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Full length article

Improving WEEE monitoring: Insights from The Netherlands

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A R T I C L E I N F O

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A B S T R A C T

About 48 % of the generated Waste Electrical and Electronic Equipment (WEEE) in the EU gets informally treated. The Netherlands are comparatively successful at monitoring these informal End-of-Life (EOL) flows. We therefore take The Netherlands as a case study to examine what is known about their WEEE flows, why, and how to improve their WEEE monitoring. We develop and quantify a system model of Electrical and Electronic Equipment (EEE) and WEEE flows in The Netherlands for 2022. We quantify 16 out of 17 stocks and flows combining various data sources for The Netherlands and mass balance accounting. Quantification succeeds largely due to investments of the Dutch Producer Responsibility Organization in reporting on informal WEEE flows. The informal inflow remains unquantified. To improve WEEE monitoring we recommend focusing additional reporting on informal EEE inflows, WEEE in business residual waste, WEEE mixed with scrap metal, and used EEE exported for reuse.

1. Introduction

Global Electrical and Electronic Equipment (EEE or electronics) consumption increased by 50 % between 2010 and 2022, from 62 mega tonnes (Mt)/year to 96 Mt/year (Baldé et al., 2024). Meanwhile, the generated Waste EEE (WEEE) has almost doubled, from 34 Mt/year to 62 Mt/year (Baldé et al., 2024). By 2030 the annually generated electronic waste (e-waste) is expected to range between 75 Mt/year and 82 Mt/year and by 2050 reach up to 110 Mt/year (Baldé et al., 2024; Parajuly et al., 2019). The drivers for the rise in WEEE generation are multiple, and include, for example, rising affluence, shorter product lifespans, and perceived obsolescence (Awasthi et al., 2018; Boubellouta and Kusch-Brandt, 2021; Kumar et al., 2017; Makov et al., 2019; Makov and Fitzpatrick, 2021; Tröger et al., 2017). All this generated e-waste requires proper management, because WEEE contains many harmful substances (Ankit et al., 2021; Wu et al., 2024). If these substances leach out they can be damaging to human health and the environment.

At the same time, WEEE contains a large variety of metals and Critical Raw Materials (CRMs) (Buechler et al., 2020; Gómez et al., 2023; Korf et al., 2019; Nili et al., 2024). This makes it interesting for recycling (Gaustad et al., 2021; Kumar et al., 2017). For example, some metal concentrations in WEEE are similar or higher than concentrations in mined ores (Gaustad et al., 2021; Gómez et al., 2023). Metals recovered from secondary sources, such as WEEE, can have lower embodied emissions compared to metals obtained from primary raw materials (Broadbent, 2016; Chen et al., 2019; Hagelüken and Goldmann, 2022). Besides that, CRM production is currently concentrated in a few countries (Charles et al., 2020). Recycling can alleviate supply chain resilience concerns that come with that (Golev et al., 2014). As a result, there are many benefits to proper WEEE recycling.

Acknowledging this the European Union (EU) took up WEEE recycling into its Circular Economy Action Plan (European Commission, 2015, 2020) . Specifically, WEEE treatment in the EU is regulated by the WEEE Directive 2012/19/EU (European Union, 2012). It lays down goals for collection and processing of WEEE. The aim is to ensure that WEEE ends up with appropriate WEEE recyclers to maximize the recovery of valuable materials. As a result of these regulations about 52 % of generated WEEE in the EU in 2018 was recycled according to the rules of the WEEE Directive, also called formal recycling (Wagner et al., 2023). This is considerable compared to the global average of around 14 % formal WEEE recycling (Baldé et al., 2024). Nevertheless, 48 % of WEEE in the EU still ends up outside of the formal recycling system (Wagner et al., 2023). Further, Habib et al. (2022) find that collection rates can differ greatly between EU member states. Collection rates denote how much of the generated e-waste has been formally collected according to the EU directive and ranged from 76 % to 16 % in 2018 (Habib et al., 2022).

WEEE that is not collected by the formal collection system can follow

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various other, in part informal, End-of-Life (EOL) pathways. Knowing how much WEEE enters each formal or informal EOL pathway reflects a country's ability to account for their WEEE. WEEE accounting therefore encompasses more WEEE flows than just what is formally collected. This knowledge is crucial to get an overview over the entire stock and flow system of EEE. It enables further research and informs policies and campaigns to achieve the goals of the WEEE Directive (Habib et al., 2022). Ultimately WEEE accounting thus informs policies that enable the circular economy and increase raw material supply chain resilience.

