certain dynamic features of the system we are assessing are ignored, i.e. potential delays between the generation of e-waste and actual disposal and recycling.e.g. [34, 36] An example is the temporary storage of e-waste by households, such as discarded cell phones and PCs in attics and basements.[37] Given the scattered data available on imports and exports of e-wastes in particular, data used for construction of the mass balance or comparisons herein are not necessarily reflecting our chosen reference year, but may refer to any year of the last decade.

3 Results and discussion

3.1 Generation of e-waste

M_{GEN} estimates for 182 countries based on a total global M_{GEN} of 35,000 kt per year, including upper and lower bound estimates, are presented in Table S2. In order to evaluate whether our top-down estimates for domestic generation of e-waste are reasonable, we compare our estimates with independently derived data for selected countries in Figure S2. We conclude that while it is often difficult to compare our top-down estimates with independent data as the latter may include a limited number of e-waste categories and/or different years, the evaluation indicates that (i) the average UNEP estimate of 35,000 kt/yr for global annual production of e-wastes in 2005 is generally supported by a comparison with independent data (Fig. 1), and (ii) GDP (PPP) can serve as a suitable proxy for distributing this number to individual countries. While there might be more accurate data available for individual countries and years than those considered herein, we are fairly confident that the "big picture" is captured in these top-down estimates, both in terms of overall amounts and their spatial distribution. As the empirical basis used for comparison in Figure S2 is limited, further refinement or optimization of our top-down estimate does not seem justified. In the following, the analysis and comparison of imports and exports with generated amounts will therefore reflect the average UNEP estimate (35,000 kt per year) as the basis for further evaluations.

3.2 Imports to non-OECD countries

While the analysis above indicates that our overall quantitative understanding of the generation of WEEE and its global distribution is reasonable, data on transboundary movements of WEEE across the globe are much more scarce and fragmented. Previous estimates of transboundary flows are also difficult to compare as data refer to different years, sub-categories of e-wastes etc. Nevertheless, as there are both independent estimates of imports and exports available, it is possible to assess whether our estimates and these existing estimates are consistent. We therefore start by summarizing available data on imports (to non-OECD countries), followed by derivation of our own estimates of exports, before trying to constrain and map the budget for transboundary movements of e-waste.

3.3.1 China

China is generally considered the largest importer and recycler of e-waste not only within Asia,[38] but globallye.g. [11, 39] and several focussed studies or reviews on e-waste in China have been published.[10, 39-42] E-waste imported to China is reported to arrive from US, Europe and other parts of the world[43] and Guiyu (GY), Qingyuan (QY), and Taizhou (TZ) are implicated as major e-waste recycling areas within China.[44]

Guiyu (23.3 N, 116.3 E) in the Chaoyang district, Shantou prefecture, Guangdong Province, South-Eastern China[45] has been claimed to be the major e-waste recycling site in China.[46] A large number of studies have been carried out in GY,[13] which has been receiving and recycling e-wastes since 1995,[47] purportedly from countries such as US and Japan.[25] It was reported that 550 kt of e-waste was processed in GY in 2004,[48] while other studies report that more than 1,000 kt of e-waste[49] or even discarded computers alone[45] is handled each year. Higher numbers have also been reported, ranging from 1,700 kt in 2007[50] and up to thousands of kilotons of domestically generated and imported e-wastes each year.[51, 52] The estimated number of workers involved in dismantling or processing e-wastes in GY varies from 30,000 – 40,000[53] to ~100,000[13] and even up to 160,000.[50] For the mass balance, we have adopted the median value of 1,350 kt/yr as our default M_{IMP} estimate for GY with ranges as presented in Table 1.

