WOT 1.2? Insights into the flows and fates of e-waste in the UK

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Abstract

In 2019 the EU Waste Electrical and Electronic Equipment (WEEE) Directive documented a sizable increase in e-waste collection targets alongside widening the scope of electrical and electronic products covered by the legislation. These changes have significant impact for the UK, where e-waste collection has been below the levels necessary to meet the targets. Understanding the flows and fates of products on and off the market becomes of paramount importance, especially for producer-led organisations who have the responsibility to achieve the targets and cover the operational costs. Historic e-waste estimation methods often assume that one product on the market will equate to one product in the waste stream. In this article, we introduce our research commissioned by the largest UK WEEE producer-led organisation, REPIC Ltd, to explain the gap in products on the market and WEEE collected, and the relationship between the two. We argue that we should move away from the "one-in-one-out" estimation to include a wider set of parameters that are tailored specifically for the UK, including those linked with the state of the market for electrical and electronic products and a broader range of socioeconomic indicators. We show how this can be achieved

by adapting a state-of-the-art e-waste estimation model, Waste Over Time, to the UK context and developing it further to include additional drivers.

Key words: e-waste estimation, WOT, dynamic model, WEEE Regulation, WEEE Directive.

1. Introduction

The UK has made great commitments to reduce waste, improve resource efficiency and invest in sustainable business (Defra, 2018: 7, BEIS 2017: 2). With such ambitions, the waste sector is once again receiving considerable attention. With government legislators setting recovery and recycling targets to encourage accountability and resource recapture, and to ensure there is suitable funding and responsible disposal to comply with such targets, it is of paramount importance to get insights into the flows and fates of complex waste such as Waste Electrical and Electronic Equipment (WEEE). Electrical and Electronic Equipment (EEE) is often in the spotlight due to an increasing number of electrical products in society and valuable resources contained within. For example, an estimated 1.6 million tonnes were generated in the UK in 2016, equating to almost 25 kgs per person (Baldé et al., 2017).

In 2019, the European Union's WEEE Directive (2012) set a substantial increase to the waste collection targets for EEE products Placed on the Market (POM). In addition, the scope of products covered by the legislation expanded to include all EEE (European Commission, 2017), unless otherwise stated (Defra, 2017; Defra, 2018). This is referred to as Open Scope. Setting realistic and robust targets is challenging due to the current consumer economy and multifaceted routes to disposal, such as second-hand markets, incorrect disposal in household bins, hoarding and theft, among other factors (Borthakur and Govind, 2017;

Dindarian et al., 2012). The legislative changes have significant implications for the UK since they are transposed into UK WEEE Regulations. Indeed, "*The proposed overall UK WEEE collection target for 2019 is 550,577 tonnes – over 57,000 tonnes higher than the total amount of household WEEE collected and reported in 2018*" (REPIC 2019: para. 2). In contrast, the recently published UK's Environment Agency data for 2017 and 2018 showed a drop in WEEE collected relative to 2016 (data is available from www.gov.uk/government/statistical-data-sets/). During the first half of 2019, 244,181 tonnes were collected, or 44% of the 2019 target.

With the Directive being premised on the principle of Extended Producer Responsibility (EPR), this places accountability, collection and funding for the end of life products with manufacturers (producers). Therefore, understanding how long products stay in the economy, dictates how much WEEE is discarded and when, and consequently how much is available for collection. Improving the understanding of the economic life-cycle and value of products is vital for producer-led organisations. With the reliance on historical data (Van Straalen et al., 2016), the changes in post-consumer disposal practices (Borthakur and Govind, 2017; Dindarian et al., 2012) provide the opportunity to re-interrogate the flows of EEE and fates of WEEE in order to see how these changes can contribute to target setting and policy delivery (Stowell, Yumashev, et al., 2018).

In this article, we report on a project commissioned by one of the largest UK producer-led organisations, REPIC Ltd. In search of better intelligence on the relationship between EEE POM and WEEE generated and collected, the project aims to investigate the relationship between the two, and to better understand WEEE target setting and the fate of used consumer EEE goods. Building upon previous academic studies enhancing the estimations of e-waste (Wang et al., 2013; Magalini et al., 2016; Van Straalen et al., 2016) and industry research (WRAP, 2011; 2012; 2016), we sought to understand this phenomenon in greater depth.

First, we argue that the amount of WEEE generated (which is available for collection) needs to be determined for legislative targets. The key factors to take into consideration to design effective compliance targets, understand the implications of Open Scope for modelling WEEE generated, and help improve the overall WEEE recycling rates, include: (i) unreported EEE and WEEE flows, in particular unregistered sellers placing EEE onto the UK market for the first time and via second-hand markets; (ii) and changes in EEE product weights, product lifespans and household residence times. In order to accurately predict WEEE generated and building on Wang et al. (2013) and Van Straalen et al. (2016), we established UK-specific trends of the following parameters: detailed production and trade figures; age distributions of the products in households and in the waste stream; and unit weight data.

Second, we argue that there is a need for a new dynamic WEEE model, which has the ability to estimate annual fluctuations in POM and Waste Generated (WG) in response to wider socio-economic conditions and specific EEE market conditions, such as inflation-adjusted GDP per capita, consumer confidence index (CCI), inflation indices (CPI or RPI), number of households, wealth distribution across the population, percentages of households with no or multiple units of a given product, and number of businesses owning a given product. We illustrate this by putting forward a proposal for what this model could look like, building upon the current state-of-the-art Waste Over Time (WOT) model (Van Straalen et al., 2016), and show how e-waste estimates could be improved as a result. Practically, we provide new insights on the socio-economic parameters that legislators should take into consideration when setting new recycling targets.

Our research in this article also extends the UK e-waste estimation literature through the adaption of the current EU-wide state-of-the-art WOT model to the UK context. This is achieved by developing a novel mapping method of measuring EEE and WEEE weight flows in order to navigate across different categorizations of databases (see supplementary data, Appendix A). This new method improves our understanding of how various aggregate EEE categories adopted in the UK and EU relate to the underlying granular product databases in the trade statistics (Eurostat), which includes the time-evolution of the mapping as old products get disconnected and new ones enter the market.

The paper has the following structure. We first introduce the study of e-waste flows and fates in the UK context, and then document our gap analysis of the UK EEE and WEEE data, available models and methodologies. We then reach out to actors operating in the relevant sectors to ascertain further insights. An assessment is then undertaken into the publicly available state-of-the-art models for quantifying products' POM, WEEE generated and collected, with the focus on mapping the EU-level results to the UK EEE categories. We identify crucial data gaps and discuss the implications in a broader waste management context, before concluding with our prototype of a new dynamic model for assessing the flows and fates of e-waste. Last, we ground these ideas in the relevant empirical context – that of EEE waste management in the UK – by providing a deeper overview of specific implications of policy translations for producer responsibility organisations.

