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Modelling the levels of Historic Waste Electrical and Electronic Equipment in Ireland

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Contents

ABSTRACT	3
KEYWORDS.....	3
1. Introduction	4
2. Literature Review.....	5
2.1 Introduction	5
2.2 Ireland and the Waste Electrical and Electronic Equipment Directive.....	5
2.3 Modelling & Quantifying WEEE in Ireland	6
2.4 WEEE in Europe	8
2.5 WEEE in Asia	9
2.6 WEEE in the Americas.....	11
2.7 WEEE in Africa.....	12
2.8 WEEE in Oceania.....	13
3. Calculating Historic WEEE in Ireland.....	14
4. WEEE Generated Model Results.....	16
5. Validation with Irish WEEE Sampling.....	24
6. Conclusion and Recommendations	29
References	30

ABSTRACT

The implementation of the WEEE Directive in Ireland introduced a formal system for the return & environmentally sound management of WEEE. Visible fees were introduced to cover the cost of the environmentally sound management of “historic WEEE”. However, very little was known about the levels of historic WEEE that would arise, which created uncertainty with regard to funding the management of this historic WEEE.

This research employed novel modelling techniques in order to determine existing WEEE levels and predict the percentages of historic WEEE in Ireland. The research focused on “cold”, "large domestic appliances" and television WEEE and calculates Irish historic WEEE levels using data from disparate sources. The model determines EEE sales, total WEEE figures and the ratio of historic to non-historic WEEE for years 2000-2020.

The research findings indicate that historic WEEE comprises well over 50% of all material returning through official WEEE take-back channels in Ireland in 2015. Model predictions range from 2015 figures showing 69% cold WEEE will be historic in nature, 59% of large domestic WEEE will historic and 77% of all television WEEE will be historic. For 2020, these figures will reduce to 45% historic WEEE for the cold category, 38% historic WEEE for large domestic appliances and 54% historic WEEE for televisions.

These model results were validated using a statistically significant sampling of WEEE in Ireland over the course of 1 year. Cold, domestic appliance and television WEEE were sampled in order to determine the actual ratio of historic versus non-historic WEEE.

KEYWORDS

WEEE, E-Waste, Recycling, Statistical Analysis, Empirical Validation

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1. Introduction

In this report, the specification, development and validation of a model for the prediction of historic WEEE return rates in the Irish market is detailed. It was developed as a collaborative work between the University of Limerick and the United Nations University (UNU), and models the Irish return stream figures for EEE, WEEE and historic WEEE for the years 2000 to 2020 inclusive.

The implementation of the Waste Electrical and Electronic Equipment (WEEE) Directive in Ireland in August 2005 was a landmark event in the recycling of electrical and electronic equipment (EEE) in Ireland. Prior to this, end-of-life practices for such equipment were unstructured with no overarching framework, and landfilling and dumping were widespread. Under the new regulations, a take-back infrastructure at civic amenity sites and retailers was established, landfilling was banned and recycling was made mandatory with a collection target of 4 kg per person per year. Furthermore, according to the directive, the environmentally sound management (ESM) of any equipment placed on the market after 15 August 2005 must be financed by the producers, and for products already on the market, visible fees were agreed. These visible fees are implemented at the time of sale of certain new equipment in order to create a fund to finance the ESM of the historic WEEE arising from products already on the market. Two “not for profit” WEEE compliance schemes were established by producers to assist with the compliance with these new obligations.

These visible fees associated with EEE sales have allowed the build-up of contingency funds for the ESM of historic WEEE; however, the question of how much money will actually be required was not fully resolved when the visible fees were agreed as the necessary information to make such a judgement was simply not available. However, those involved in the collection of WEEE in Ireland have observed that historical WEEE continues to show up in significant quantities at all WEEE collection points across the country. At that time there was no way of accurately measuring or predicting the return rates of historic WEEE, hence it was still unclear how much longer before all of the historic WEEE has made its way back into the return stream for recycling. This paper details research carried out to address this and other related uncertainties, in order to provide an evidential basis for the continued use of visible fees and predict the return rates of historic WEEE in Ireland in the future.

Section 2 of this paper contains a brief review of the WEEE Directive and related WEEE/e-waste literature from a global and regional viewpoint. The specification and development of the model created through this body of work, herein referred to as the “WEEE Generated Model”, are described in Section 3. Section 4 details the modelling results and presents the predicted levels of EEE, WEEE and historic WEEE in Ireland up to the year 2020. The validation of the model and its findings are described in Section 5. This validation was performed by comparing the model results with sampled data collected from various Irish civic amenity sites, retailers and WEEE recycling facilities. Finally, the conclusions and recommendations from the project are presented in Section 6.