Qingyuan (23.4 N, 113.1 E), located approximately 50 km north of Guangzhou, is considered the second largest recycling area for e-waste in Guangdong Province, Southern China.[44, 54] According to Hu et al.,[55] e-waste recycling has a history of more than three decades, involving approximately 1,000 recycling sites and more than 50,000 workers, while Luo et al.[56] suggest that 80,000 workers are involved in dismantling and recycling within the two administrative towns, Longtang (TOC art) and Shijao. Estimated amounts of e-waste handled in QY varies from approximately 700 kt/yr[19] to 1,000 kt/yr[55] and up to 1,700 kt/yr,[56] and includes computers, printers, cables, TVs, transformers and other electrical equipment with most e-waste originating from overseas.[19]

Taizhou is located in the Zhejiang Province, East China (~28.5°N, ~121.5°E[20]), with Luqiao and Fengjiang among the major hubs. About 40,000 workers are said to be involved with 90% of the wastes originating mainly from Japan, the US, Western Europe and Russia.[57, 58] Other studies claim that as many as 50,000 workers are involved in dismantling activities in TZ.[59] The total amount of e-waste handled was 1,690 kt in 2005 and increased to 2,630 kt in 2009, according to Fu et al.,[60] while a study published in 2007 states that more than 2,200 kt of e-waste was being dismantled.[57] Recycling of transformers, capacitors and printed circuit boards has been conducted since the late 1970s / early 1980s in TZ[20, 60, 61] while computers, cables, cell phones, TVs, refrigerators and other domestic appliances have been imported since the 1990s.[60, 61] For this study, we have selected 1,690 kt/yr as both our default and lower bound M_{IMP} estimate, with 2,200 kt/yr as the upper bound (Table 1).

Total Import Based on literature data, the default estimate for the amount of e-wastes treated in GY, QY and TZ alone during the reference year 2005 is ~4,040 kt (2,940 kt – 5,900 kt) (Table 1), corresponding to 11.5% of the total amounts generated world-wide. Yet, it is clear that the recycling activities in China extend beyond these well-known localities in the Pearl and Yangtze river deltas.[39, 41, 62-65] According to Deng et al.[43] and references therein, more than 1,000 kt of e-wastes are imported into China annually, while Greenpeace in China has indicated that it could be as much as 35,000 kt.[66] As the data on imports or handling of e-wastes for China as a whole vary wildly (Table 1), they are less useful for deriving an estimate for the entire country. There are also convincing arguments suggesting that the higher end estimates e.g. [42, 66] for China are significantly overestimated.[67]

In GY, QY and TZ, between 120,000 and 290,000 workers are involved with an average estimate of 205,000 (Table 1). As many as 700,000 workers were employed in the Chinese e-waste recycling industry in 2007 with 98% in the informal recycling sector.[66] The total figure agrees well with numbers by Wang et al.[68] who recently report that 440,000 people are working in informal e-waste collection while the informal recycling industries additionally engages 250,000 people. Assuming 205,000 workers were engaged at GY, QY and TZ, the total amount of e-waste processed by the informal recycling industries in China (250,000 workers total) is scaled upwards to ~4,900 kt (~3,600 kt -~7,200 kt) for the reference year 2005. In comparison, our default estimate of M_{GEN} for China is ~3,300 kt (1,900 to 4,750 kt). If it is assumed that 40% of the e-waste generated domestically within China is dismantled by these informal recycling industries[53] (i.e., ~1,300 kt), the import of e-waste to China (M_{IMP}) is reduced to ~3,600 kt (~2,800 to ~5,300 kt) (Table 1). These numbers are at the higher end of recent estimates for the illegal import of e-waste into China, which was estimated to be between 1,500 kt/yr and 3,300 kt/yr[42] while the domestic generation of e-waste (PCs, printers, mobile phones, TVs and refrigerators only) was estimated at 2,200 kt in 2007.[69]

Our import estimate to China is almost an order of magnitude lower than an estimate of 28,000 kt/yr for 2010.[10, 42] According to Zhang et al.[10] this estimate is based on an annual global generation of e-waste of 40,000 kt[34], with 70% of all e-waste presently being processed in China, citing Robinson.[1] The fraction of global e-waste processed in China (70%) was attributed to a paper from 2006 by Liu et al.,[70] which is a case study on e-waste mass flows in Beijing reporting that 70% of obsolete appliances in the city could be collected for possible recycling (if convenient services existed). While the origin of this estimate (28,000 kt) is difficult to trace, it has been cited repeatedly in the literature[63, 71-73].

