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Waste electrical and electronic equipment (WEEE) in Denmark: Flows, quantities and management

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ABSTRACT

In this study, we comprehensively map and estimate the flows of electrical and electronic equipment (EEE) and the corresponding waste (WEEE) in Denmark. The quantitative analysis is supplemented with a thorough diagnosis of the WEEE management system. Dynamic material flow analysis (MFA) is used to estimate the flows for the period of 1990–2025. The estimates are based on sales data of 61 household products – equivalent to 80% (by weight) of the total household EEE – and their lifespans modelled using Weibull distribution function. Building on this, the potential resources available for recovery over time, and their corresponding revenues are evaluated. The results show that the amount of WEEE generated per year increased from 45 to 81 kilo tons (kt) between 1990 and 2015. The amount of EEE put on market (PoM), on the other hand, peaked to 101 kt in 2006 from 61 kt in 1991, but declined to 84 kt in 2015. In terms of the PoM quantity, the EEE market is found saturated, and can be expected to remain largely unchanged over the next decade. Consequently, there will not be any significant increase in WEEE quantities. Denmark has a well-established WEEE management system that has been performing adequately against the WEEE Directive. However, the new set of legislations means a need for recalibration of the performance indicators for the system. A more robust and systematic documentation of the flows will support the WEEE management system in achieving higher resource recovery.

1. Introduction

With the rapid technological advancement and economic development, the multiplicity and use of electrical and electronic equipment (EEE) have increased drastically over the last two decades. Consequently, the amount of end-of-life (EoL) products, synonymously known as electronic waste (e-waste) or waste electrical and electronic equipment (WEEE), is also on the rise. Nearly 50 million metric tons (Mt) of WEEE is forecasted globally for the year 2018, which will be a 50% increase compared to 2010. European countries alone produced 11.6 Mt of WEEE in 2014 with an average of 15.6 kg per capita (Balde et al., 2015b).

While the increasing amount is a challenge for its management system, WEEE also offers a secondary source of valuable resources that are readily available for recycling. This not only reduces the demand for finite primary resources, but also brings economic and environmental benefits through avoided adverse impacts of primary production (Habib et al., 2015; Mudd, 2010). In order to plan effective management strategies, policy makers and EoL actors need a better understanding of the system, including information on the amount of WEEE generation, material composition, and their availability for resource recovery (Zeng et al., 2015). Lack of insight into such potentials can keep countries from implementing the right strategies.

In 2014, the amount of per capita put on market (PoM) EEE was 21 kg in Denmark, the seventh highest among the 31 European countries (DPA-System, 2015; Eurostat, 2016). Household EEE consisted 77% of the total PoM amount, and more than 97% of the collected WEEE was collected from households. As of 2015, an average Danish household owns at least 27 common EEE items, with a total number of products in use being 33 million units across Denmark. Fig. 1 shows the increasing trend of household possession of different EEE items in Denmark between 1990 and 2015.

As a member state of the European Union, Denmark has a WEEE management system that complies with the WEEE Directive (European Parliament, 2003). Starting from August 2005, the Directive required the member states to establish a separate collection and treatment system for household WEEE. Reporting of the quantities of PoM EEE, collected WEEE and their subsequent treatment also became mandatory. The Danish Producer Respon-

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Table 1
Process description.

Process	Description
1. Producers	Original equipment manufacturers and resellers of new products
2. New products	Put on market (PoM) Electrical and electronic equipment (EEE)
3. Households	Users of the PoM EEE, where EEE is stocked as • In-use stock: EEE that are functional and in use • Hibernating stock: EEE that are functional, but not in use • Obsolete stock: EEE that are neither functional nor in use
4. Preparation for reuse	Second-hand stores, refurbishment shops, and user-to-user resale platforms
5. Official collection	Collection facilitated by municipalities, collective schemes, retail stores, and producers
6. Other collection routes	EoL product collection outside the official system
7. EoL products	EEE discarded of by its user with no intention of using it again
8. Preprocessor	First stop in the WEEE treatment chain (consists of dismantling, shredding & separation)
9. Recyclates	Outgoing material/component streams resulting from the preprocessing of WEEE
10. End processor	Final stop in the WEEE treatment chain, where materials are recovered in their pure form

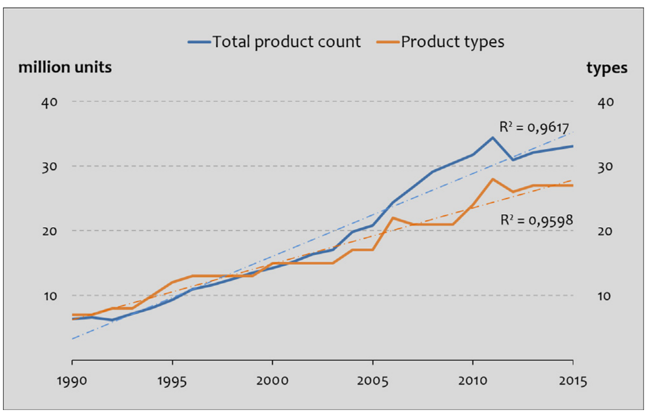

Fig. 1. Trend of increasing use of electrical and electronic products in households in Denmark [adapted from (Statistics Denmark, 2016)].

sibility System (DPA-System, formerly known as WEEE-System) started reporting these data from 2006. These reports are based on the data provided by the registered producers (PoM data) and by the local authorities, who facilitate the collection (WEEE collection data). Further, these reports provide some information on treatment of the collected WEEE as per the requirement of the Directive (DPA-System, 2015).