2. Literature Review

2.1 Introduction

WEEE (also sometimes referred to as e-waste) is one of the fastest-growing solid waste streams across the globe. **Dwivedy and Mittal, 2010** attribute this rapid growth to factors such as continuous technological innovations, combined with increasing consumer demand, which has led to a rapid proliferation of electronic devices on the market. With this ever-increasing market for EEE, correspondingly large quantities of WEEE are being generated. Furthermore, this phenomenon is compounded at present by decreasing product lifespans and an increasing range of new and different product types, as highlighted in a recent article from the German Environment Agency (UBA).¹ This review presents an overview of the WEEE Directive, the software tools and systems used in the development of the WEEE flows model and a review of WEEE quantification studies worldwide.

In 2014, the UNU-IAS published the first global e-Waste (or WEEE) monitor report (**Baldé et al., 2015**). In this document, the authors describe the emergence of e-waste, or WEEE, as one of the fastest-growing waste streams worldwide, with complex characteristics and an aggressive growth history, facilitated by the shorter times-to-market of modern technology and ever-shortening product lifespans.

The authors of the report estimated that the amount of e-waste generated globally in 2014 was approximately 41.8 million tonnes. Of this, approximately 6.5 million tonnes was reported as being formally treated by national take-back and recycling/reuse schemes. In the EU alone, 700,000 tonnes of WEEE ends up in rubbish/waste bins annually. The amount of e-waste is expected to grow to 49.8 million tonnes by 2018, with an annual growth rate of 4% to 5%.

Most of the e-waste surveyed in the report was generated in Asia: 16 million tonnes in 2014. The highest per inhabitant e-waste quantity (15.6 kg/inhabitant) was generated in Europe, with a total e-waste generation total (including Russia) of 11.6 million tonnes. Oceania generated the lowest quantity of e-waste, 0.6 million tonnes. However, on a per-inhabitant scale, the amount was nearly as high as in Europe (15.2 kg/inhabitant).

Africa generated the lowest amount of e-waste per inhabitant: only 1.7 kg/inhabitant was generated in 2014. This equates to 1.9 million tonnes of e-waste for the whole continent. The Americas generated 11.7 million tonnes of e-waste in 2014 (North America generated 7.9 million tonnes, Central America generated 1.1 million tonnes and South America generated 2.7 million tonnes), which represented 12.2 kg/inhabitant.

In the EU, approximately 40% of the WEEE generated annually is treated through approved recycling and reuse channels at present (see **Magalini et al., 2016** for more information); in the USA and Canada, the level is around 12%; for China and Japan, it is around 24–30%; and in Australia, it is around 1%.

2.2 Ireland and the Waste Electrical and Electronic Equipment Directive

To improve the end-of-life handling of WEEE (which can cause major environmental and health problems if not properly managed), lessen the impact of such waste on the environment, contribute to a circular economy and enhance resource efficiency in this sector, the WEEE Directive was introduced in the European Union (EU). The first EU WEEE Directive (2002/96/EC) was passed in 2002 as a producer responsibility directive which sought to improve the sustainable management of electronics at the end of their life by promoting the reuse, recycling and recovery of WEEE.

In Ireland, after its transposition to national law, all producers and distributors (retailers) of EEE had to comply with the 2005 National WEEE Regulations [Statutory Instrument (S.I.) No. 340 of 2005]. These regulations catered for both commercial [i.e.

¹ <http://www.endseurope.com/article/45200/uba-calls-for-product-resource-efficiency-policies>

“business to business” (B2B)] and domestic [i.e. “business to consumer” (B2C)] producers and distributors. The original WEEE Directive set an initial collection target of 4 kg, on average, per head of population per year of WEEE from private households (to be achieved by 31 December 2006).

In December 2008, the European Commission proposed that the original WEEE Directive be revised in order to address a number of shortfalls. These shortfalls were related to, for example, the unparalleled increase in the magnitude of the waste stream, which meant that original collection targets needed to be revised; the need to address illegal shipments of WEEE outside the EU by enforcing compliance with Waste Shipment Regulations more stringently; allowing reuse organisations access to WEEE material and the revision of the method for calculating collection rates in various member countries in the future.