Accounting efforts can generally be divided into national studies and European studies. National studies were, for example, undertaken to quantify WEEE in Irish scrap metal recycling (Ryan-Fogarty et al., 2021) or WEEE flows in Belgium (Huisman, 2013). European level studies provided data on WEEE scavenging (Magalini and Stillhart, 2019) and exports (Baldé et al., 2016). Habib et al. (2022) highlight that the ability to account for different EOL WEEE flows in European countries varies significantly, with 26 of the 30 studied countries showing a considerable data gap between generated WEEE and accounted for WEEE. The main issues were underreporting of flows, i.e. the accounted-for WEEE does not sum up to the generated WEEE, or even a lack of data on flows. For example, in 7 countries all flows are reported, yet there is still a gap, which indicates underreporting in one or more flows. In 12 countries information on the flow of WEEE in scrap metal recycling was absent, while in 6 countries information on WEEE in scrap metal recycling as well as WEEE export was missing. WEEE accounting thus needs improvement to inform effective policies that reduce informal and increase formal collection.

The only country in the study of Habib et al. (2022) with no gap between generated and accounted for WEEE are The Netherlands. Therefore we select The Netherlands as a case study and analyze what is known and quantifiable about the Dutch electronic stock and flows, and why. We assess what information is still missing and what recommendations can be derived to improve future WEEE accounting efforts. The insights are intended to inform policy makers and researchers about the reasons why WEEE accounting is rather successful in The Netherlands and to produce recommendations that guide future data collection efforts intended to improve WEEE accounting and ultimately formal WEEE collection in Europe and beyond.

For this case study we first establish a material flow model of EEE in The Netherlands at the national level, that covers the lifecycle stages of electronics from entering the market to their EOL collection. We then parse through the model and analyze which sources are available to quantify each stock and flow. We give preference to publicly available sources over own calculations to show the current state of knowledge. Then we reflect on the results and the available sources. Ultimately we make concrete recommendations how to improve WEEE accounting in the future.

2. Material and methods

2.1. Descriptive model

We first create a descriptive model of the Dutch electronics system (Fig. 1). The model reflects the stocks and flows associated with electronics that are purchased, used and discarded by households and businesses in The Netherlands in 2022. This means we consider all WEEE that was produced within the system boundary of The Netherlands. The modeled system starts with the electronics being placed on the market (POM) i.e., sold, irrespective of whether they have been imported or domestically produced. The POM is thus equivalent to EEE entering the use-phase in the Dutch economy. EEE that only transits through The Netherlands for sale in another country is not part of the model's inflows, because it is not used in The Netherlands. The model ends with WEEE collection. Further processing steps may take place within The Netherlands or abroad, but are out of scope, because our study focuses on national WEEE monitoring. Electronics which are reused and refurbished for use in The Netherlands are considered part of the in-use stock. Electronics which are reused abroad are covered in the legal export for reuse flow.

The stocks are measured in kilo tonnes (kt) and flows in kt per year (kt/year). Both include all electronics covered by the EU WEEE Directive (Directive 2012/19/EU, 2012). We aggregate all flows to the national total to enable an overview of the system and harmonize different categorization systems of the various sources.

In the absence of a standardized format for modelling EEE and WEEE flows, we developed our own MFA system model (Fig. 1) using literature to identify the relevant processes of the Dutch electronics system (Baldé et al., 2020; Forti et al., 2020; Habib et al., 2022; Huisman et al., 2012, 2015; Parajuly et al., 2017). At the center of the model is the stock of EEE in Dutch households and businesses. This is where electronics accumulate in society. All products, whether in use, unused (hibernating), or broken but not discarded are included in this stock, in line with Hopstaken and van der Maesen (2023) from which we derive stock information. A product is only considered an outflow and thus WEEE once it has been discarded. The stock size is important to estimate future outflows.

To increase the detail of our resulting system model we disaggregate four flow groups (POM inflow, formal collection, informal collection, exports) into their constituents.

We disaggregate the POM inflow into products that are formally and informally placed on the market (black inflows in Fig. 1). The formal inflow refers to EEE that was registered as POM and for which the EU's Extended Producer Responsibility (EPR) fee is paid (Forti et al., 2018). The informal inflow refers to product sales of companies that use channels such as cross-border shipping that do not involve paying the EPR fee. This is also called free riding and creates an unfair competitive

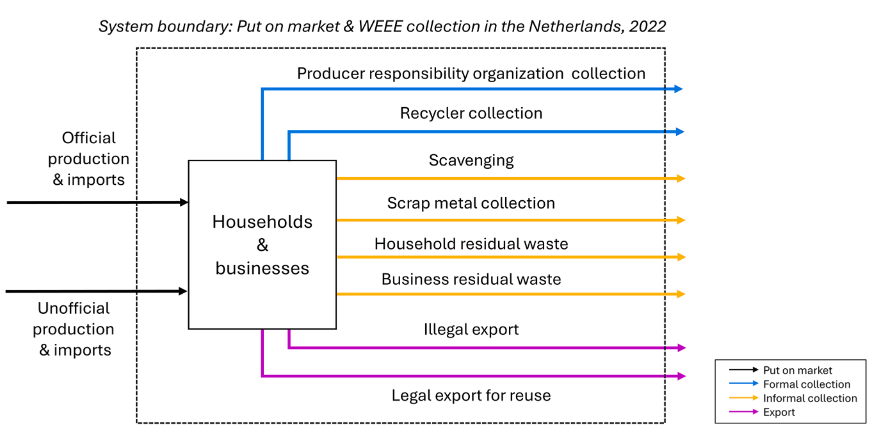

Fig. 1. Descriptive stock and flow model of the Dutch electronics system in 2022.

advantage (OECD, 2018).