2. The study of e-waste flows in the UK

The transposition of Open Scope into UK law came into effect on January 1st, 2019. As a result, the UK chose to convert the previous 14 closed categories to 14 Open Scope categories (Defra, 2017; 2018). The Open Scope categories are extending to include all EEE, unless explicitly specified otherwise. At the time of this research, collection targets were set to be increased from 45% to 65% of EEE POM in the three preceding years, or 85% if based on WEEE Generated (WG) estimates (European Commission, 2017). These amendments, which are now part of the EU-wide legislation, have specific implications to EEE Producers and Producer Compliance Schemes (PCSs) in relation to the ability to meet the new collection targets and compliance costs. Against the backdrop of the legislative changes, REPIC Ltd, which is the largest WEEE PCS in the UK representing WEEE members who account for half of the weight of electrical and electronic products sold in the UK every year (www.repic.co.uk), commissioned the Pentland Centre for Sustainability in Business, Lancaster University (www.lancaster.ac.uk/pentland/), to independently investigate and report on existing econometric post-consumer forecasting models. The main aim was to understand what socio-economic factors could be included to improve existing models for estimating the generation of WEEE.

The key aims of the study were to: identify possible improvements in EEE and WEEE quantification, including near-term forecasting; estimate WEEE generated to enable REPIC to plan accordingly; scope further work to develop a dynamic flow model for the UK to improve the forecasts of WEEE generated and help set more robust collection targets; and, provide recommendations for further work to fill a prioritised list of data gaps.

The research was undertaken in five distinct phases that all fed into each other as outlined in the schematic in Figure 1.

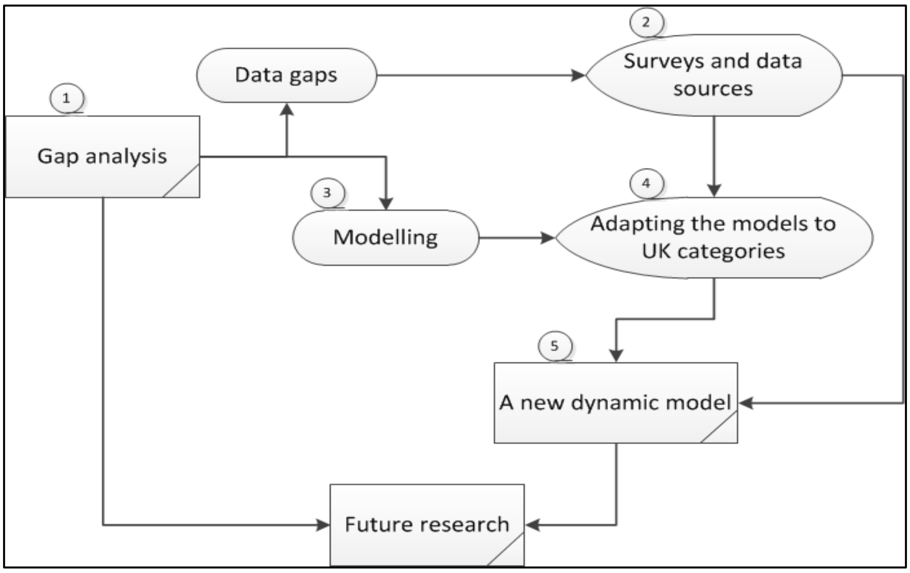


Figure 1. Project phases.

2.1 Gap analysis

This nine-month desk based part-time pilot study took place between October 2017 and June 2018. It involved: 39 reports and 44 academic research papers reviewed, 7 models and methodologies assessed for applicability to the UK context, 5 technical WEEE experts contacted and consulted, 3 WEEE economists and executives from DEFRA consulted, 46 datasets reviewed and analysed, 70 organisations and individuals surveyed.

The scope of the project was limited to key policies, product categories and codes, as outlined in Table 1 below. We explored UK EEE POM, WG, WEEE destinations and trends (B2C only) and excluded Second-hand or Used EEE (SHEEE/UEEE) and batteries.

Table 1. Key policies, product categories and codes

Key Policies
EU WEEE Directive (2012/19/EU)
UK WEEE Regulations (2013) (as amended)
Implementation Regulation (2017/699)
Move to Open Scope (2019)

Product Categories and Codes
6 EU Open Scope Categories
14 UK WEEE Categories
54 United Nations University (UNU) Codes (referred to as "UNU keys")
500 PRODCOM (PCC) Codes (approx.)
1150 Combined Nomenclature (CN) Codes (approx.)

We firstly examined existing UK EEE and WEEE data, models and methodologies available both publicly and via REPIC Ltd, and identified the key missing information (see results in section 3). In the e-waste estimation gap analysis, several models and methodologies were identified, showing what (W)EEE estimation tools and forecasting methods are currently available, and where possible improvements could be needed. A comprehensive of available data models and code lists can be found in the PROSUM 5.5 Report (www.prosumproject.eu). Each data source was scored on the relevance of the discussed methods in the context of forecasting (W)EEE in the UK, based on whether: it enables WEEE forecasting, it enables EEE forecasting, it involves estimation or survey data of designed lifespan and/or household residence time of EEE products, the required data is available, and, it is applicable to any aggregate WEEE category.

2.2 Survey and data sources

We attempted to obtain data to meet the most common shortfalls identified in the gap analysis: unreported EEE and WEEE flows (e.g. exported used EEE, EEE reused within the country, the amount of WEEE in residual waste, theft and illegal export), product lifespans, residence times, product trends, reliability of publicly available datasets (B2B is largely absent), consumer demographics, technology trends, and socio-economic trends. In parallel, we reviewed potential sources of raw data, both available publicly (e.g. Eurostat; company reports), provided by REPIC, and included in earlier surveys. This additional review corroborated the shortfalls identified by the gap analysis.

In an attempt to fill some of the gaps identified, two surveys were designed and sent out to 29 producers (e.g. retailers, manufacturers etc.) and 41 waste collectors (local authorities, treatment facilities, waste management companies), all of whom are REPIC members. We targeted companies who manufactured key EEE products in the 14 UK categories, have B2C sales, predicted growth trends, and who have products that are likely to be caught by Open Scope. The questionnaires included a series of sense-making questions that explore the currently available data and methods. To producers, specific questions were designed to examine their top-three product lines, and the WEEE quantification of those products. To the waste collectors, specific questions were designed to zoom in on the operational costs and key barriers of recovery and recycling practices. A series of open-ended questions in the survey provided a chance to collect managerial insights and concerns on the challenges and future trends of POM and WEEE.

The questionnaires were sent out between December 2017 and May 2018. The overall response rate was 27% (11 partial and 7 full responses by the producers, and 9 partial and 6 full responses by the recyclers). This response rate is above the expected average for survey respondents (Robson, 2002). Survey responses were consolidated, and key features of product-level data were identified that could contribute to influencing (W)EEE flows, such as fast market growth, decreasing average product weight, short residence time regardless of product lifespan, and distribution by unregistered sellers. The qualitative results of the survey were analysed as structured interviews (Robson, 2002) in order to identify key challenges for WEEE management. All data that directly related to the identities of respondents were removed to ensure anonymity.