The collection target of 4 kg per capita per year set by the Directive has been easily achieved in Denmark (with, for example, 12.7 kg per capita collected in 2014). Although the data on PoM EEE and collected WEEE are reported comprehensively, there have been no previous studies to estimate the actual WEEE generation in Denmark. The Directive did not require any mandatory quantification at national level, and the collection target was fixed – regardless of the amount of WEEE generated. However, a number of substantial changes were made in the recast of the Directive (European Parliament, 2012). The Directive (recast) requires the new collection targets to be based on the amount of PoM EEE of three preceding years or the WEEE generated in the same year. It implies that more robust record keeping and calculations will be required to document the performance of WEEE management system.

Bigum et al. (2013) have empirically studied the amount of wrongfully discarded WEEE in residual waste from Danish households. In another study, Habib et al. (2014) considered selected electronic products in order to quantify the secondary supply of rare earth-based permanent magnets for Denmark. However, there are no previous studies on WEEE quantification considering a wide range of EEE items. Without the quantification of the WEEE amounts, the actual potential of material recovery cannot be properly understood. It also keeps both the authorities and recyclers from tracking the amounts leaking out of the official collection channels. Neither major mining activities nor treatment facilities for final recovery of plastics and metals from WEEE exist in Denmark. The current generalized preprocessing based on 'shred-and-separate' approach results in loss of potential revenues, which is exported outside the country in the form of material recyclates (Parajuly et al., 2016). In this context, the knowledge of EEE and WEEE flows is important for a country like Denmark in order to exploit the potential – especially during collection and preprocessing – of available resources in WEEE.

In this study, we comprehensively map the flows and systematically quantify WEEE generation in Denmark. Material flow analysis (MFA) is used to estimate the WEEE generation from household products. MFA, which is based on the principle of material conservation, is an established tool for decision support in waste and resource management (Brunner and Rechberger, 2004). Different MFA models have been used for quantifying WEEE at national levels (Duygan and Meylan, 2015; Kalmykova et al., 2015; Zeng et al., 2015; Zhang et al., 2012). Dynamic MFA models are used to understand the pathways, stocks, and flows of products and materials over time (Muller et al., 2014). Such models are usually based on the input (sales) data and the lifetime distribution function of different products in a socio-economic system in order to quantify the dynamics and magnitude of EoL products (Zeng et al., 2015).

The MFA in this study is supplemented with a thorough diagnosis of the WEEE management system and its performance indicators. To our knowledge, this is the first analysis of WEEE generation, recovery potentials, and management system in Denmark. We envision that this study will help the concerned stakeholders to evaluate the existing policies, understand the implications of the future compliance, and support the transition towards meeting the new set of legislative requirements.

The main objectives of this study are to:

a) scientifically assess the quantities of WEEE generated in Danish household and thus the availability of secondary resources;
b) systematically describe the flows of products along their life stages, including the flows not covered by the official channel (such as reuse and complementary recycling); and
c) identify the challenges and opportunities towards efficient resource recovery from EoL electronics against the changing legislations and market conditions.

2. Methodology

2.1. System definition

Our system definition in Fig. 2 shows all the processes and flows relevant to EEE and WEEE management system for Denmark. The description of each process and flow is provided in Tables 1 and 2 respectively.