3.3.2 India

Geographically, most informal recycling activities in India take place within major urban centres (e.g. Delhi, Mumbai, Chennai, Kolkata and Bangalore), with some dispersal into smaller towns outside these major cities.[74] Considerable uncertainty remains regarding amounts of e-waste both generated and imported in India.[74] Yet, India has been suggested to be second to China in processing e-waste with 70% believed imported from abroad.[75] An early report from the organisation Toxics Link claimed that in 2003 most of the country's computer waste was imported, rather than generated domestically,[76] whereas a later report suggests that these two quantities are almost equal.[77] A frequently cited estimate of the import of e-waste into India by 2007 is 50 kt/yr[74, 78], but previous assessments in India appear to have a limited scope on e-waste from IT products and consumer electronics (PC, mobiles and TVs)[74] whereby data on heavier items and domestic goods may have been largely ignored in available inventories.[74] In contrast, Zoeteman et al.[30] suggest that the import of e-waste into India was much higher in 2005 (850 kt), but the empirical basis for this estimate appears limited. Data on the number of workers involved in e-waste recycling also differ between studies. Toxics Link initially proposed that more than 1 million workers are involved in manual recycling operations,[76] but the total number of people working exclusively on e-waste in the informal sector was more recently estimated at ~25,000.[74] Recognizing that major uncertainties remain and official data are lacking,[79] we have used the average of the two available estimates (450 kt/yr) as our default M_{IMP} estimate with 50 kt and 850 kt as the lower and upper bounds for India, respectively.

3.3.3 West Africa

Data for five West African countries (Nigeria, Ghana, Cote d'Ivore, Benin and Liberia) are summarized in a report prepared by the Secretariat of the Basel Convention.[80]

Nigeria The import of used electrical and electronic products (UEEE) into Nigeria was estimated at 600 kt in 2010 in the national e-waste assessment report. Of this amount, ~30% was not functional.[81] However, imported UEEE will most likely end up as e-waste in Nigeria, albeit with a time-lag. In other words, any UEEE is also counted as e-waste in this study. The same report suggested that the import of UEEE may have been higher by up to 70% in the recent past.[81] For this study, we therefore assume that the import of e-wastes into Nigeria during the reference year 2005 was higher by about 35% (M_{IMP} = 810 kt/yr) with 600 kt/yr and 1020 kt/yr as upper and lower bounds, respectively (Table 1). These data appear consistent with an earlier study, which estimated the import of used PCs and monitors alone to be ~77 kt/yr during the 2nd half of the last decade.[82] Informal recycling activities are believed to occur all over Nigeria, with 72,000 – 108,000 workers engaged.[81]

Ghana, Cote d'Ivore, Benin and Liberia The report on West Africa states that 150 kt of used EEE was imported to Ghana in 2009.[80] However, a report on e-waste in Ghana considered an accurate determination of the imported amounts impossible.[83] On the basis of the West African report, the amount of UEEE imported to Cote d'Ivore, Benin and Liberia are estimated to be 12 kt, 4.8 kt and 0.35 kt in 2009. These data do not allow for providing uncertainty estimates in Table 1.