2.3 Model assessment

We identified and assessed publicly available state-of-the-art models for quantifying POM, WG and WEEE collected, with the focus on their applicability to the UK context (e.g. Yu et al., 2010; Wang et al., 2013; Kalmykova et al., 2015; Van Straalen et al., 2016; Magalini et al., 2016; Thiébaud et al., 2017). Seven publicly available models to predict POM and WEEE arising were investigated. These models are based on various methodologies of quantifying POM and WEEE described in the literature. The most useful class of models are based on input-output-analysis (IOA). A prime example, often used by other researchers, is the 'sales-stock-lifespan' model developed by (Wang et al., 2013). Further details on a selection of methods appear in Table 2.

Table 2. A selection of available WEEE modelling tools.

Name of the Model	Focus	POM and WG categories	Methodology
Waste Over Time (Statistics Netherlands)	POM, WG	UNU, EU10, EU6 (CN for trade, PCC for manufacturing data)	POM & residence times
EU Excel WEEE calculation tool, UK version	POM, WG	UNU, EU10, EU6	POM & residence times
WRAP	WEEE flows	UK14	Disposal, processing and destination splits

The IOA models analysed tend to include the following elements. First, historic EEE POM data is collected from a reliable source, e.g. producers and government data. Second, EEE household residence times are approximated with a Weibull distribution, which is typically used to model the failure rate of a product over time. This allows for predictions along the lines of "in the n^{th} year after a given EEE product is put on the market, X% of the sold units will become WEEE". Third, EEE POM is forecast to all future years for which WEEE is to be forecast, based on historic trends. Fourth, the forecasting of WEEE arising relies on historic EEE POM data, forecasts of EEE POM and the residence time distributions. Fifth, stock levels can also be taken into consideration. Stocks are generally defined as the number of items stored in households and/or businesses, regardless of whether they're still functioning or in use. Finally, the current generation of the IOA models tend to be driven by the POM data only, while the stock data, if available, serves to calibrate the products residence times. This breaks the immediate link between fluctuations in POM and WEEE associated with stock replacement. Several other methodologies are discussed in Magalini et al. (2016), ProSUM 5.5 (2017) and ProSUM 3.1 (2017), including sales with average lifespan (Wang et al., 2013), Carnegie Mellon methodology (Dwivedy and Mittal, 2010), and stock and lifespan distribution (Huisman et al., 2012) and leeching method (Araujo et al., 2012). Material Flow Analysis (MFA) is often used to determine the fate of WEEE and its components (Yu et al., 2010; Kalmykova, et al., 2015; Thiébaud et al., 2017).

Eventually, the Waste Over Time (WOT) IOA-type model (Van Straalen et al., 2016) was identified as the most comprehensive tool currently available in terms of the granularity of the underlying historic data and near-term forecasting capabilities. WOT uses historic data for trade (expressed in CN codes) and manufacturing (expressed in PCC codes) for each EU Member State, available from Eurostat, to reconstruct POM as far back as 1980 for 54 aggregate EEE product categories referred to as UNU codes (Baldé et al., 2015). It then applies product household residence time distributions for each UNU category inferred from available age profile studies and manufacturing lifespan data, to translate historic POM into WG. Due to its advanced features, WOT was therefore used as the default model for the analysis.

In addition to studying the documentation of the WOT and EU Excel models, we conducted technical discussions with some of the leading experts in modelling EEE and WEEE flows (based in UNU, Statistics Netherlands and Sofies).

2.4 Mapping weight flows across datasets

We proceed by mapping the results from the WOT model, which are presented in 54 UNU keys and 6 EU categories, to the 14 UK categories. The research team developed a novel mapping method to track weight flows from one set of aggregate EEE categories to another. The new method was required because multiple UNU keys map onto more than one UK category, making it impossible to simply add together the weight flows for each of the UNU keys in order to get the corresponding flows for the UK categories. The same applies to the UK-EU categories mapping, which is required in order to report the UK data for POM and WEEE collected using 6 generic EU categories from 2019 onwards (Figure **2**).