We disaggregate formal WEEE collection into collection by the Dutch Producer Responsibility Organization (PRO) called Stichting OPEN as well as collection by recycling companies directly (orange outflows in Fig. 1).

The informal collection flow is also called complementary or non-compliant recycling (blue outflows in Fig. 1) (Baldé et al., 2020; Gonda et al., 2019; Huisman et al., 2012). It reflects collected WEEE that does not count towards the EU WEEE recycling goals, because it is not recycled according to EU standards (WEEE Forum, 2020). We disaggregate this flow into its constituent parts of WEEE in 1) scrap metal recycling, 2) residual waste from households, 3) residual waste from businesses, and 4) scavenging (Habib et al., 2022; Wagner et al., 2023).

Lastly, we differentiate the group of export flows into legal export of used EEE (UEEE) for reuse and illegal WEEE export (purple outflows in Fig. 1). Often WEEE export takes place under the guise of reuse but is, in practice, processed by uncertified or artisanal recyclers abroad. The export of UEEE for reuse is legal, but export of WEEE is illegal (Geeraerts et al., 2015; Inspectie Leefomgeving en Transport, 2023).

2.2. Data source selection

We use the descriptive model to identify which data sources are available and best suited to quantify each flow and stock data point. In total we identified nine key data sources from scientific papers, gray literature, and official monitoring activities and statistics to quantify these stocks and flows (Table 1).

We selected data sources based on a preference order. The highest preference was given to recent data sources that measure physical flows through sampling in The Netherlands. Where this was not available we used older sources reporting on The Netherlands containing flow ratios which we can apply to current data. The lowest preference is given to data sources which report on other regions.

2.3. Quantification and mass balancing

The stock and the five flows of official production and import, OPEN collection, WEEE in household residual waste, and legal UEEE export are taken directly from the sources.

We estimate six flows and the net addition to stock based on the collected data. WEEE in business residual waste is calculated by multiplying the share of WEEE found in the samples with the total generated residual waste from businesses (1).

$$WEEE_{business\ residual\ waste} = residual\ waste_{business} \times \%_{WEEE} \tag{1}$$

To calculate scavenging we use the scavenging rate per inhabitant provided by Habib et al. (2022). Then we multiply the rate with the number of inhabitants in The Netherlands in 2022 (2).

$$WEEE_{scavenged} = \frac{WEEE_{scavenged}}{inhabitant} * Population_{Netherlands} \tag{2}$$

The flows of WEEE in scrap metal recycling, and illegally exported WEEE are estimated using mass balance accounting, as the sum of all outflows must be equal to the total generated WEEE. The yearly generated WEEE in The Netherlands is estimated and reported to the EU by the Dutch National WEEE Register (NWR), following the Common EU Methodology (European Commission, 2017). This method estimates annual WEEE outflows by combining mandatory yearly POM data reported by electronics producers and importers with a Weibull survival curve. The inflow of unofficial production & imports remains unquantified due to a lack of data. It is also not possible to quantify the inflow using mass-balance, because two flows, informal POM and net addition to stock, are undetermined.

To estimate WEEE mixed in scrap metal and illegally exported WEEE we assume that our model quantified all outflows of the stock, except these two. We then perform a number of calculations to arrive at an estimate for each flow. For that we use the same approach as Baldé et al. (2020). We first quantify as many flows as possible. The sum of all quantified flows is called $WEEE_{accounted\ for}$ because our model accounts for this mass (3). Next we subtract the $WEEE_{accounted\ for}$ from the $WEEE_{generated}$ resulting in the $WEEE_{unaccounted\ for}$. We assign 84 % of $WEEE_{unaccounted\ for}$ to WEEE in scrap metal recycling (4). The splitting ratio comes from Huisman et al. (2012). Their research showed that 84 % of the unaccounted for WEEE flows in The Netherlands likely end up

Table 1
Overview of stock and flow groups and names plus data sources used to quantify the model. Unquantified flows are marked with a dash. Three flows are calculated using mass balance accounting.