The revised (recast) WEEE Directive [Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE)] was published on 4 July 2012 and came into effect on 13 August 2013. Member States had to transpose the revised WEEE Directive into national legislation by 14 February 2014. Key differences in the recast WEEE Directive include:

- More ambitious collection targets [a 45% take-back of what is placed on the market averaged across the previous 3 years' placed-on-the-market (POM) figures] to apply from 2016. This target will increase to 65% of EEE placed on the market or, alternatively, 85% based on WEEE generated after 2019. The existing collection target of at least 4 kg per person remained in place until the end of 2015.
- An increase in recovery targets: mandatory collection targets have increased to 65% of the average weight of EEE placed on the market over the previous 3 years in each Member State. The recycling and recovery targets increased by 5% on the basis of weight.
- The scope has been widened to include all EEE, except specific exemptions. In addition, the categories have been reorganisation into six types or “families”. After 14 August 2018, all types of WEEE will be covered (i.e. there will be an “open scope”).
- The free take-back of small household appliances (no more than 25 cm) to retail stores (with a sales area of at least 400 m²), regardless of whether the customer buys a new product or not.

Ireland's 2014 WEEE Regulations [European Union (Waste Electrical and Electronic Equipment) Regulations 2014 (S.I. No. 149 of 2014)] replaced the 2005 and 2011 regulations and amendments, and give effect to the provisions of the EU WEEE Directive 2012/19/EC in national legislation.

2.3 Modelling & Quantifying WEEE in Ireland

The historic WEEE rates for a variety of product classes in Ireland are presented in this journal paper. These predictions are generated using models of the EEE stock in the Irish market, recycling and return rates of WEEE in Ireland and numerous other contributing factors. In order to attain an accurate estimation of quantities such as the timing and distribution of disposed consumer electronics/appliances for use in such models, it is essential to accurately map and model these datasets for the sustainable and efficient prediction of end-of-life consumer durables (**Kang and Schoenung, 2006a**).

Models, as simplified representations of these real systems, can both reproduce, recreate (“portrait” models) and anticipate (“paragon” models) the systems involved and are crucial for providing a representation and understanding of the real system (**Pérez Ríos, 2010**). Lending credence to these considerations, research such as that conducted by **Ongondo et al., 2011**,

which globally reviewed the management of EEE waste management, concluded that the reported global quantities of WEEE are grossly underestimated.

Several authors have proposed models to forecast the waste flow of durable goods which may be used for comparison with the modelling method presented in this paper. Some reports focus on the product, quantifying the number or weight of one (or many) consumer durable product(s) (e.g. **Oguchi et al., 2008; Yang et al. 2008**). Other approaches involve studying the flows of materials from consumer durables and quantifying these flows at the material (e.g. lead, plastics, copper and glass) level, such as the work presented in **Elshkaki et al., 2005, Spatari et al., 2005** and **Gregory et al., 2009**.

In general, the different evaluation methods available for quantifying e-waste generation (including methods such as **Walk, 2004; Yu et al., 2010; Araújo et al., 2012; Lau et al., 2013, Wang et al., 2013**) can be classified into four distinct groups:

1. **Disposal related analysis** uses e-waste figures obtained from collection channels, treatment facilities and disposal sites. It usually requires empirical data from parallel disposal streams to estimate overall WEEE generation.
2. **Time-series analyses (projections)** extrapolate historical data into the future. This type of analysis can also be applied to fill in the gaps of past unknown years from available datasets.
3. **Factor models** tend to use determinant factors for correlation and are based on hypothesised causal relationships between exogenous factors, such as population size and income level versus e-waste generation (see **Beigl et al., 2003; Huisman et al., 2008; Huisman, 2010**). This is the least explored analysis method because of the associated complex anthropological effects, high uncertainty with regard to long-term patterns and the considerable requirement for advanced modelling techniques.
4. **Input–output analysis** is the most frequently used method and there are multiple model variations. This analysis method has been applied to estimate e-waste generation in many regional and country studies, including by **He et al., 2006, Kang and Schoenung, 2006b, Peralta and Fontanos, 2006, Yang et al., 2008, Robinson, 2009, Dwivedy and Mittal, 2010, Chung, 2011, Zhang et al., 2011, Araújo et al., 2012, and Polák and Drápalová, 2012**. This method quantitatively evaluates the sources, pathways and final sinks of material flows, as illustrated by **Walk, 2004, Beigl et al., 2003** and **Chung et al. 2011**.