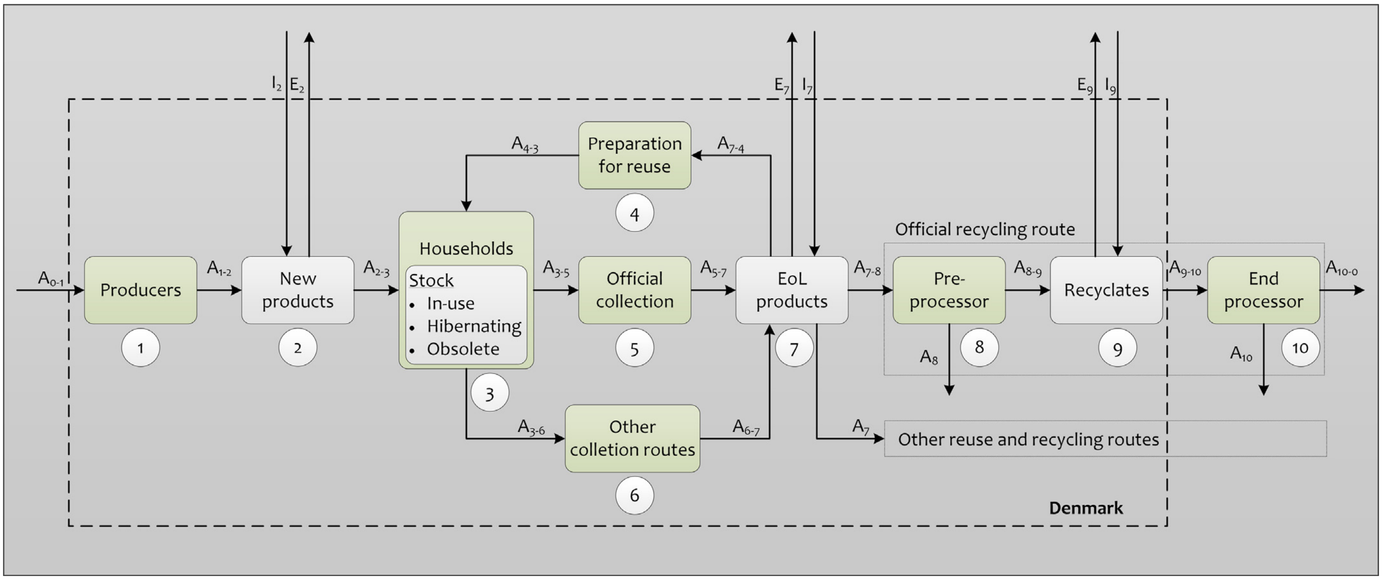

Fig. 2. Flow of products and embodied materials along their life stages within and outside the spatial boundary of Denmark.

Table 2
Flow description.

Flows	Description
A_{0-1}	Resources used in EEE
A_{1-2}	New products entering EEE market
I_2, E_2	Import and export of new products
A_{2-3}	PoM EEE
$A_{3-5} = A_{5-7}$	EoL products collected through the official collection system
$A_{3-6} = A_{6-7}$	EoL products collected through complementary channels
$A_{4-3} = A_{7-4}$	EoL products going for reuse in households
I_7, E_7	Import and export of EoL products (as used products or WEEE)
A_{7-8}	WEEE entering the official recycling route
A_7	WEEE processed outside the official system
A_{8-9}	Outgoing material streams from preprocessing plants
A_8	Material losses occurring during preprocessing
I_9, E_9	Import and export of material recyclates
A_{9-10}	Material streams going to end processing plants
A_{10}	Material losses occurring during end processing
A_{10-0}	Materials recovered as secondary resources

2.2. *Quantification of flows*

After identifying all processes and flows, we quantitatively analyzed the PoM EEE (Flow A_{2-3}) and the corresponding WEEE (Flows A_{3-5} and A_{3-6}) over the period of 1990–2025. This covers the past years for which sales data were available, and the next decade to come (the duration of scenarios in the future is kept short considering the uncertainties related to the development of EEE sector; see Section 3.4 for details). The following provides sources of data and methodology used for this analysis.

2.2.1. *PoM EEE*

We considered 61 different product types, for which sales data were readily available. This includes the most common household products from four categories: 1 – Large household appliances (LHA), 2 – Small household appliances (SHA), 3 – IT & telecommunication equipment (ITE), and 4 – Consumer electronics (CE). All the products are listed in Table S1 in Supplementary material (SM) together with their sales data.

Fig. 3 summarizes the time series for the quantitative analysis used in this study, and the sources and methods used to obtain the relevant data. Primarily, the sales data reported by the market research firm Euromonitor International (2016) were used. According to Euromonitor, the data are collected from different sources including national statistics, retailers, trade associations etc. For LHA, the sales data were also available from the Danish Association for Suppliers of Electrical Domestic Appliances (FEHA, 2016) for the period of 1991–2012, which included 8 product types for 1991–2000, 10 types for 2001–2008, and 15 types for 2009 onwards. We had a cross check and found these two sources to be consistent with each other.

We considered the sales data between 1991 and 2015 to be the baseline, and used linear extrapolation to backcast the historic sales data for LHA to 1956. Assuming the maximum life of a product to be 35 years, products sold in and after 1956 can be thus covered in the calculation of WEEE generated from 1991 onwards. The sales data of SHA before 2009, and ITE and CE before 2010 were not available. Therefore, the historic sales data for these categories were calculated based on LHA. For this, we assumed that the products from other categories were sold in the same ratio to the products in the category LHA. For the future projection, we used a no-growth scenario considering a saturated market with no significant demographic and/or economic changes (which has been the trend in the past decade not only in Denmark, but also in other similar countries such as Sweden, Norway, and Austria; see details in Fig. S2 in SM). The sales for each year from 2016 to 2025 are assumed to be the average of preceding six years.

The sales data provided the number of units of products. These units were converted into the weight of PoM EEE by using the average weight of each product type. The average weight of 44 out of the 61 products were empirically determined, which builds on a sorting and dismantling experiment performed for the household WEEE collected at the municipal collection points in Denmark (unpublished work). The remaining were adapted from Wang et al. (2012) and Zeng et al. (2015). Please refer to Table S2 in SM for the details.