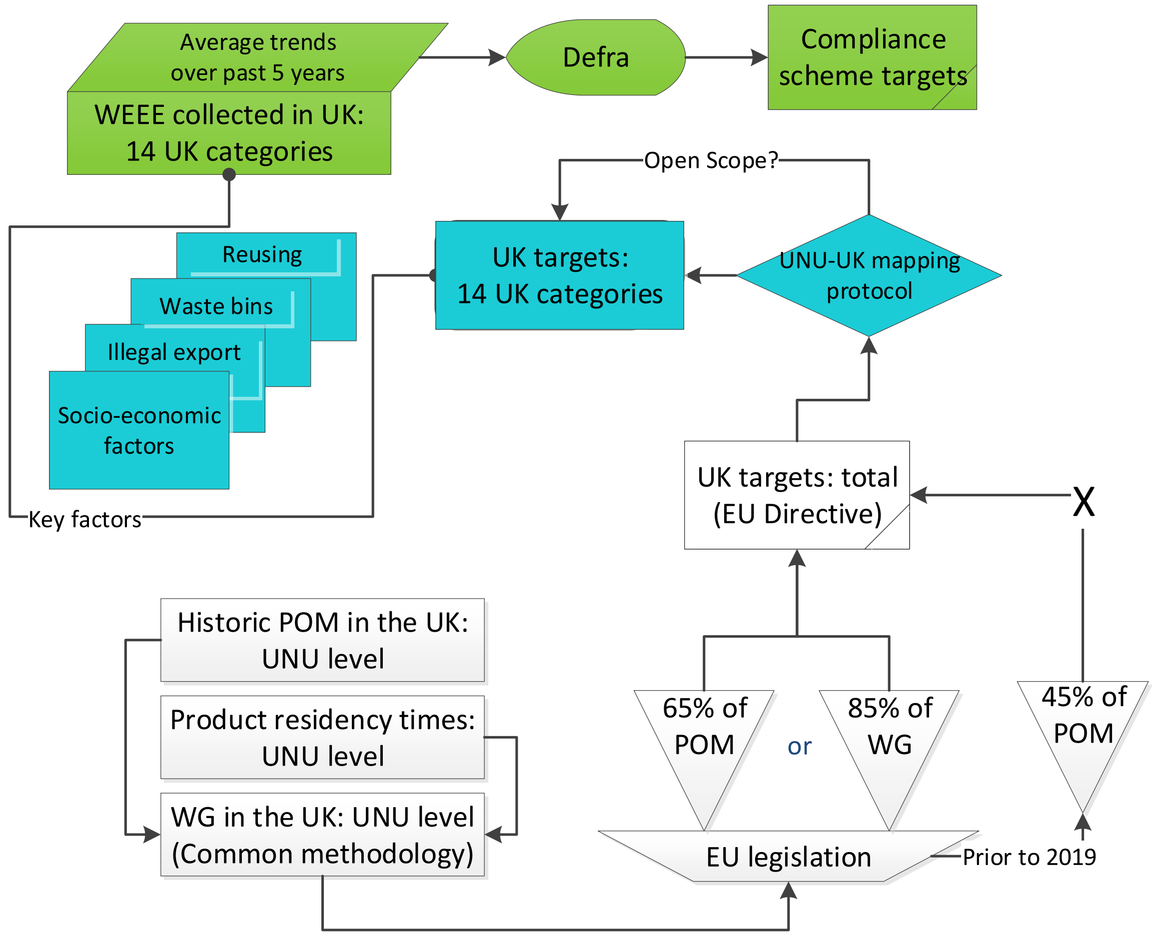


Figure 2. Relationship between the WOT model, target setting, and the inclusion of relevant UK and socio-economic parameters.

Mapping aggregate categories such as UNU and UK onto one another requires a higher level of granularity in terms of differentiation between the products. Such granularity is provided by CN product codes. A considerable amount of time and effort was invested into establishing the most complete list of CN products that are in the scope in the UK, both currently and under the Open Scope regulations. Part of this analysis involved updating the existing mapping between CN codes and UK categories, and creating a new mapping for the codes that previously did not have one.

We also investigated historic changes in the mappings between CN, PCC, UNU and UK categories, and developed time-varying UNU-UK-EU protocols that reflect on these changes and project the WOT model output onto the UK categories. There are separate UNU-UK-EU mapping protocols for POM and WEEE because the latter consists of EEE products that were being sold throughout the historic period (according to the residence time distributions), and therefore the WEEE mapping in a given year includes the POM mappings for all the previous years. Furthermore, the POM mapping protocols provide a methodology for filling the data gaps for POM on the CN level, which involved developing an intermediate PCC-UK protocol.

2.5 Suggested features of a prototype dynamic model for e-waste

We demonstrated in the previous section that the current generation of the WEEE quantification tools, such as the WOT model, are based on historic EEE POM and product residence times (Van Straalen et al., 2016). Although the POM data in these tools captures historic variations in sales and production across a wide range of products, there is no underlying economic model to link these variations with wider socio-economic conditions. Moreover, the residence times are largely static, implying that the results for WG are smooth and do not reflect on year-on-year fluctuations in the WEEE arising observed in the official data (e.g. 2019 collection target being 57,000 tonnes higher than the total amount collected in the previous year). Therefore, the key suggested feature of a new model, which will build on the existing WEEE tools, is the ability to estimate annual fluctuations in POM and WG in response to varying wider socio-economic conditions and specific EEE market conditions in the UK.

The wider socio-economic parameters will include the UK's inflation-adjusted GDP per capita, consumer confidence index (CCI), inflation indices (CPI or RPI), number of households, wealth distribution across the population, percentages of households with no or multiple units of a given product, number of businesses owning a given product, etc. The specific EEE market parameters will include inflation-adjusted prices of a given EEE product and other replacement, as well as new market drivers that affect the sales, trends in units' weight and so on, depending on the product.

3. Results

3.1 UK EEE and WEEE data, models and methodologies

The e-waste estimation gap analysis results highlighted the variety of products that are contained in each of the 14 UK (W)EEE categories (e.g. Yu et al 2010). The residence times and weights of these products can vary substantially, even within their respective categories (e.g. Wang et al., 2013; Bakas et al., 2014; Van Eygen et al., 2016; Wilson et al., 2017). Thus, in order to predict the total amount of WEEE arising, the analysis indicated that it would be better to initially work with more refined product categories, so that typical weights and residence times are more similar within each category (Van Straalen et al., 2016). Once the WEEE predictions have been made for these more granular categories, these can then be merged to obtain results for the 14 UK categories. To make accurate predictions, it is therefore necessary to have the following information for each product category of interest. First, historic sales data, as a product count per year, which would ideally span back to the 1980s, as some of the products sold back then still contribute to WEEE arising today (ibid).

Second, average item weight in the category (ibid). Third, product residence time distribution (Wang et al., 2013; Van Straalen et al., 2016).

Residence time distributions can vary over time. For example, recent trends show that product lifetimes are generally becoming shorter, which may lead to shorter residence times. One way to estimate residence time distributions is to ask producers to estimate after how many years 25%, 50%, 75% and 90% of the items in a category will have been discarded (TemaNord, 2009). It is not unusual to have an initial spike of WEEE resulting from a new product on the market, e.g. due to teething problems or some customers disliking the product. Therefore, producers should also be asked to estimate the percentage of items discarded in the first year.

A common issue for WEEE forecasting methods is that historic sales data can be difficult to obtain. While this doesn't matter much for products with shorter residence times, it is a problem for products with longer residence times. To resolve this, extrapolation/back-casting techniques are sometimes used (e.g. Bakas et al., 2014) to estimate EEE POM data as far back as the 1980s.

To establish EEE POM the WOT model (Van Straalen et al., 2016) uses sales data. When national production data is available instead, imports and exports need to be taken into account. In that case, the total sales of EEE are usually calculated as follows:

EEE sales = total domestic production + imports – exports

This is known as the Apparent Consumption method (ProSUM 3.1, 2017).

Some product categories have reached a saturation point, beyond which sales and disposal are strongly correlated. For example, the purchase of a new washing machine is likely linked with the disposal of the old one. New technology, which has not yet reached a saturation point, often shows an initially accelerating penetration rate. This eventually slows down and then levels out at some approximate saturation point. TVs however may be moved to another room in the building. An example of this can be found in a study to derive the penetration of computers over time in Algeria (Hamouda, et al., 2017).

The key findings from the gap analysis can be summarised as follows. First, the best available (W)EEE forecasting methods use historic sales data, in combination with product lifespan or residence time distributions, in order to forecast WEEE. Second, the best available (W)EEE forecasting methods have not previously been tailored for the 14 UK categories. Third, one drawback of current methods is that lifespan distributions are fixed based on the year of sale, while in reality lifespan distributions are likely to change due to various factors, such as economic influences, consumer preferences and new product developments (or lack thereof). The prototype dynamic model developed during Phase 5 of the project provides a feasible way of rectifying this shortcoming.

3.2 Unreported flows

Our survey led to both quantitative and qualitative insights from producers, retailers (dealing in second-hand goods) and those operating in the reuse or recycling space. The results included individual product line or aggregate category-level estimates for residence times, unregistered sellers, product trends and other factors.