Group	Name	Short description	Data source
POM	Official production & import	Products sold by companies that are complying with the EU EPR rules.	NWR (2023)
	Unofficial production & import	Products sold by companies which are not complying with the EU EPR rules.	-
	Stock	The in-use stock of EEE in businesses and households.	Hopstaken & van der Maesen (2023) , Oudshoorn (2023)
	Net addition to stock	The net change in stock in a given year based on the sum of inflows minus the sum of outflows.	Mass balance accounting
Total WEEE generated		The sum of all WEEE generated in The Netherlands in 2022 irrespective of the collection stream.	NWR (2023)
Formal collection	Total formal collection	Sum of collection by Stichting OPEN and recyclers.	NWR (2023)
	OPEN collection	WEEE collection through the official channels and logistics network of Stichting OPEN.	Stichting OPEN (2023), Oudshoorn (2024a)
	Recycler collection	Some recyclers have separate agreements with WEEE collectors.	Stichting OEPN (2023)
Informal collection	Scavenging	Removing of products or components from WEEE headed to recycling.	Habib et al. (2022)
	Scrap metal recycling	WEEE that is not recycled according to the WEEE Directive.	Mass balance accounting, Huisman et al. (2012)
	Residual waste – households	WEEE discarded by households in the residual waste system.	Leenaars (2023)
	Residual waste – business	WEEE discarded by businesses in the residual waste system.	De AfvalSpiegel & Witteveen+Bos (2023)
Export	Illegal export	WEEE that was exported to another country where it was not processed according to the EU WEEE Directive.	Mass balance accounting
	Legal export for reuse	Functioning EEE that is exported to third countries for reuse. Leaves the Dutch stock, enters the receiving country's stock.	NWR (2023), Assumption by authors, Baldé & van den Brink (2020)

in scrap metal recycling.

$$WEEE_{accounted\ for} = \sum WEEE\ flows_{quantified} \tag{3}$$

$$WEEE_{scrap\ metal\ recycling} = \left(WEEE_{generated} - WEEE_{accounted\ for}\right) \times 84\% \tag{4}$$

Assuming that we have accounted for all other flows we assign the remaining 16 % of $WEEE_{unaccounted\ for}$ to illegal WEEE exports. Additionally, Baldé et al. (2020) mention that between 20 % to 30 % of UEEE export for reuse is actually illegal WEEE export, because products are broken. To account for this we subtract 25 % of our assumed UEEE export for reuse flow and add it to the illegal WEEE exports flow (5). We therefore assume that actual UEEE exports are 75 % of the reported flow (6).

$$WEEE_{illegal\ export} = \left(WEEE_{generated} - WEEE_{accounted\ for}\right) \times 16\% + UEEE_{reported\ export} \times 25\% \tag{5}$$

$$UEEE_{exported} = UEEE_{reported\ export} \times 75\% \tag{6}$$

The reported values for UEEE export varied considerably by source. The lower end is based on company reporting to the National WEEE Register (NWR)(2023). However, the report states that this is likely an underestimate of real UEEE exports. The upper end stems from a study by Baldé and van den Brink (2020) on Dutch UEEE exports in 2018. Their results are six times higher than reported UEEE exports from the NWR. We therefore estimate a third UEEE export flow. Our estimate is based on historic estimates of UEEE exports between 2019 and 2021 (NWR, 2023). For their estimates the Dutch Central Bureau of Statistics (CBS) uses trade statistics and price data (NWR, 2024). They provide an estimate for 2022 as well. However, this estimate suggests about a 50 % decrease in UEEE exports to the previous year, which the report authors deem unlikely, as they suggest that they likely underestimate the flow. We therefore extrapolate the historic data from 2019 to 2021 to 2022 instead of using the estimated value from the CBS. This results in an estimated UEEE export for reuse of 20 kt/year. We consider this the most likely scenario, because it aligns with the historically estimated trends (NWR, 2023).

To account for the three possible UEEE export flows we create three UEEE export scenarios. In each scenario we calculate the mass balance using a different value for UEEE export. First we use the reported quantity of UEEE to the NWR, then we use our own estimate based on the historic extrapolation mentioned above and lastly we use the estimate of Baldé and van den Brink (2020). As a result we present the quantities of WEEE in scrap metal and illegally exported WEEE as ranges. This reflects the varying export for reuse quantities.

2.4. Data source characterization

Lastly we analyze four pieces of meta-information of the data sources. First we look at the type of publication, i.e. a report, an academic publication, national statistics. Then we assess the authorship. Next we determine the commissioner that requested the data. Finally, we look at the reporting interval of each source to evaluate whether this data is generated regularly or not. The results allow us to devise recommendations how to set up structural reporting on WEEE flows to improve WEEE monitoring, enable dynamic MFA studies on informal WEEE flows, and ultimately increase formal WEEE collection.