2.2.2. *WEEE*

Weibull distribution function has been widely used for defining the lifetime of products in order to estimate WEEE generation (Balde et al., 2015a; Elshkaki, 2005; Kalmykova et al., 2015; Polak and Drapalova, 2012; Zeng et al., 2015; Zhang et al., 2012). This approach takes into account the dynamic nature of product obsolescence, contrary to the assumption of fixed product lifespan (Zhang et al., 2012). The lifespan profile (of the sales cohort) is defined by the shape and scale parameters (α and β, respectively). The maximum lifetime of a product is considered to be 35 years,

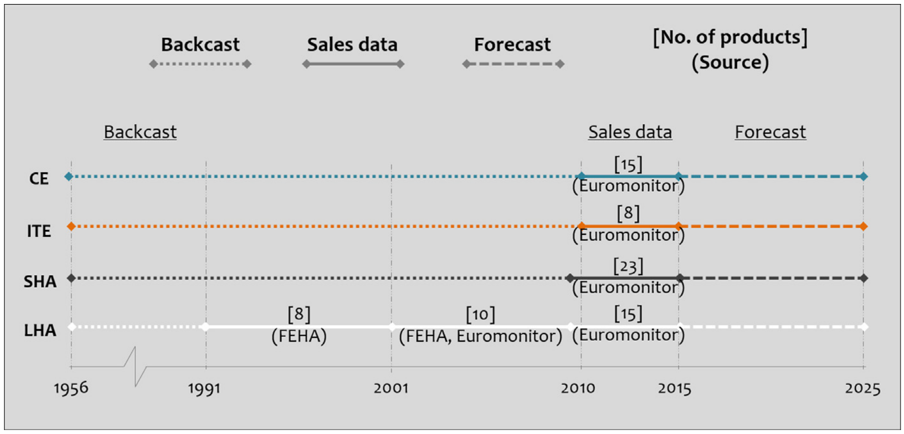

Fig. 3. Sources and methods used to obtain the data for the different categories over time. The solid lines indicate the readily available sales data in the corresponding years for the number of products specified within [square brackets] and their sources within (round brackets). The short- and long- dotted lines show the period for which the data were backcasted and forecasted, respectively.

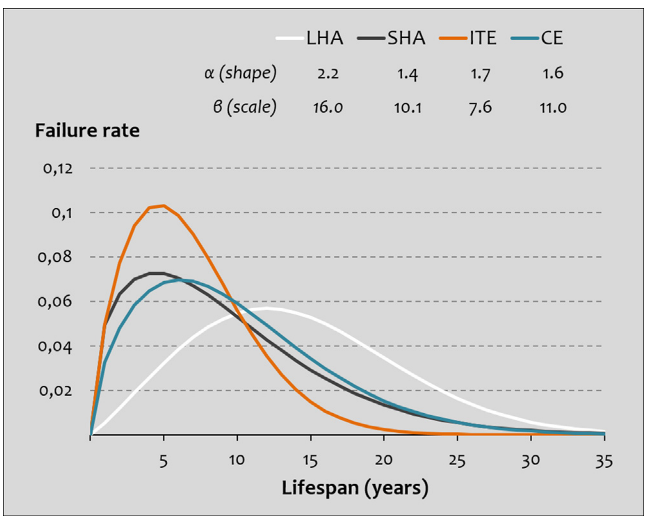

Fig. 4. Probability density function of failure rate for the four categories.

within which the probability of all products coming to their EoL sums up to 1 for the given α and β values.

Balde et al. (2015a) have made available these parameters for various products in the Netherlands, France, and Belgium. We adapted the average α and β values at category level for the products from four categories: LHA, SHA, ITE, and CE. The failure rates were calculated in Microsoft Excel 2010 using the shape and scale parameters. Fig. 4 shows the resulting probability distribution and failure rates for the four categories.

WEEE generation for each year starting from 1957 to 2025 was then calculated using these failure rates. The amount of WEEE generated for each year is given by the following equation:

$$WEEE_{(y)} = \sum_{i=1}^{4} P_{i(1956)} * f_{i(y-1956)} + P_{i(1957)} * f_{i(y-1957)} + \ldots\ldots + P_{i(y-1)} * f_{i(y-1)}, \quad (1)$$

where
$WEEE_{(y)}$ = amount of WEEE generated in year y,
i = category of WEEE (LHA, SHA, ITE, and CE),
$P_{i(y)}$ = amount of category i EEE put-on-market in year y, and
f = failure rate.

2.2.3. Secondary resources

Building on the estimated amounts of WEEE generation, we quantified the amount of secondary resources available for recycling. The material composition for this calculation is partly based on our empirical study and partly adapted from Oguchi et al. (2011). When the material composition of the exact product type was not available, the composition of another similar product was used. The material compositions of individual products were then aggregated to category level and the secondary resources available were calculated for each category. For this conversion from product to category material composition, weighted average was used based on the product sales data for 2015. The secondary resource available in the WEEE generated each year is given by:

$$S_{jy} = \sum_{i=1}^{4} WEEE_{i(y)} * c_{ij}, \quad (2)$$

where
S_{jy} = resource j available as WEEE in year y,
$WEEE_{i(y)}$ = amount of Category i WEEE in year y, and
c_{ij} = content of resource j in Category i WEEE.

Finally, the potential revenues were calculated using the material composition and their market price adapted from Cucchiella et al. (2015) and our empirical study. See Table S3 in SM for the details.