The models presented in this paper rely heavily on the input-output analysis method. In particular, the work carried out in 2007 by the UNU-IAS (United Nations University Institute for the Advanced Study of Sustainability) on a review of WEEE (**Huisman et al., 2008**) made for a major contribution to the scientific basis for the recasting of the WEEE Directive and forms the basis for the model used in this research paper. This extended study led to a fundamentally altered recast WEEE Directive proposal². Complimentary research in the form of the Dutch WEEE flows study by **Huisman et al., 2012** provided for a more detailed and complete quantitative assessment of the WEEE flows, both in the Netherlands and the EU. The study focused on all WEEE types (but did not distinguish between WEEE and historic WEEE), developing methods to estimate quantities of WEEE based on historic sales data, average residence times, and stocks in households and businesses.

This study (and associated work) resulted in the development of a new and unprecedentedly accurate WEEE Generated Model by the UNU, which calculates WEEE amounts based on interrelated historic sales data, average residence times, and stocks in households and businesses. This UNU WEEE Generated Model is combined with Irish national statistics for this research.

² <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0019>

2.4 WEEE in Europe

In the United Kingdom, **Haig et al., 2011** describes research conducted by the WRAP organisation modelling flows of electronic products, producing estimates for the amount of material that will reach the end of its useful life in each year until 2020³. According to this research, the total tonnage of EEE POM (including unregistered goods) in the UK for 2015 was estimated to be 2,001kt. This figure is expected to rise to 2,098kt by 2020, a 19% increase on the same figure for 2015. The estimated total UK WEEE generated in 2015 was 1,528kt. By 2020, figures for WEEE generated are expected to increase by 1% and comparable figures for reported WEEE are expected to rise by 7%.

These WRAP studies estimated the current and future flows of EEE and WEEE in and out of the UK. The key goals of the reports were to forecast the likely volumes of used electrical and electronic equipment (UEEE) arising in the UK at the time and in future; to identify the main routes for the disposal and reprocessing of WEEE arising in the UK, both within and outside the formal WEEE processing infrastructure; and to quantify the likely flows of material separately for each WEEE category through each of the main disposal and reprocessing routes.

The projections used a normal distribution method to estimate lifespan distributions of products, in conjunction with sales data, to predict the quantities of WEEE arising in the UK and estimate material flows through the different parts of the treatment system after the decision is made by the user to dispose of a product.

In the TemaNord group report to the Nordic Council's subgroup on EEE waste (**Nordic Council of Ministers, 2009**), a method to calculate or measure the amount of WEEE generated in the Nordic states was presented. The main purpose of the project was to establish a method to measure WEEE generated. Although the method described in the report was originally developed for use in the Scandinavian countries, it can readily be expanded to cater for other countries and regions. This WEEE-measurement approach also allows for comparison and exchanges of experiences amongst the members. Furthermore, the approach is adaptable and can be updated as new information and datasets become available.

Pannuzzo, 2014 presented a treatise on WEEE in Finland, where EEE devices characterised by a high content of precious metals were considered. Temporal connections between POM products and WEEE collection/recycling in Finland were investigated, taking into account factors such as product lifespan and consumer behaviour. Statistical (historical) data for the report were gathered from official statistics and miscellaneous literature sources. These official statistics, literature data and surveys, which were carried out in the Helsinki metropolitan area, were used to perform a material flow analysis by means of mass balances. These results were then evaluated from an economic point view.

In Italy, **Magalini et al., 2016** present the results of a study done on the WEEE generated at a national level in the year 2011, the first of its kind in Italy. This study quantified household WEEE generated in Italy and highlighted consumers' WEEE disposal habits and attitudes in the country. The study found that household EEE put on market in 2011 in Italy amounted to 18.3 kg/inhabitant. The average annual EEE put on market nationally over the preceding three years (2008-2010) was 18.5 kg/inhabitant. Household WEEE generated in 2011 amounted to 16.30 kg/inhabitant, with the formal WEEE system collecting and treating 4.29 kg/inhabitant. For that year, this amounted to only 35.8% of the PoM target of 12 kg/inhabitant and 31.1% of the WG collection target of 13.8 kg/inhabitant.