3.3.4 Total imports

Quantitative information on imports of e-waste or UEEE to other non-OECD countries was not available for this study. However, several studies, including the two reviews by Li et al.[84] and Ongondo et al.,[33] have implicated additional non-OECD countries as importers. According to the former study, Kenya, Liberia, Senegal, South Africa and Uganda are additional destinations in Africa, while Cambodia, Malaysia, Pakistan, Philippines, and Vietnam are implicated as importers in Asia.[84] There are also individual reports discussing imports of e-waste to Thailand[85] and Bangladesh.[7] It is therefore likely that the actual imports to non-OECD countries as summarized in Table 1 are underestimated. Our final quantitative budget for total import to non-OECD is 5,023 kt (3,642 kt - 7,331 kt), which is 14.4 % (10.4% - 20.9%) of the default estimate for the global generation of e-waste or 23% (16.7% - 33.5%) of the e-waste generated within the OECD alone. The latter estimates form the baseline for comparison with export estimates.

3.4 Exports from OECD

Available estimates of transboundary exports of e-waste out of the OECD are highly variable and some of these figures have a way of taking on a life of their own.[4] For example, two studies independently claim that nearly 80% of all e-waste generated in developed countries is currently exported to developing nations,[10, 86] both citing Hicks et al.[87] Hicks et al., in turn, quoted an extensively cited report, published in 2002 by the Basel Action Network (BAN), in which it was claimed that 50 to 80% of the e-waste collected for recycling in the western USA is exported to Asia, of which 90% is destined for China.[3] Yet, the authors of the BAN report admit that nobody really knows the exact amounts of e-waste exported and that these figures are based on informed industry sources.[3] It is also important to stress that there is a significant difference between amounts generated and amounts collected for recycling. A study on the management and fate of major fractions of consumer electronics and IT/communications equipment in the US for the years 2003-2005[88] indicates that most of this e-waste was destined for domestic landfills, while approximately 20% was collected for recycling (f_{COL}, see Equation 2).[89] If combined with the BAN estimates for fraction exported (f_{EXP}) above, these data suggest that 10% to 16% of the e-waste generated annually in the US was exported with 5% - 12.8% destined for Asia. This estimate is in better agreement with a more rigorous material flow analysis of used computers alone in USA for 2010 for which it was estimated that between 6% and 29% are exported abroad for reuse and recycling.[90] The BAN estimate has also been questioned by the US International Trade Commission[91] and is contradicted by a recent study which suggests that the amount of used electronics (TVs, computers, mobile phones and monitors) exported abroad from the US to *any other* country by 2010 was 27 kt.[92] This represents 1.7% out of 1,600 kt of used electronics generated in 2010 - or only 3.1% of the amounts collected.[92] Still, the same research group found that 78-81% of used laptops exported from the US in 2010 were sent to non-OECD countries with Asia as the main destination.[93] However, the authors admit that approaches relying on trade data methodologies inevitably will tend to underestimate total exports.[93]

According to the European Environment Agency (EEA), between 8,000 and 10,000 kt of e-waste was generated in the EU in 2008. By extrapolating German data, the EEA estimated that between 550 and 1,300 kt of UEEE / e-waste was exported out of the European Union the same year which corresponds to between 5.5% and 16.3%.[94] A study from the UK in 2003 indicate a similar magnitude with an estimated 160 kt of e-waste exported in 2003[95], which corresponds to 12 % of the estimated amounts produced domestically in 2005 (1,385 kt).[34] Destinations included Eastern Europe, Africa (Nigeria, Uganda, Ghana and Kenya), the Indian sub-continent and other countries in Asia.[95] While less data is available for exports from OECD countries in the Asian region[5, 33], it has been claimed that more than a third of the Japanese e-waste is not accounted for.[4]

While controversy and uncertainty are likely to remain significant on the issue of exports from OECD to developing regions, these examples illustrate the notorious difficulties in assigning reliable export estimates to non-OECD countries using “forward” approaches. Although the scope of our analysis is restricted to the export from OECD to non-OECD countries, we reiterate that the assumption of uni-directional flows has been questioned by Lepawsky and co-workers[7, 28] as well as others[27] which highlights that the “trade and traffic” is not merely about transport from “rich” to “poor” countries, but that there are significant intra-regional movements.[28, 94] Adding to the difficulty of tracking flows is that many destinations are merely transhipment points.e.g. [92, 93] For example, some of the e-waste imported into China may arrive through Hong Kong, yet as much as 80% of selected household e-wastes (TVs, washing machines, air conditioners, refrigerators and PCs) generated in Hong Kong may be exported.[96]