The producer members who responded to the survey covered a wide range of product lines, ranging from kitchen appliances, dish washers, to Wi-Fi routers, indicating a good coverage of small and large appliances as well as consumer equipment. The data indicated several factors with the potential to significantly influence (W)EEE flows: fast market growth; decreasing average product weight; residence times shorter than product lifespan; and product distribution by unregistered sellers.

The most significant result was the difference between designed product lifespan and household residence time (64% of the respondents), suggesting that in order to estimate WEEE arising based on historic sales data, it is not sufficient to adopt the technological parameters, such as designed lifespan, from producers. In contrast, it is crucial to gather household-level data of product residence through the consumer end, and/or predict WEEE arising in relation to a wider socioeconomic context.

37% of respondents indicated that unregistered sellers had become a concern for certain products, mainly small appliances and consumer equipment. Neither our survey nor the data discovery have been able to provide any more details about unregistered sellers, but our survey results indicate that they might contribute to 5-10% of market share for given products. Such result resonates with an estimation in 2019 on the digital marketplace in Europe (www.eunomia.co.uk/tackling-freeriding-epr-online-sales).

Survey respondents were asked to estimate the past and future market change of (W)EEE across the 14 UK categories. The surveyed producers and the collectors shared similar insights on the changing patterns of (W)EEE, suggesting that some product categories will have a fast market growth. The volume of WEEE would most likely increase in product unit count, but many products are becoming lighter. The product diversities in all categories are going to increase, which might lead to even more complexity to the implementation of Open Scope.

The survey mainly looked into the following aspects of WEEE management insights: data and methodology gaps for EEE and WEEE quantification, managerial challenges, operational costs of WEEE collection and recovery, and concerns on future trends.

The results revealed that within the industry, the data and methods of estimating EEE and WEEE are extremely limited. The producers and collectors mentioned that the following managerial waste management challenges were not taken into account when setting targets for legislation. First, unreported flows, second-hand markets, discrepancies in product lifespan and household residence times, and component part removal/theft were indicated as factors that could impact the differences between WG and WEEE collected and cause an imbalance in National Target setting for producer compliance. Second, for cooling appliances, the UK market has limited capacity of processing this category as only few suitable recyclers are based in the UK, while leads to high gate fee charges to dispose of these units. Third, price sensitivity of scrap/iron is an issue: if there is any future price disruptiveness in the scrap value, it would be financially difficult for the facilities that operate the dismantling process; in contrast, if spot prices are high, the producer compliance scheme access to WEEE will reduce. Fourth, retailers in the market may conduct activities that indirectly restrict the access to WEEE by the PCS; for example, retailers collect old products on home delivery for a fee paid by the consumer, so they have an income stream to offset the cost of collection, while some retailers are even building their own recycling plants. Fifth, small appliances are less viable to reuse, as new goods continue to be put on the market at low cost and with limited durability. Sixth, the producer compliance system does not always meet the full cost of collection, transport and processing, other than for Local Authorities, so there can be a cost attached for other third parties involved in reuse and/or recycling. Finally, the illegal export and extraction of higher value scrap provides a demand for material outside the legal system.

The collector, recycling and reuse respondents had concerns with the increase in costs for WEEE management. This was attributed to several factors, including: increases in labour costs, insurance premiums, and fuel prices; changes in product weights; investment in plant technology; on-going training requirements outlined in legislation (The Waste Management Licensing Regulations 1994); compliance with legislative and industry standards; low gate fees; complementary flows; uncertainty of feedstocks; reduction in the value of metals and plastics; and the availability of producer compliance scheme funding. This indicates that there are a wide range of factors that impact on WEEE generated and collected, which need to be included in future modelling techniques.

We also discovered that the major concerns, besides the changing weight/size of (W)EEE, for future trends in innovation and technology, are around battery and internet technologies. Despite batteries not being included in the weight of EEE and WEEE, the collectors raised significant concerns. As an increasing part of the market moves to rechargeable from single use, the time that batteries remain on the market is lengthening. Rechargeable batteries normally last the lifetime of the product. This gives concerns regarding recovery capacity, disassembly, and fire safety issues in WEEE collection and storage. Other concerns regarding future trends include the increasing use of internet-based components in household appliances (e.g., smart kitchen, voice recognition technologies), so that more products will have Wi-Fi components, leading to potential difficulties of dismantling and recovery. Other technologies mentioned included transparent TVs and AI robots.

The foreseen changes in recycling and compliance centred on anticipating changes in legislation (e.g. change that could put current operations at risk companies), moving recycling target, and market changes. The following concerns were mentioned. First, the ever-tightening restrictions on hazardous chemicals in new EEE products will further limit the viability and demand for recycled materials from WEEE, at least for the manufacture of new EEE. Second, there are concerns about the legislation that increases compliance targets, changes the compliance fee mechanism and management of waste streams, but does not factor in product weight changes. Third, there are uncertainties in material market from recycling: some material streams be pushed to one side e.g. plastics exports, while the overall impacts on the material market of improved recycling rates are poorly understood. Fourth, a reduction of certain WEEE flows this could trigger recycling plant closures, as the plant capacity can no longer be met. Finally, there is an inevitable uncertainty due to the UK leaving the EU.

Some respondents shared new data regarding product weights and residence times. This helped to check the relevant settings in the WOT model, but significant or substantial new data was not provided.

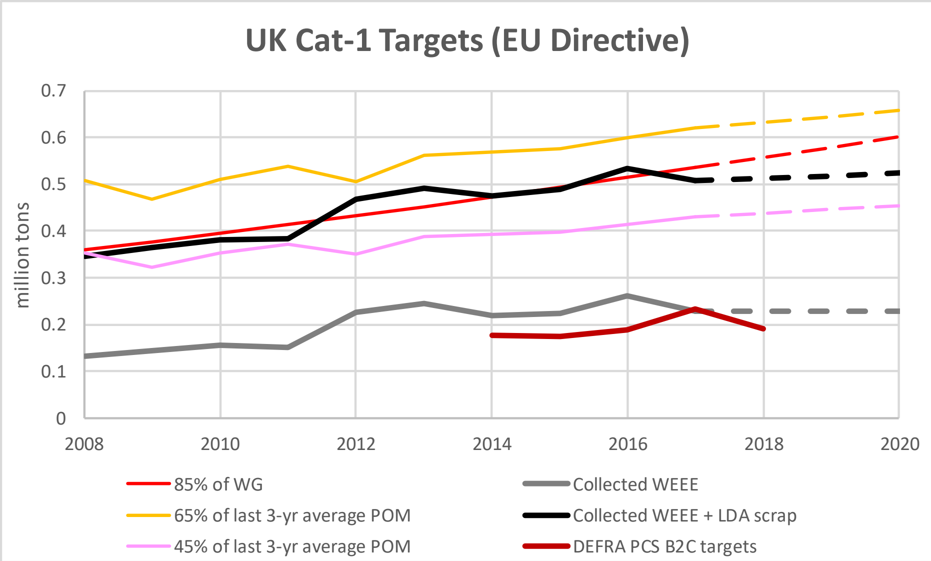
3.3 A new UNU-UK mapping method and WEEE targets for UK categories