3. Results and discussion

3.1. PoM EEE and WEEE quantities

The amounts of PoM EEE and the corresponding WEEE generation were quantified at the category level for LHA, SHA, ITE, and CE. Fig. 5 shows the estimated amounts for each category for the period between 1990 and 2025. As it can be seen, the amount of the PoM EEE peaked in the year 2006 with a total of 101 kt, growing from 60 kt in 1990. In the following years, however, it declined to reach 84 kt in 2015, and it is not expected to change significantly in near future. The share of each category to the total amount of EEE has remained consistent with little change over time, with LHA being the most significant part. During the period of 2009–2015, for which complete sales data were available, the share of LHA increased from 70 to 74%, while SHA and ITE both increased by 1% to reach 7 and 10% respectively. The weight share of CE declined from 15 to 10% during the same period.

Our estimates show that the annual WEEE generation increased from 45 to 81 kt between 1990 and 2015 with a growth rate of 2–3% each year until 2011. However, this growth started slowing down

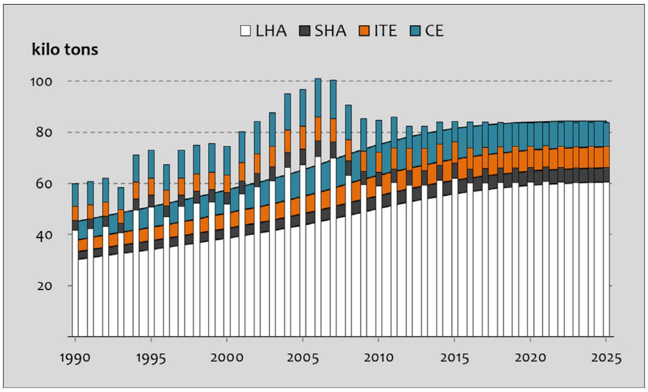

Fig. 5. Quantity of new products put on market (bars) and the EoL products (curved area) for 1990–2025.

from 2012, and the WEEE generation is projected not to change significantly over the next decade. It is important to mention here that our estimates are based on only 61 products and thus do not cover all EEE types. Nevertheless, compared to the PoM data reported by the DPA-system for 2006–2014, our estimates on average cover 80% of total household EEE. See Section 3.4 for the details.

We compared the trend of EEE and WEEE generation in Denmark with two Scandinavian neighbors (Norway and Sweden) and another European country with similar socio-economic features (Austria). The amounts of PoM EEE and collected WEEE for the period of 2006–2013 in all four countries have been largely consistent with virtually no growth after 2008 (see Fig. S2 in SM). This trend suggests a saturated EEE market as well as the presence of well-established WEEE collection systems in these countries. Assuming no significant change in population growth or individual purchasing power, this trend can be expected to remain constant in the coming years.

In countries with increasing population and economic development, the outlook appears very different. In China, for example, per capita WEEE generation is forecasted to increase from 6 kg in 2014 to 18 kg in 2030 (Zeng et al., 2015). In India, the amount of WEEE increased from 146 kt in 2005 to 800 kt in 2012 (Sharma et al., 2016). In Brazil, the per capita WEEE generation increased from 3.8 kg in 2008 to 7 kg in 2014 (de Souza et al., 2016). The growth rates in these major developing countries indicate a continuing increase in global amount of WEEE. Countries like Denmark, however, will see a little change.

3.2. Secondary resources and potential revenue

We translated the WEEE quantities into secondary resources available for recovery and the associated economic potential. Fig. 6 shows the amount of key resources over time, presented in four groups: 1 – common materials (plastics and base metals (Al, Cu, Fe)), 2 – common metals (Pb, Sn, Zn), 3 – less common metals (Ba, Bi, Co, Ga, Sr, Ta), and 4 – precious metals (Ag, Au, Pd).

The amounts of common materials follow the similar pattern compared to that of WEEE over time. For example, the amounts of Fe and plastic have increased from 21 and 16 kt in 1990 to 38 and 30 kt in 2015, respectively. These amounts will increase slowly up to 40 and 31 kt by 2025. Other resources, including precious metals show different patterns of increase, reaching their peak around 2013 followed by a smooth decline. The total amount of Au, for example, increased from 0.6 t in 1990 to 1.04 t in 2013 and projected to go down to 0.97 t in 2025. Similarly, the amounts of Sn, Ba, Ta, and Ag decrease rapidly after the peak. The trends show that the base materials, which are mainly used in the structural components of the products, remain largely unchanged. On the other hand, the specialty and precious metals, which are used in trace amounts in the products – usually for achieving specific functionality – fluctuate more. This change in material composition of WEEE could be attributed the change in the composition of products types over time.

The potential revenue carried by the secondary resources available in WEEE is shown in Fig. 7. The total revenue increased from €69 million in 1990 to €122 million in 2015. Au and plastic are the two key resources, carrying more than half of the total revenue. Cu is the next important metal that represents more than 15% of the potential revenue, while remaining is made up largely by Fe and Ba. However, the actual exploitable revenues could significantly vary among different resources depending on the technological and economic feasibility of their recovery. Further, the actual material recovery also depends on the type of products and their EoL management system. For example, precious metals (e.g. Au and Pd) are concentrated in printed circuit boards (PCBs), therefore, selective dismantling and separate processing of PCBs are preferable for their efficient recovery (Ardente et al., 2014). In a typical setup supported by such dismantling process, precious metals as well base metals (Al, Cu and Fe) can be effectively recovered by the existing recycling system, whereas plastics and less common metals (including rare earth elements) have considerably low recycling rates (Habib et al., 2015; Parajuly et al., 2016).