3. Results

Combining academic and grey literature with mass balancing, we are able to quantify 16 out of 17 stocks and flows of the Dutch EEE and WEEE system (Fig. 3). The missing flow is the inflow of products informally placed on the market, for which no data reporting or methods to calculate were found. To indicate this lack of data we leave the inflow unquantified in Fig. 3. To still allow the use of mass balance accounting in downstream flows, we set the informal inflow to be zero, reflecting a simplified assumption that it is marginal compared to the formal POM. This means that the net addition to stock, scrap metal collection, and illegal export are minimum estimates.

The results of our mass balance calculations show that previously unreported WEEE mixed with scrap metal ranges between 89 and 110 kt/year. In 2022 Stichting OPEN conducted a takeback scheme that compensated metal recyclers for redirecting WEEE from their facilities to certified WEEE recyclers. This redirected 42 kt/year of WEEE from scrap metal recycling, to the formal collection stream (Oudshoorn, 2024b). In the scenario we consider most likely thus 55 kt/year of WEEE remain mixed with scrap metal, after deducting WEEE collected from the takeback scheme.

We furthermore quantify the previously unknown flow of illegal WEEE exports, which we estimate is around 16 kt/year, with differences between the scenarios being around 1 %. Table 2 shows the results of the balancing item flows under each of the three UEEE export scenarios. For detailed calculations of each stock and flow see the supporting information.

3.1. Characterizing the data sources

We assess the type of source material, the authoring organization, the commissioner and the reporting interval for each stock and flow in Fig. 2. A large majority of the sources are reports or internal data from the PRO. Similarly most sources are written by the PRO, with consultants and academic researchers accounting for only 32 % of the authorship. The sources were most often commissioned by the PRO while the remaining commissioners account for 32 % of the sources. Lastly, 10 data points are collected annually while the remaining 9 are from one-time studies.

4. Discussion

4.1. Possible implications of missing data on informal inflows

The informal inflow of products could not be quantified, because there are no reported mass flows nor methods to estimate this flow. Therefore its shares of the total POM in The Netherlands, stocks, and end-of-life flows are also unknown.

While there are no data for The Netherlands a report from the UK estimates informal inflows to be 5 % to 10 % of the official inflow (Sayers and Peagam, 2020). For The Netherlands this would mean an additional inflow of 41 kt/year to 83 kt/year of EEE in 2022. This would be similar mass flows as WEEE in residual waste from businesses (40 kt/year) or all WEEE mixed with scrap metal before the takeback scheme effect (91 kt/year). The transferability of these results, however, is difficult because the countries experience different economic circumstances. For example, The Netherlands are in the European Single Market and the UK are not. As a result the legislation on importing of goods differs and The Netherlands also have an “open” border with their neighboring EU member states. Due to these differences we decide not to assume the same informal POM estimates as Sayers and Peagam (2020).

Table 2
Scenario variations of UEEE export and the effects on mass balance estimated outflows in The Netherlands in 2022. 25 % of export for reuse are assumed to be WEEE and thus count towards illegal exports instead (Baldé et al., 2020). Scrap metal recycling shows mass ending in metal recycling after deducting WEEE collected through the takeback scheme.

Scenario	Scrap metal recycling (kt/year)	Illegal export (kt/year)
5 kt/year UEEE export	68	14
20 kt/year UEEE export	55	16
30 kt/year UEEE export	47	16