Inferences about exports are sometimes made from analysis of formal trade data alone, while illicit flows are unaccounted e.g. [28] and it may be questioned whether formal trade data are representative for any flow of e-wastes. However, many of the import data for China and West Africa which are compiled and discussed herein (3.2) provide strong support for the notion that most of these imports originate from OECD countries, rather than being a result of intraregional flows within non-OECD regions. As there are additional non-OECD countries implicated as importers of e-waste not accounted for, the true exports from OECD to non-OECD regions could still be underestimated.

3.5 Global mass balance

Because of the large uncertainties in existing OECD export estimates, we assume that all OECD countries export the same fraction of domestically generated e-waste amounts (i.e., default $M_{EXP} = 0.23M_{GEN}$, range $0.17–0.34M_{GEN}$) (Section 3.3.4). A graphical representation of the final budget (default scenario) is presented in Figure 1. While it is estimated that OECD and non-OECD regions account for 62.4% and

37.6% of the total global generation of e-waste, respectively, our default estimate suggest that the net amount (M_{NET}) processed in the non-OECD region (51.9%) exceeds that within OECD (48.1%) because of exports from the latter to the former region. The results in Fig 1 furthermore suggests that the amounts generated in North America (24.3%) or EU countries members of the OECD (22.8%), are comparable with the amounts generated in other non-OECD countries (23%). However, the amounts imported (or exported) from other non-OECD countries remain unknown (Fig 1). The largest export from OECD in percentage of the total amounts generated worldwide is attributed to North America (5.6%), followed by the European Union (5.2%), Asia (2.0%) and other OECD countries (1.5%), while the largest import is estimated for China (10.3%), West Africa (2.8%) and India (1.3%).

As the import/export estimates are subject to uncertainties (Table 1), the outcome depends on the scenario selected. Under the minimum import scenario, OECD remains the dominant region for M_{NET} (52%), while both the default and maximum import scenarios indicate that M_{NET} is higher within the non-OECD region (Table S4). Furthermore, the net amount of e-waste processed in the non-OECD region (M_{NET}) is dominated by domestic generation (M_{GEN}) within that region, rather than by imports from OECD countries, irrespective of scenario (see also Tables 1 and S4).

In order to further visualize our results for the default scenario, we have prepared global maps for M_{GEN}, M_{IMP}, M_{EXP} and M_{NET} in Figure S3. In this study, the export estimates were derived using a simple inverse approach based on import estimates alone in order to fulfil the mass balance. Our mass balance for 2005 therefore relies on the critical assumption that all imports (Fig S3b) are caused by exports from the OECD-region alone (Fig S3c), which implies that the export estimates from OECD are biased high in this study in spite of e-waste imports to non-OECD possibly being underestimated.

3.6 Research needs

The merit and limitations of various qualitative and quantitative approaches to characterize transboundary flows of used electronics have recently been presented by Miller et al.[29] who point out that a mass balance approach is not the only potential methodology. Many of the assumptions made in order to construct the mass balance should also be considered with a healthy scepticism. Uncertainties in our understanding of global flows are likely to persist beyond this study because of the lack of data on illicit exports, which indicates that estimates of e-waste flows relying on official trade data alone is at risk of being biased low due to ignorance. Future studies seeking to quantify the export of e-wastes to developing regions should therefore aim to include all possible flows of e-wastes (both licit and illicit). The often illicit nature of such exports calls for complementary approaches to track the sources, flows and destinations of e-wastes,[29] such as by use of GPS-based monitoringe.g. [68, 97] as well as contaminant forensics and chemical fingerprinting techniques. Alternative quantitative approaches which could provide further insights into transboundary flows of e-waste include recycler and collector surveys and enforcement / seizure data from customs reports.[29]