3.3. WEEE management in Denmark

3.3.1. Collection

Denmark has been performing consistently well with respect to the collection target (i.e., 4 kg per capita per year) set by the WEEE Directive. However, the recast of the Directive requires:

> From 2019, the minimum collection rate to be achieved annually shall be 65% of the average weight of EEE placed on the market in the three preceding years in the Member State concerned, or alternatively 85% of WEEE generated on the territory of that Member State.

We compared the trend of existing collection with the estimated amount of WEEE generation in the future and the new targets. As shown in Fig. 8, the collection for the years 2006–2013 is close to the 65% target. According to the Directive (recast), 85% of WEEE generated is broadly equivalent to 65% of the PoM EEE averaged over three preceding years. However, our estimates suggest a significant difference between these two numbers. This means there is a room for error, and the targets are not equally applicable for countries like Denmark.

It is important to understand not only the gap between PoM EEE and collected WEEE quantities, but also what is actually being collected. The numbers reported by DPA (Fig. S1 in SM) show a significant gap between PoM EEE and collected WEEE for the collection fraction 'small appliances', which covers all household products of categories SHA, ITE and CE. It shows that not all EoL products coming out from the households enter the official WEEE collection system. On average, 64% of overall PoM EEE (the same year) was collected between 2006 and 2014, but this average is only 40% for the fraction 'small appliances'.

3.3.2. Recycling

As reported by the DPA-system, most of the collected WEEE in Denmark goes for material and energy recovery. For the four categories, 74% to 88% of recycling rates have been reported for the period of 2006–2014 (see SM, Table S4). According to the Directive (recast, Article 11 (2)):

> The achievement of the targets shall be calculated, for each category, by dividing the weight of the WEEE that enters the

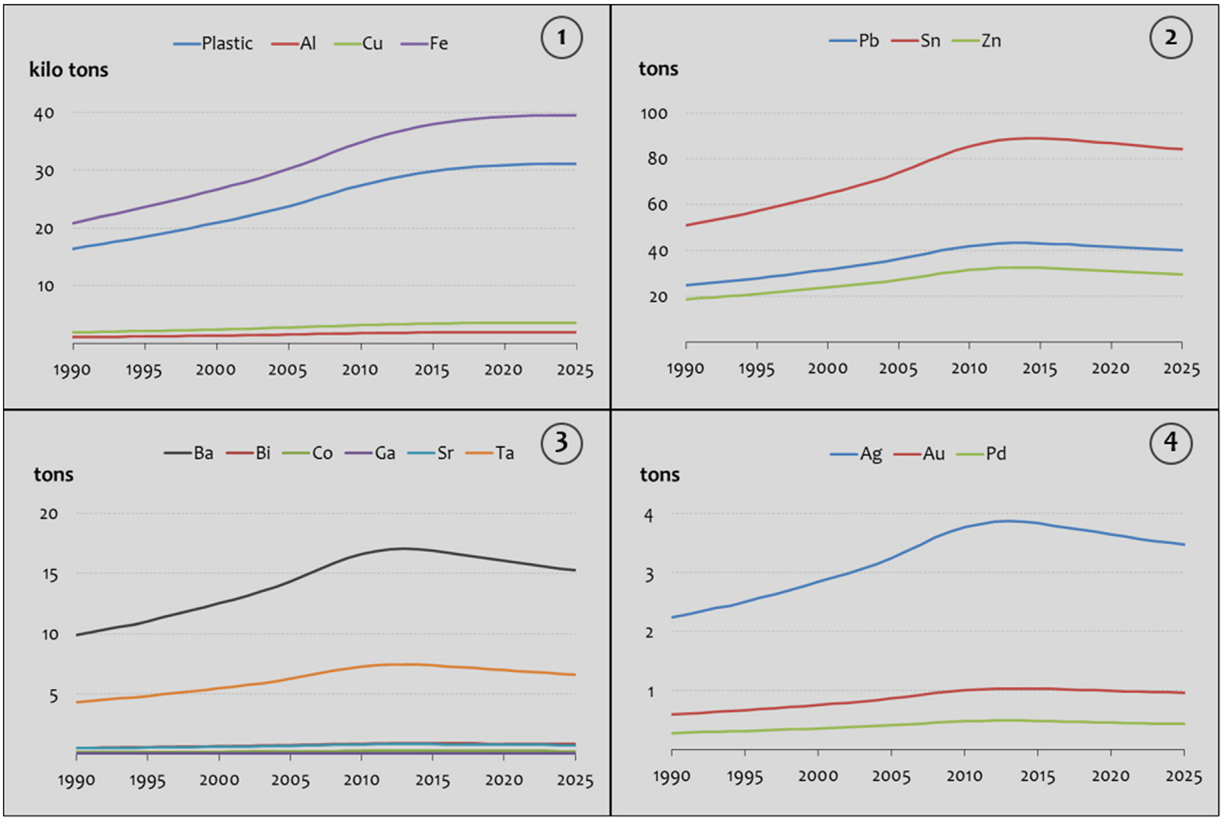

Fig. 6. Amount of resources available for recycling in the EoL household products.