In France, **Bahers et al., 2017** considers the WEEE chain and flows using the material flow analysis (MFA) method. The research presents a detailed case study of the EPR implementation for WEEE in the Midi-Pyrénées Region and the Toulouse urban area. Based on this MFA analysis, the results give an insight into operational activities dealing with circulation of waste material in France and highlight the main shortcomings of this WEEE management system, including lack of involvement by local authorities and consumers, dispersion channels and a low recycling rate at the local level.

³ http://www.valpak.co.uk/docs/default-source/environmental-consulting/eee530-uk-weee-flows-final_publish.pdf

In their report, **Wielenga et al., 2013** considered the WEEE situation in Belgium. The research presents work commissioned by Recupel, investigating the market structure and the mass balance of (W)EEE in Belgium. Specifically, the 2 research questions considered are determining how much EEE is put on the market in Belgium annually and the amount of WEEE generated in the country over a similar timeframe. The research found that for 2011, EEE introduced to the market totaled 26.2 kg per inhabitant, calculated based on national statistics on the production, import and export of EEE. The amount of WEEE generated from the market for the same year is calculated at 22.4 kg per inhabitant. The authors note that this is a reasonably accurate estimation, but it is based on a limited dataset for Belgium and therefore may possibly be improved in future studies.

In Denmark, **Parajuly et al., 2016** comprehensively mapped and estimated the flows of EEE and WEEE in Denmark, using a quantitative analysis method supplemented with a thorough diagnosis of the WEEE management system. Dynamic material flow analysis (MFA) was 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 in Denmark –with their lifespans modelled using Weibull distribution function. The models show that for Denmark, 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 to be saturated, and can be expected to remain largely unchanged over the next decade. Denmark has a well-established WEEE management system that has been performing adequately against the WEEE Directive. However, new legislation means a need for recalibration of the performance indicators for the country, where a more robust and systematic documentation of the flows will support the WEEE management system in achieving higher resource recovery.

In **Magalini et al., 2015**, the current WEEE situation in Romania is discussed. Here, a person owns on average 72kg of Electric and Electronic Equipment (EEE). Of this, 7.35kg/person is disposed of as WEEE. A maximum of 30% of this generated WEEE gets collected within the official collection systems and is reported as national result, a further 21% is given to relatives and friends with the remainder ending up in unofficial channels and bad disposal habits: WEEE that is taken to the waste bins, handed over to street collectors of scrap or randomly discarded.

Finally, in **Hilty et al., 2017** the authors investigate the service lifetime, storage time and disposal pathways of ten electronic device types in Switzerland, Based on data gathered from an online survey and structured interviews, the authors differentiate between new and secondhand devices, computing the histograms, averages, and medians of the different product lifecycles and their changes over time. From this data, the authors determine that the average service lifetime varies from 3.3 years for mobile phones to 10.8 years for large loudspeakers, with the average storage time varying from 0.8 years for flat panel display televisions to 3.6 years, again for large loudspeaker systems. Most service lifetime histograms for the 10 product categories are positively skewed and show substantial differences among the various device types. The storage time histograms are very similar across all products and indicate a similar storage behavior for most device types. The data on disposal pathways shows that a large proportion of devices are stored and reused before they reach the collection scheme in Switzerland.

2.5 WEEE in Asia

In South Korea, there have traditionally been no official statistics for annual WEEE generation or collection. **Kim et al., 2013** addressed this by estimating the annual amount of WEEE generated in South Korea between 2000 and 2020 for eight different products, as well as estimating the annual percentage of WEEE collected through the EPR bill (for more information, see **Wen et al., 2009**) recycling programme between 2003 and 2009.

They did this by estimating the amount of WEEE generated using a population balance model (PBM) in conjunction with a lifespan distribution analysis. Different WEEE generation methods have different advantages and disadvantages, depending on the estimation model used (**Wen et al., 2009**). For example, the PBM has been used in many academic studies (e.g. **Oguchi et**

al., 2006; **Yamasue et al.**, 2009; **Yoshida et al.**, 2009). Here, the authors claim that the main advantage of the PBM approach is that over- or underestimation of WEEE generation is less likely than with other approaches because the model utilises the mass balance principle of inflow (shipment volume), outflow (waste volume) and stock (ownership volume). In addition, it is a time-series material flow analysis model which allows for the estimation of past and future WEEE generation. However, PBM estimations are severely limited if estimating the amount of WEEE generated for products that have a fast growth phase or are declining stage on the market, as the parameters of lifespan distribution vary quite significantly under these conditions.