There is an obvious need to develop scenarios for the current situation and into the future as the amounts of e-waste generated is still on the rise due to increased consumption, often combined with shortened lifespan of EEE.[10] While our analysis indicate that it is plausible that the global generation of e-wastes was 35,000 kt in 2005, new estimates indicate an increase up to 48,900 kt in 2012, which is predicted to increase to 65,400 kt by 2017.[98] A disturbing feature of the increase in e-waste generation, when seen in combination with the control measures being implemented in destinations like China,e.g. [60] is that future flows of e-waste may be diverted to less affluent countries or jurisdictions where costs related to environmental regulation are minimized[7, 28] unless exports are more efficiently controlled and curbed. It is therefore a need to monitor the possible extent, dynamics and magnitude of possible shifts in flows and destinations of e-waste. Clearly, rational control strategies will require a better understanding of how much e-waste, containing both valuable constituents as well as toxics, are circulating around the globe.

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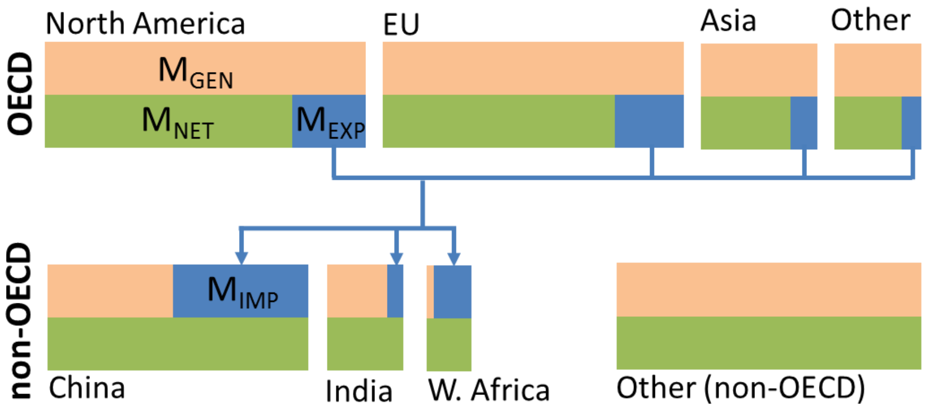
Table 1: Quantitative data on treated amounts (China), import of e-waste (India) or used EEE in either working or non-working condition (African countries) as adopted from the literature, along with import estimates derived for this study.

Country	Literature		This study (kt/yr)	
	Amount (kt/yr) (min-max)	Number of workers	Treated Default (min-max)	Imported
China (GY)	550 [48] - >2,000 [51]	30,000 [30] - 160,000 [50]	1,350 (550 - 2,000)	
China (QY)	700 [19] - 1,700 [56]	50,000 [55] - 80,000 [56]	1,000 (700 - 1,700)	
China (TZ)	1,690 [60] - 2,200 [61]	40,000 [58] - 50,000 [59]	1,690 (1,690 - 2,200)	
China (GY,QY,TZ)	2,940 - >5,900	205,000 (120,000 - 290,000)	4,040 (2,940 - 5,900)	
China (Total)	1,000 [43] - 35,000 [66]	250,000 [68]	4,900 (3,600 - 7,200)	3,600 (2,800 - 5,300)
India	50 [78] - 850 [30]	25,000 [74] - >1,000,000 [76]		450 (50 - 850)
Nigeria	600[1] [81]	72,000 - 100,800 [81]		810 (600 - 1,020)
Ghana	150 [80]			150
Cote d'Ivore	12 [80]			12
Benin	4.8 [80]			4.8
Liberia	0.35 [80]			0.35
Total for selected non-OECD countries				5,000 (3,600 - 7,300)

Figure 1: Graphical representation of the e-waste mass balance. The width of each box scales according to amount.



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