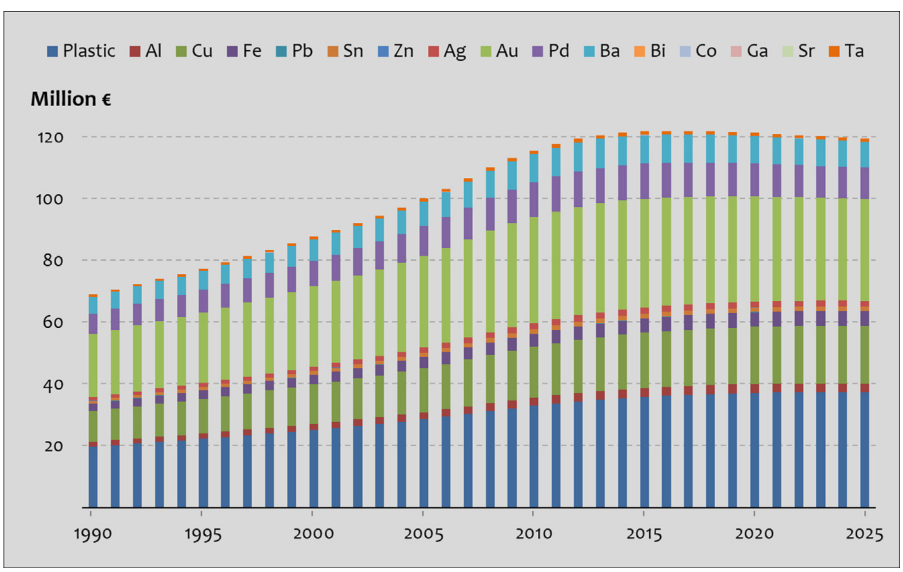

Fig. 7. Potential revenue of the secondary resources in the estimated quantities of WEEE.

recovery or recycling/preparing for re-use facility [. . ..] by the weight of all separately collected WEEE for each category, expressed as a percentage.

This can be expressed using the flows from Fig. 2 (assuming the net trade of EoL products to be zero):

$$\text{Recycling rate (Directive target)} = \frac{A_{7-8} + A_{7-4}}{A_{5-7}}. \quad (3)$$

However, looking at the whole system level, this indicator does not reflect the true material recycling rate as it excludes the complementary flow of WEEE (A_{6-7}) from the equation. Moreover, it does not consider the losses that occur in the WEEE treatment chain ($A_{8 \text{and}}$ A_{10}) or the EoL products handled outside the official recycling routes (A_7). In order to reflect the true material recovery, the calculation should include the remaining recycling routes in the equation.

The targets set by the Directive (recast) also include reuse of EoL products. However, the above equation does not include the products entering reuse market without coming to the official WEEE collection system. A significant amount of used and EoL products

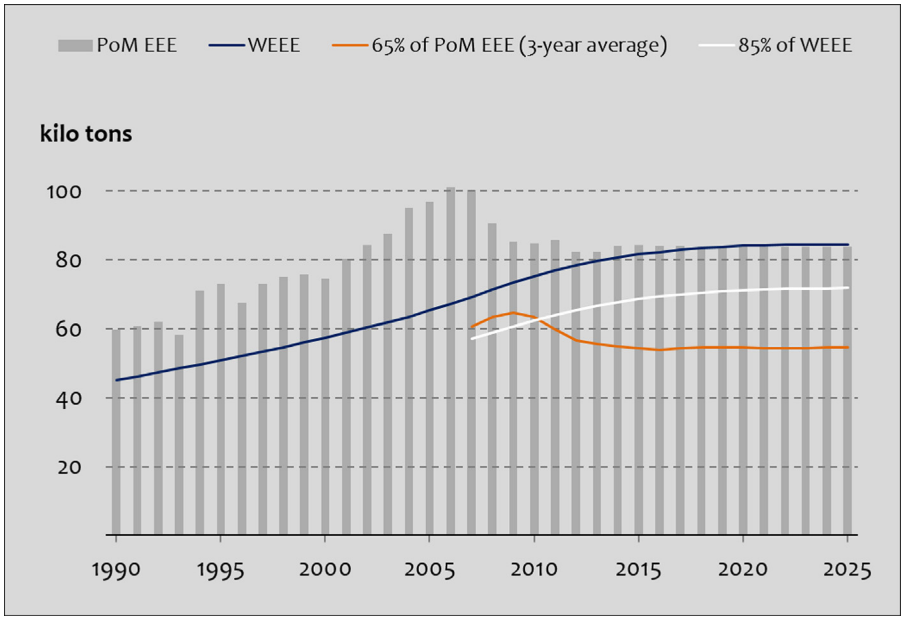

Fig. 8. Illustration of products sales (PoM EEE), WEEE generation, and collection scenarios. The lines '65% of PoM EEE (3-year average)' and '85% of WEEE' represent the collection targets defined by the WEEE Directive (recast).