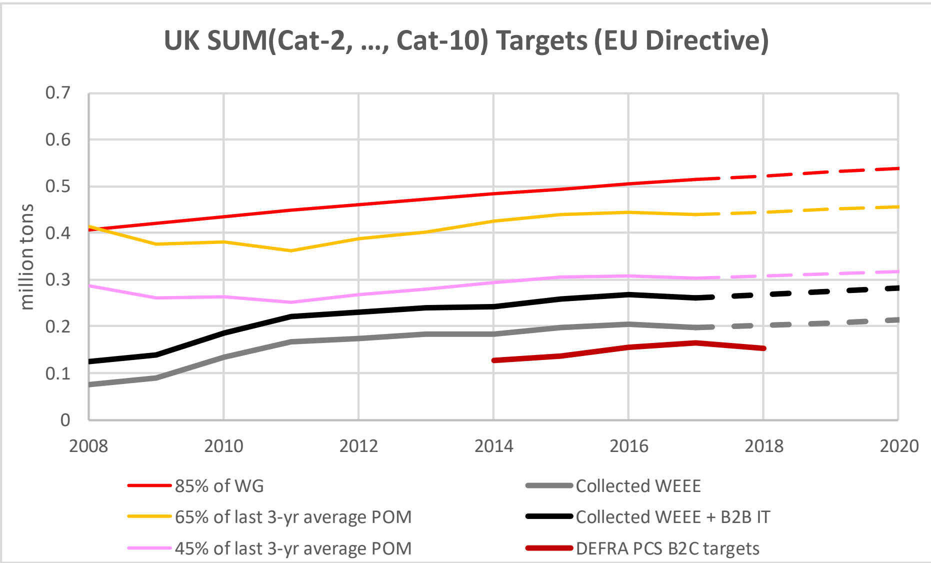
According to article 7.1 of the WEEE Directive 2012/19/EU, the UK-wide collection targets are defined either using the 45% or 65% of the average POM from the previous 3 years, or 85% of WG in a given year. Projecting them on the individual UK (W)EEE categories, although this is not part of the current EU Directive, should help assess how far the collected WEEE is from the theoretical levels of WG in each category. This would indicate where the total unknown WEEE is, which includes WEEE lost to landfill, theft and illegal exports, as well as show category-level lags between POM and WG, which are important for future planning. Combining this information with improved data on legitimate flows and substantiated estimates (light iron scrap from large domestic appliances (LDA); B2B IT from asset recovery companies) could ultimately be used to drive further improvements in the PCS WEEE collection targets and reduce WEEE losses. As part of any improvements, it may be necessary to educate consumers on proper WEEE disposal, and work closely with local authorities and other actors to reduce the amount of WEEE or components stolen, managed illegally, and disposed of in landfill/incineration.

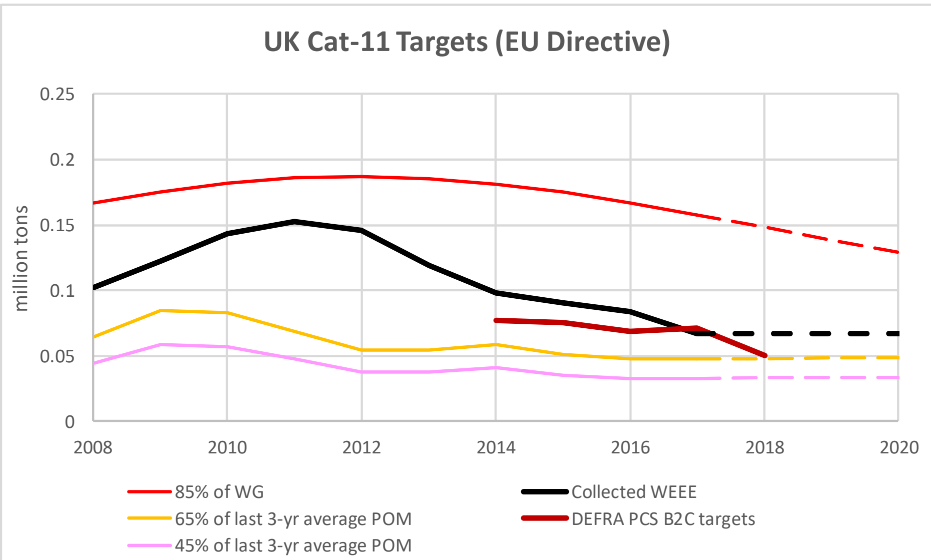
Developing UK category-level targets based on the EU Directive is dependent upon the mapping of the WOT1.2 results for POM and WG (UNU level) onto UK categories. These new "indicative targets" based on the EU Directive are different from the producer compliance schemes WEEE collection targets set by DEFRA, as the latter are based on calculating average trends in WEEE collected within each UK category over the past 4 years. We used the WOT1.2 estimates for POM and WG based on new UNU-UK mapping protocols to assess the 45% POM, 65% POM and 85% WG targets for the WEEE collected separately for UK Cat 1 (LDA), sum of Cat 2-10 ("small mixed WEEE", SMW), Cat 11 (TVs and computer displays) and Cat 12 (cooling equipment with refrigerants). The results, presented in 4 subplots in Figure 3, reveal category-specific challenges facing the sector in order to reduce WEEE losses and improve recycling rates, which are particularly acute for the small mixed WEEE.

To derive the UNU-UK mapping protocol, we identified two extensive lists of CN codes relevant to UK EEE market: one prepared by WEEE Europe in conjunction with REPIC, which has CN codes mapped onto UNU and UK categories; and WOT (Van Straalen et al., 2016), with CN mappings onto PCC and UNU codes, but no UK categories. These lists have 671 and 762 and CN codes, respectively, of which 292 codes overlap, while the rest are unique to each of the two lists. Combined, the two lists contain 1150 unique CN codes. We reviewed all the CN codes from the two lists combined, assigning UK codes to the WOT CN codes not on the WEEE Europe list for the first time, and updating the UK codes for the WEEE Europe list (part of which overlaps with WOT). We also indicated possible changes to the CN-UK mapping due to the implementation of Open Scope, which involved a technical conversation with e-waste economists from DEFRA. This was a difficult and sometimes ambiguous task given the terms used to describe the CN codes, and the on-going development of the UK guidance on scope. This assessment is, therefore, on-going.

The analysis of the CN-UK mapping defined by these lists showed that multiple UNU keys map to 2 or more UK categories. Therefore, to convert the UNU-level WOT model output for POM and WG into 14 UK categories, fractional weight flow splits are required, which define the new UNU-UK mapping protocols. The protocols are different for POM and WG, with the latter relying on historic versions of the former, and both types of protocols are time-varying, which reflects on the evolution of the individual products and aggregate categories with time. A detailed technical description of the new mapping protocols is provided in the Supplementary Materials.