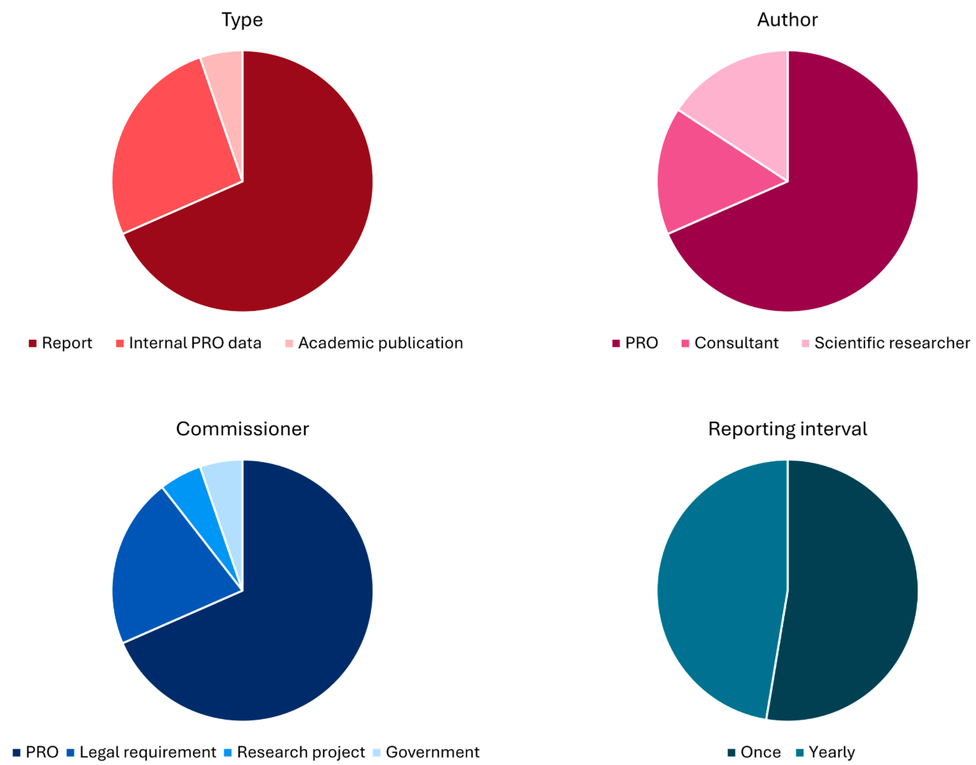

Fig. 2. Overview over document type, initiator and reporting interval for each quantified stock and flows. The underlying data for this figure can be found in the supporting information. PRO is Producer Responsibility Organization.

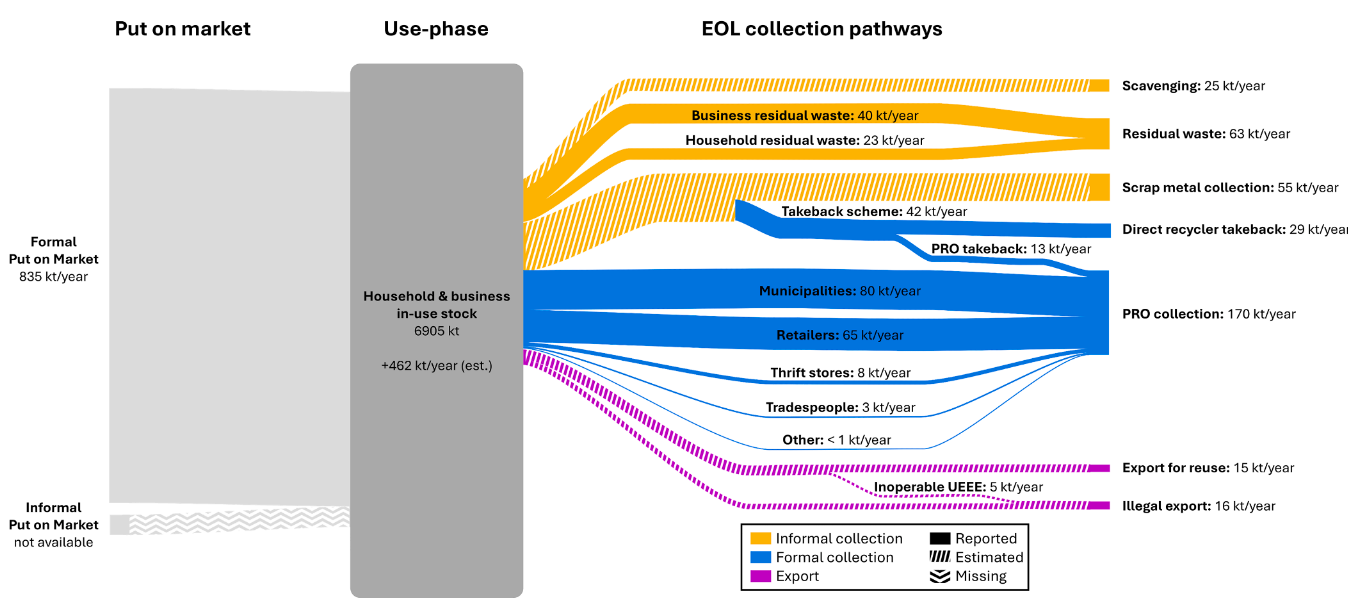

Fig. 3. Quantified stocks and flows and quantification method of the Dutch electronics system in 2022. The informal put on market flow is unknown, thus the net addition to stock, scrap metal collection, and illegal export are minimum estimates. UEEE is Used Electrical and Electronic Equipment, PRO is Producer Responsibility Organization.

Even if we assumed the informal inflow share to be 5 % to 10 % in The Netherlands in 2022, this would not affect the results. This is because of the static snapshot of our MFA model. The inflows in 2022 enter the use-phase. Thus they will not become WEEE for some time. To account for informal POM outflows, we would need informal inflow data from the previous years to be represented in the generated WEEE flow in 2022. However, we did not come across this data during our research. If future studies want to consider the generated WEEE from informal inflows, this data or methods to estimate past informal inflows need to be developed immediately.