Lee et al., 2007 also modelled WEEE generation in South Korea from sales data and product lifespan information. The study employed the use of the estimation “delay model” (see **Van der Voet et al.**, 2002) which has been widely used in the field of WEEE generation estimation. The authors used this model to estimate the amount of WEEE generated for four end-of-life household electronic appliances between 2000 and 2005 on the assumption that the average lifespan of the four items was about 10 years. Also in South Korea, **Jang and Kim**, 2010 modelled the number of end-of-life mobile phones generated between 2000 and 2007 using data on the number of new subscribers, in conjunction with data on the number of phones purchased domestically in each of the years between 2000 and 2007.

In China, **Zeng et al.**, 2017 have found that the WEEE/e-waste has become a global issue in the areas of environmental pollution, resource recycling, and sustainable industry. China is not only one of the largest producer and consumer of EEE globally, but the researchers have found that the country is also seriously polluted from illegal e-waste importation and informal recycling. The authors specifically examine the history of e-waste management in China, especially as related to the legislation system and seek to outline the lessons and shortcomings found.

Comparing China and India in terms of e-waste management, **Awasthi & Li**, 2017 argue that with such a large quantity of e-waste being generated in both India and China, both countries still suffer from an entrenched informal e-waste processing sector. Consequently, valuable e-waste materials are disposed of in landfills rather than being properly reused and recycled. The authors note that the major portion of e-waste in China and India is collected by the informal sector and treated with primitive methods. Additionally, unscrupulous agents also play a role by mislabelling e-waste and exporting it illegally to developing countries. The implementation of e-waste management laws and policies for proper e-waste collection, treatment and recycling are proposed to address this. Furthermore, better consumer education on the dangers of e-waste contamination, the restriction of the illegal movement of e-waste across borders and support for the development of a formal, regulated e-waste processing industry by funding incentive programs constructing recycling infrastructure are also proposed. These measures should increase the recycling capacity and decrease the amount of WEEE contaminating the environment and endangering human health in both countries.

Looking at India, **Borthakur & Govind**, 2016 consider the e-waste problem and attempt to review two key elements greatly accountable for influencing sustainable e-waste management initiatives: namely ‘Disposal Behaviour’ and ‘Awareness’. The research performs an extensive review of these factors from a global context and identifies measures adopted by the consumers of different countries to dispose of their e-waste.

Authors **Imran et al.**, 2017 review the e-waste situation at present in Pakistan. Pakistan receives thousands of tons of e-waste from developed countries such as the USA and Europe. This research models and estimates the e-waste flows in Pakistan and assesses potential quantities of recyclable metallic and non-metallic components. Research found that, on average, 95,415 tons of e-waste is imported into Pakistan annually. It contains a variety of metals such as gold, silver, copper and non-metals like plastics and glass as well as hazardous materials. It was also found out that all the recycling activity takes place in informal sectors without any consideration to environmental pollution and safety of workers. From the research, improvements in the existing legal framework regarding import and recycling of e-waste have been proposed, including take back facilities, prohibition of illegal import and good environmental management.

In Japan, **Oguchi et al., 2006** carried out a questionnaire-based survey related to the equipment owned by households and enterprises, and, specifically, the WEEE lifetime of such items. In particular, the study estimated the life-cycle profiles for 23 different types of EEE. Using these lifetime distributions, the quantity of waste equipment was estimated for the years 2003 to 2008. The analysis found that, in Japan, the average lifetimes of relatively expensive equipment tend to be longer than the lifetimes of less expensive items, whereas small to medium-sized equipment tend to have relatively short lifetimes. The total WEEE arising numbers for the 23 types of equipment considered was estimated to be 130 million units, of which waste cellular phones accounted for 45 million units.

Of related interest, **Oguchi et al., 2008** conducted a product flow analysis (PFA) for 94 consumer durables in Japan to obtain a complete picture of the domestic flow. Data on domestic shipment, average weight and average lifespan of each product were surveyed and estimated based on statistics and product catalogues from manufacturers. Using these data, the quantity of domestic shipment and waste from households and enterprises was modelled as inflow and outflow to the system.