UK Cat-1 Targets (EU Directive)
million tons
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2008
2010
2012
2014
2016
2018
2020
85% of WG
65% of last 3-yr average POM
45% of last 3-yr average POM
Collected WEEE
Collected WEEE + LDA scrap
DEFRA PCS B2C targets


UK SUM(Cat-2, ..., Cat-10) Targets (EU Directive)
million tons
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2008
2010
2012
2014
2016
2018
2020
85% of WG
65% of last 3-yr average POM
45% of last 3-yr average POM
Collected WEEE
Collected WEEE + B2B IT
DEFRA PCS B2C targets


UK Cat-11 Targets (EU Directive)
million tons
0.25
0.2
0.15
0.1
0.05
0
2008
2010
2012
2014
2016
2018
2020
85% of WG
65% of last 3-yr average POM
45% of last 3-yr average POM
Collected WEEE
DEFRA PCS B2C targets

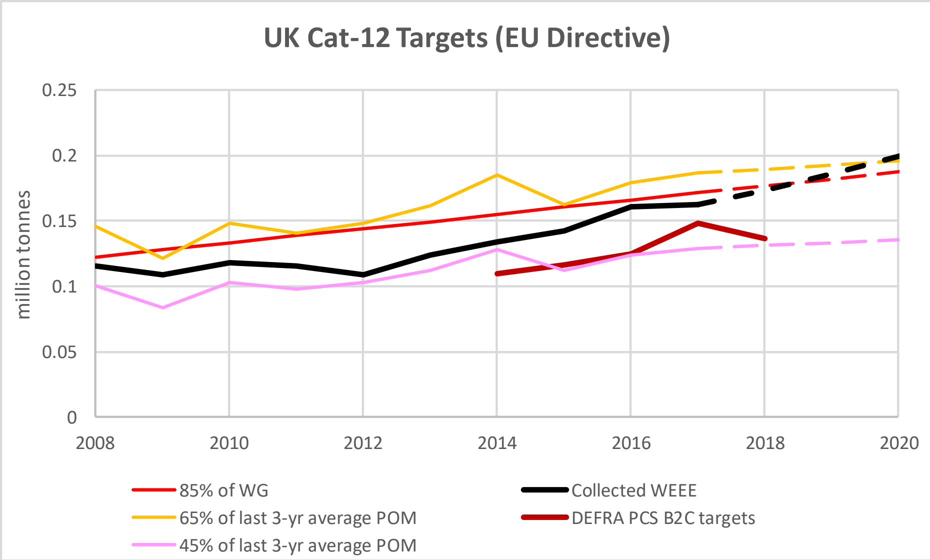


Figure 3. The Indicative "85% of WG" and "65% and 45% of POM" Targets for UK Cat-1 (LDA), 2-10 (SMW), 11 (displays) and 12 (cooling equipment), based on the EU Directive and projected on UK categories using time-varying UNU-UK protocol. The plots also show WEEE Collected with substantiated estimates for LDA scrap (Cat 1) and B2B IT (Cat 2-10), and DEFRA PCS targets for 2014-2018.

3.4 A prototype dynamic model: case study for fridges

Building upon all of the above, we developed a prototype for a new dynamic model for POM and WG, as called for by Wang et al. (2013), and identified the crucial data gaps. The new model is driven by several socio-economic and market parameters that have not been included in the current generation of the IOA models. The prototype is able to reconstruct historic POM estimates from WOT with a good degree of accuracy and provides a plausible explanation of how both POM and WEEE generated have been responding to year-on-year fluctuations in the economy. In the results for fridges presented in Figure 4 and Figure 5 (number of units sold and discarded), we used UK ONS data (www.ons.gov.uk) for index-linked GDP and number of households, along with reconstructions of historic inflation-adjusted prices per unit. We also introduced an elasticity parameter for product replacement behaviour depending on the disposable income relative to the unit's price, which affects the product residence time when the market is mature. These features allow the estimates for WG to respond to socio-economic and market fluctuations. Further details of the model and its calibration based on the data are provided in the Supplementary Materials.

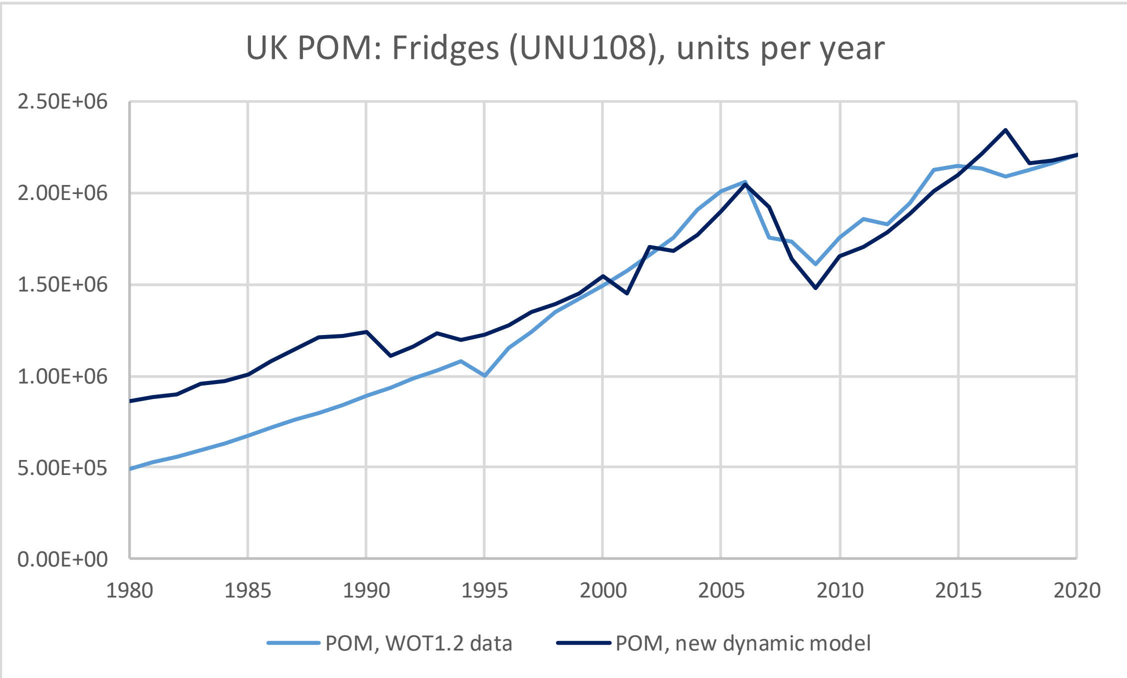


Figure 4. Modelled POM (units) for fridges in the UK, which provides the closest match to the WOT1.2 data for POM (number of units) between 1995 and 2021, plotted against the latter. Source: new dynamic model (prototype) driven by a number of socio-economic and market parameters.