(especially ITE and CE) enter their second life via commercial as well as user-to-user selling platforms. Further, reuse needs a separate evaluation, as it can also be found within the system boundary of 'in-use'. Only the WEEE – excluding the EoL products for reuse – should be used for calculating the collection and recycling rates. As it can be seen, the metrics used for calculating recycling rates can be influenced by the different flows in the WEEE system. In order to make the recycling rates comparable across different countries (or regions), it is important to understand all flows in a WEEE management system and include them in a consistent manner.

Efficient recovery of secondary resources allows environmental benefits that come from the avoided mining of these resources. Moreover, resource recovery from EoL products helps reducing the potential supply risks of important resources – an issue of increasing concern for industries and governments alike. Therefore, efficient collection and recycling of WEEE needs to be prioritized at policy level.

3.3.3. Complementary flows

Today, the EoL products collected outside the official system are not included in the equation of calculating recycling and recovery rates. Exclusion of such flows not only affects the performance indicators of the WEEE management system, but also lessens the possibilities of recovering more value from the EoL products. The true recycling achievements should be compared with what is available, and not only with the amount that is already collected.

The amounts of EoL products (flow A_{3-6} in Fig. 2) that do not enter the official WEEE management system have not been quantified. The amount of stockpiled products, both during and after use in the households, is also unknown. Considerable amounts of used products are diverted from the WEEE flows through user-to-user platforms, stores that repair and resale the used items, or as an act of charity. These flows (represented by the flow A_{7-4} in Fig. 2) need to be quantified and the delay caused by the reuse of products also needs to be addressed. Quantification of these complementary flows and their inclusion in the metrics will make the recycling indicators more robust and precise.

In order to keep track of the resource flows more precisely and transparently, harmonization of data sources and reporting methodology is also crucial. The sales data available (from both Statistics Denmark and Euromonitor) for EEE give us the number (or count) of marketed products, whereas the quantity reported by the producers (to the DPA-System) is the weight of PoM EEE. The information on how the number of products is translated into weight is not available. This suggests a lack of clarity among different stakeholders on their role and format of reporting data. There is also a lack of documentation for products imported or exported at personal levels, and the household stocks of products in use, hibernating and/or stockpiled after being obsolete. More bottom-up analysis and consumer surveys are therefore needed.

3.4. Limitations and uncertainties

Although we provide a comprehensive view of the products' life cycle and quantify the flow using dynamic MFA, we acknowledge a few limitations and uncertainties in our analysis.

The first limitation has been the number of products included in this study. Due to the lack of sales data, we considered only 61 product types from four categories, which leaves out other EEE items available in market and the WEEE stream. Nevertheless, the 61 product types cover on average 80% (by weight) of the total PoM compared to what is reported by DPA for the period of 2006–2014. This shows that the products we considered sufficiently represent the household EEE and the corresponding WEEE. Considering the increasing number of EEE items entering the market every year, it will remain a challenge to include the whole spectra of product types for a given time window.

The weight and material composition of products are key variables for this study but they bear some degree of uncertainties. We considered fixed values for these product characteristics at category level, but in reality, they may change with the continuing technological evolution. The change in the material composition is especially crucial because the content of precious metals may have been decreasing. The recent decades have seen such an evolution, especially in the IT equipment and consumer electronic products such as computers, tablets, music players, televisions, and mobile phones. These factors play an important role in the availability of EoL products and the secondary resource in WEEE.

The lifespan of products are the key for dynamic MFA studies; however, we have very little information on product lifespans based on firsthand statistics (Liu and Muller, 2013; Oguchi et al., 2010). Due to the lack of specific Danish data, product lifespan is adapted from a study conducted for the Netherlands, France, and Belgium. The lifespan may also change overtime (e.g., due to changing consumer behavior and product design), which is an important factor to consider in future WEEE MFA studies.

We counted all the future generation of secondary resources for potential revenues. In reality, of course, not all the recycling and recovery would be technically possible due to, for example, contamination and accumulation of alloying elements. More importantly, the resource recovery is hampered when the recovery of valuable elements itself is not economically feasible and/or the total recycling cost – including the proper treatment and disposal of hazardous substances – is too high. The expected revenues from the resources in WEEE can also be influenced due to fluctuating market conditions, the grade of resource, and geographical location.

We did not include a quantitative uncertainty analysis for these parameters in this study because there is little information available on their historical and potential future trend. Moreover, the expected revenues from the resources in WEEE can be influenced due to fluctuating market conditions. Given the diversity and evolution of EEE items, it will require significant efforts to reflect the dynamic nature of product characteristics and their EoL recovery potential. We see this as a common challenge that both the WEEE and the MFA research community should take in the future.

4. Conclusions

The study affords a detailed understanding of the WEEE flows in Denmark – both qualitatively and quantitatively. The systematic quantification of the WEEE and the secondary resources is supported by a comprehensive analysis of the WEEE management system. Although the performance of the system has been sufficient against current WEEE Directive, new set of legislations will require higher collection and recycling rates. A more robust and transparent documentation of the flows will help achieve these targets and improve the overall resource recovery from WEEE.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.08.004.

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