If data on informal inflows over time were available this would affect our stock and several EOL flow estimates. Firstly, the generated WEEE would increase, because a country's generated WEEE is calculated based on POM data and estimated lifetime curves (European Commission, 2017). If more WEEE is generated then all flows that were calculated using mass balance accounting will increase. Therefore, our estimates for illegal export and WEEE in scrap metal recycling are lower estimates. Similarly, stock estimates based on POM data and lifetime curves would be underestimated. Overall this means WEEE ending in informal EOL pathways may be underestimated and thus not used in the circular economy. Nevertheless, studies and expert opinions suggest that informal inflows are small compared to formal inflows (OECD, 2018; Sayers and Peagam, 2020). Therefore, we expect that the effect on our model results would also be small, though their ratios may increase in the future. In 2023, a major new web shop was launched in The Netherlands (Hall, 2023). At the same time the e-commerce market is growing and customers increasingly turn towards cross-border shipping websites (Reid, 2024). This could suggest a potential increase of the informal inflow of EEE in the coming years.

4.2. Reflecting on scrap metal recycling and illegal export

Previous research has estimated WEEE in scrap metal recycling in The Netherlands to be around 110 kt/year in 2010 and 100 kt/year in 2018 (Baldé et al., 2020; Huisman et al., 2012). This corresponds to 38 % and 30 % of WEEE available for collection respectively. In comparison, our most likely scenario estimates 97 kt/year or 28 % of WEEE available for collection is mixed with scrap metal. The takeback scheme of Stichting OPEN reduced this by 43 %, suggesting a considerable effectiveness. Therefore, we expect that ultimately about 55 kt/year of WEEE ended up in metal recycling.

The takeback scheme results establish a bottom line of WEEE in scrap metal recycling. Our estimated flow mass lies between this lower threshold and the historic values taken from Huisman et al. (2012) and Baldé et al. (2020), which gives us confidence in our estimate.

One possible reason for the slight reduction of WEEE in scrap metal recycling could be the increased use of plastics in EEE (Bill et al., 2019). This reduces the WEEE's metal content and thus makes it less attractive for metal recyclers. Yet, the absolute amount of EEE increased over time (NWR, 2023). This makes it difficult to foresee trends of WEEE in scrap metal recycling.

Our results indicate an increasing trend of illegal export compared to an estimated 8 kt/year to 14 kt/year in 2010, and 12 kt/year to 20 kt/year in 2018 (Brink et al., 2021; Huisman et al., 2012). Formal collection, however, has dropped since 2021(NWR, 2023), likely due to the COVID pandemic. At the same time generated WEEE steadily increased since 2018. The rising illegal export suggests that with growing WEEE generation and lower formal collection rates an increasing part of WEEE is illegally exported. From a policy perspective this is a challenge, because illegal export is a difficult flow to affect for authorities due to its clandestine nature, and because the WEEE leaves their sphere of influence.

4.3. Reporting on informal flows

The results show that most data sources that were used for this research are either mandatory reporting according to the WEEE Directive or reports commissioned by the Dutch PRO and a result of EU requirements. The reports commissioned by Stichting OPEN are especially useful for accounting of the Dutch WEEE flows, because they provide data on stock and flows for which no reporting is required by the WEEE Directive (European Commission, 2024), such as the EEE stock, UEEE exports, and the informal outflows of WEEE in residual waste from households, and WEEE in scrap metal recycling. These additional datapoints allow us to fill in data for the informal flows of our system model. This then reduces the number of unknown mass flows that we have to estimate with mass balance accounting. Overall this results in less assumptions on flows and thus more reliable results. Additionally, reporting on informal flows can make the PRO aware of shifts in the EOL flows, for example as a result of a new policy measure. This allows them to assess the success of such measures and can inform improvement options. Important to note is that even incomplete reporting can be useful. Incomplete reports, for example on UEEE exported for reuse flows reported by companies, or WEEE redirected from scrap metal recycling can provide important information. These incomplete reports can, like in our case, be useful to establish boundaries or magnitudes of flows. These can then be used to verify results that are based on assumptions. It is therefore the Dutch PRO's and others investment in additional reporting on informal flows, beyond what is required by the EU, that enables The Netherlands to account relatively well for their WEEE flows.

4.4. Reporting intervals

Our analysis also shows that many sources report annually. This is useful for WEEE accounting, because it can indicate trends over time. For example, we used the estimates of UEEE exported for reuse from 2019 to 2021 to inform our own estimated UEEE export for 2022. Currently most of the yearly reported data is mandated under the EU WEEE Directive such as information on POM, generated WEEE, and formal WEEE collection (European Commission, 2024). However, with yearly reporting on WEEE in household residual waste and estimates for UEEE export for reuse, The Netherlands also collect data on additional flows. Assessing these flows over time can be useful when evaluating trends, especially after the introduction of new policy measures. Looking at WEEE in household residual waste, for example, shows that it has been decreasing over the last 9 years (Leenaars, 2023). Nevertheless several datapoints are still documented infrequently, such as WEEE in business residual waste, stock data or WEEE in scrap metal recycling. Illegal flows such as export of WEEE are never documented. Instead we have to rely on studies in receiving countries and mass balance accounting to quantify this flow. However, the receiving country does not receive shipments exclusively from a single country. This complicates the attribution of shipments to specific countries. Overall the yearly reporting on 10 flows ensures precise accounting for these flows and supports the estimation of the remaining stock and flows.