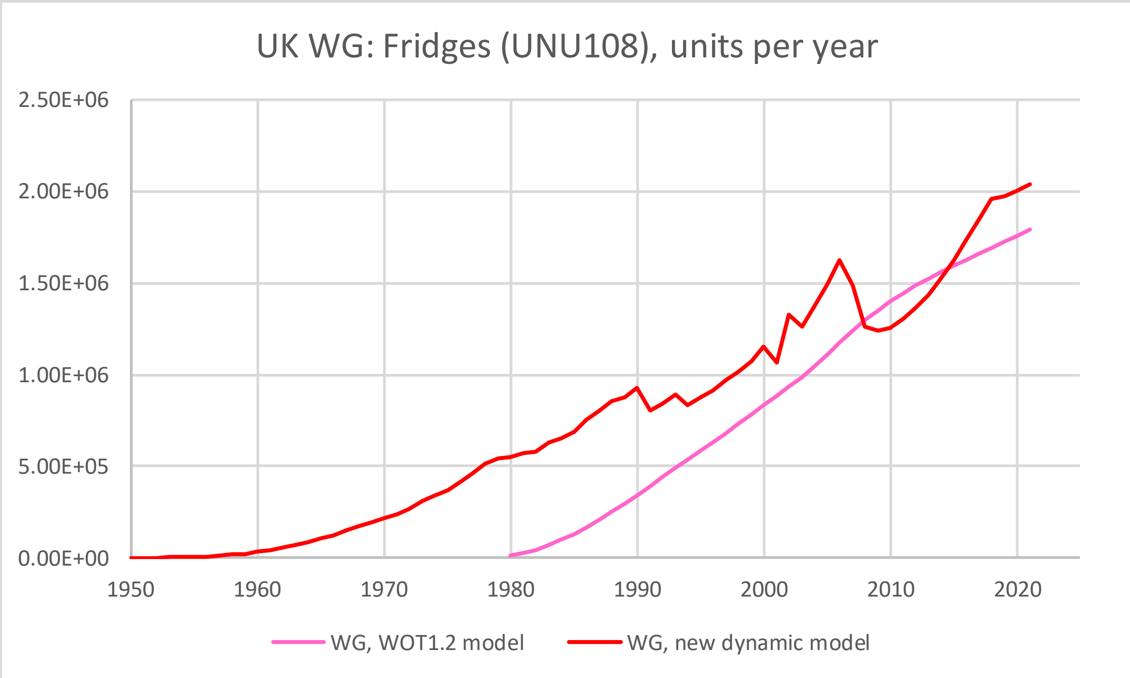


Figure 5. Modelled WG (units) for fridges in the UK corresponding to the optimal solution for the POM with the closest fit to the WOT1.2 data (number of units) between 1995 and 2021. The WG from WOT1.2 is also plotted for reference. Source: new dynamic model (prototype).

4. Discussion and conclusion

Our research enhances UK e-waste estimations through the adaption of the current EU-wide Waste Over Time (WOT) model for e-waste generation. Addressing Wang et al. (2013) and Van Straalen et al. (2016) call to include wider socio-economic parameters we have shared how this could be undertaken in a UK context. Starting with highlighting how this could be achieved by creating a novel mapping method to track and match weight flows from one set of aggregate EEE categories to another. This novel method improved our understanding of how the aggregate EEE categories adopted in the UK and EU relate to the underlying granular product databases in the trade statistics (Eurostat), which includes the time-evolution of the mapping as old products get disconnected and new ones enter the market.

In addition, we provide new insights into the socio-economic parameters that policy makers should take into consideration when setting new targets to enhance overall recycling rates. A wider set of parameters need be taken into consideration, as current forecasting methods are reliant on predetermined lifespan distributions for weight-based calculations of EEE POM and WG. Our gap analysis and survey results indicate disparities between EEE POM, WG and WEEE collected that can trigger an imbalance in National Target setting. Focus areas should include: Mass Balance – missing components (e.g. compressors, hard-drives etc.) and changing product weights should be better represented; Product lifespan and residence times – more information needs to be gathered from households since current data mostly comes from producers; Unreported Flows – further insights into second-hand or used EEE, legal and illegal WEEE flows are required.

Our findings compliment previous industry studies with some similar findings (WRAP, 2011; 2012; 2016). Collecting data within the areas indicated above should be prioritised, as this would not only provide input into a new dynamic model, but will improve intelligence about the implications of Open Scope, compliance target setting, compliance costs and current and future protocols. Capturing products as they enter the market, their weight and their fates would also provide insights into EEE POM and WG trends. Accurate information on product lifespan and residence times would give much needed insights into time horizons from EEE POM to WG and the basis for target setting. In addition, gathering further intelligence on unreported flows will identify system losses and possible entry points for unregistered sellers.

These new insights could help redirect the flows of EEE POM and WEEE, e.g. by boosting the demand for secondary materials from WEEE and/or by stimulating growth in the second hand or used EEE sector. The desired outcomes of these investigations are especially important given the UK's Circular Economy and Clean Growth strategy (BEIS, 2017), which includes an ambitious target to achieve zero waste by 2050 (Defra, 2018a).

In conclusion, we argue that there is a need to move beyond the "one-in-one-out" assumption in order to have a more robust understanding of UK EEE and WEEE flows. This requires the following data: historic production and trade statistics, in combination with product lifespan distributions that can be derived from surveys; outputs for EEE POM and WG that are tailored for the 14 UK Categories; socio-economic factors that reflect consumption trends; market and technology trends that impact on purchase, weight, end of life patterns, reuse and recycling; and, better quantification of the fates of WEEE which are unreported or unknown. Utilising these data-driven insights would be beneficial both to practitioners operating in this space, and researchers focusing on e-waste estimations regardless of EU member state.

The next step of developing the dynamic model is to build on the existing body of qualitative and quantitative research on EEE markets to derive statistical relationships between the socio-economic and market conditions introduced above, and the products' annual sales, stock and residence times. Where the data is not available, the quantifications of the proposed relationships will rely on tailor-made surveys across the EEE sector. Although considerable further development of the dynamic model is needed at this stage, we suggest that adopting some of the principles showcased in the prototype model presented here could already assist UK and other EU countries with getting a better insight into flows and fates of waste. In turn, having more robust estimates for Waste Generated (WG) and improving knowledge of unreported flows of WEEE could enable a richer understanding of the amount of WEEE available for collection, and assist with future policy setting aimed at increasing the collected WEEE.

Author Contributions

AS, SD, LL and DY conceived the research, AS, LL and ISB undertook the gap analysis and designed the survey with SD and DY. AS and LL disseminated and analysed the survey data, ISB, DY and SD analysed the quantitative data. DY and ISB developed the mapping protocols, DY developed the dynamic model. All wrote the paper.

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