4.5. Improvement options

Based on our findings we suggest, in the long-term, to develop methods for informal inflow quantification. However, its clandestine and distributed nature and difficulty to use mass-balance accounting to estimate it make it very challenging to quantify. In the short term we suggest to focus efforts on WEEE in business residual waste, WEEE mixed with scrap metal, and UEEE that is exported for reuse. These flows promise far-reaching insights or are facing low hurdles for implementation.

Setting up regular reporting for WEEE in business residual waste is comparatively easy for two reasons: First, Stichting OPEN already organizes annual sampling of WEEE in household residual waste. This means the expertise to conduct the assessment of business residual waste already exists and can be transferred and adapted. Moreover, business residual waste is primarily collected through a formal waste management system. This simplifies sampling and increases reliability as there are no or negligible unaccounted for informal residual waste management flows. Knowing about WEEE in business residual waste over time would allow assessing trends as well as improved mass balance accounting due to more quantified flows.

Measuring WEEE mixed with scrap metal can provide insights into domestic co-processing of WEEE in metal recycling. This is relevant, because our research suggests that it is the second largest informal outflow. Additionally, this could provide information on WEEE export, because WEEE is often illegally exported as part of legal scrap metal exports (Brink et al., 2021). Metal recyclers that are already engaging in Stichting OPEN's WEEE takeback scheme could be potential partners for such a study.

Lastly, we suggest improving the data on UEEE export for reuse. While some data on this flow is available, its estimate show a wide spread. Similarly to WEEE in business residual waste the administrative structure to collect more precise data from companies already exists. In fact, reporting is a legal requirement for UEEE exporters (NWR, 2023). Thus, in theory everything is in place for better data collection. This would enable more reliable mass balance accounting and therefore better estimates of unknown flows.

4.6. Benefits for other countries

The Netherlands have already established best practices for data collection on several informal flows. Countries with similarly organized waste management systems as The Netherlands could copy these methods. Overall the resulting improved WEEE accounting could enable targeted policies to increase formal WEEE collection. A harmonization of WEEE accounting methods would also allow for better comparability between results of different countries.

In countries where the waste collection system differs significantly, the quantification methods used in The Netherlands could serve as a foundation. Then the methods can be adapted to fit their specific local context. Increased WEEE accounting outside of the EU would also allow the improved tracking of illegal WEEE flows. A better understanding of global illegally traded WEEE could contribute to greater collaboration between countries to prevent these flows in the future.

5. Conclusion

Monitoring informal WEEE flows is crucial to design policies that enable a circular economy. Our case study of The Netherlands shows that WEEE accounting is a suitable tool to gain this insight. By combining open source data with information from the national PRO and basic MFA principles we quantified 16 of 17 stocks and flows and produce, to our knowledge, the most detailed breakdown of formal and informal WEEE collection pathways currently available in the literature. Successful WEEE monitoring is not only useful to assess progress to a fully circular economy, but also enables decision-makers to evaluate the effectiveness of policies, such as the takeback scheme for WEEE in scrap metal collection.

At the same time our study shows that also countries with relatively successful WEEE monitoring, like The Netherlands, still have data gaps. Most notably the lack of data on the informal inflow of EEE. Addressing this data gap is essential, as it impacts our long-term capacity to estimate annual WEEE generation. This, in turn, hinders effective monitoring and management of WEEE flows, ultimately affecting policy development aimed at fostering a circular economy and ensuring resilient material supply chains.

As a result reporting on informal flows and exports should be expanded and conducted annually for reliable monitoring in the future. We specifically suggest to focus efforts on WEEE in business residual waste, WEEE mixed with scrap metal, and UEEE that is exported for reuse in the short-term, because these flows can provide promising insights and likely have lower implementation hurdles. In the long-term informal inflows should be monitored too.

The success of Dutch WEEE monitoring is due to the extensive voluntary reporting. We therefore conclude that further reporting on flows is essential to improve national WEEE monitoring. The factors leading to successful WEEE monitoring in The Netherlands are not unique. It is the willingness to invest into voluntary reporting on flows which enables success, which is replicable in other countries, given sufficient funding, especially for other EU member states, which operate formalized waste management systems and under the same EU regulations.

Ultimately, managing e-waste is highly complex due to the many stakeholders and interests involved. Successful WEEE monitoring, enabled by extensive, regular reporting, supports decision-makers to better assess the status quo, evaluate the success of interventions and develop new policies that ultimately lead to a more circular and resilient economy.

CRediT authorship contribution statement

Pablo Ilgemann: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Tomer Fishman:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Ralph Oudshoorn:** Writing – review & editing, Investigation. **Arnold Tukker:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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