This study was the first to report on the complete picture of domestic product flow of consumer durables in Japan. On the basis of the results, the target items for Japan's recycling laws were validated in terms of market share, landfill waste reduction (because the total waste weight of 9 target items accounts for 68% of the total 94 items) and overall return on investment. The number of waste products was relatively large for items such as cellular phones, video cassette recorders (VCRs) and notebook PCs (which contain numerous hazardous and/or valuable substances), but, as expected, their combined waste weight was small. The waste product to collection ratio for the nine selected target items ranged from 2% to 56% on a weight basis (and from 4% to 59% on a number basis), because some waste products are taken to industrial waste treatment facilities and exported. In addition, at the post-consumer stage, approximately 46–68% of the waste products are still unidentified in the flow diagram for the 94 items. These products might have been treated as municipal or industrial waste, exported or illegally dumped; therefore, their flow is still to be clarified through further research.

2.6 WEEE in the Americas

In the study by **Araújo et al., 2012**, the authors considered the generation of WEEE in Brazil. In developing countries such as Brazil, the sales of EEE are increasing dramatically. Usually, there is no reliable data about the quantities of such WEEE generated. A new law for solid waste management was brought into force in Brazil in 2010. This has meant that the necessary infrastructure to ensure the ESM of WEEE has been designed, developed and implemented in the country. This paper considers some of the models used for WEEE estimation and calculation as part of this infrastructure in Brazil.

Elsewhere in Brazil, **Moura et al., 2017** consider the perceptions and practices of institutional users (IUs) and technical assistances (TAs) of electronic equipment. The study analyses the relationships between these two sectors, the electronic equipment (EEs) and their waste, in Blumenau, Brazil between the years 2010 and 2015. The results show a downward trend for the useful life perception of the equipment considered. Moreover, the study identifies informal recycling companies of electronic waste (e-waste) as a market that has increased in Brazil. It was also observed that over time there has not been a major change in knowledge about laws of e-waste.

In North America, **Duan et al., 2014** consider the e-waste market in the U.S.A, specifically looking at the limited corroborated quantitative data on the export of used electronics from the U.S.A. The authors advance a methodology to quantify these export flows (in terms of whole units) for used electronics from the U.S.A using detailed export trade data, and demonstrate the methodology using laptops.

Tansel, 2017 reviews the challenges associated with increasing e-waste levels both nationally in the USA and at a global level. The authors show how the increasing demand for raw materials (especially for rare earth and minor elements) and unregulated e-waste recycling operations in developing and underdeveloped countries are contributing to the growing concerns for e-waste

management. Although the markets for recycled materials are increasing, the authors fear that it is still not sufficient to address the deficit and feel that there are major development challenges ahead for the necessary e-waste management infrastructure and accountability as well as development of effective materials recovery technologies and product design.

In Canada, **Kumar et al., 2017** presents an overview of the statistics on global e-waste generation and the sales of new electrical equipment and electronics in general. According to the authors, the total amount of e-waste produced has reached approximately 41 million tonnes in 2014 and is increasing at a rate of 3–5% every year. A correlation between e-waste generated, gross domestic product and the population of Canada has been explored, which suggests that the GDP of any country has a direct correlation with the amount of e-waste produced by that country. The paper also describes the importance, benefits and current state-of-the-art for recycling and recycling facilities in Canada.

2.7 WEEE in Africa

In Africa, **Egeonu & Herat, 2016** considers the management of e-waste across the continent. Managing e-waste in an environmental safe manner has remained a major problem for many countries around the world. In developed countries, the management of e-waste is considered a serious issue and forms part of the core policy direction of the government. On the other hand, developing countries in general are yet to effectively manage the problem of e-waste or make it a central part of the government's policy decisions. However, this has led to massive generation and indiscriminate disposal of e-waste in certain African countries and continuous trans-boundary movement of these toxic more so, owing to the lack of proper legislation and effective enforcement, the processing of e-waste is left primarily in the hands of the informal recycling sector that is either inadequately equipped with the right facilities and tools or lack the contemporary knowledge of recycling e-waste through environmental sound management (ESM) techniques. This article aims to present a review of some of these challenges and issues faced by African countries in managing their e-waste in a sustainable way.

In Ghana, **Hörtl et al., 2017** present an e-waste case study for Ghana. A huge proportion of the global e-waste is exported from the industrial countries to developing countries such as Ghana, to save costs and due to the lack of recycling plants in developed countries. The significant environmental and social problem in Ghana in this context is that the electronic devices are mostly recycled in informal plants. This means that the burden for the people and the environment increases due to this informal and improper treatment of the e-waste. The problem is evident, and research, business and government initiatives aim to address this development in Ghana. Specifically, the paper investigates the current approaches employed for solving the e-waste problem with respect to legal options and also regarding voluntary agreements and the provision of information in Ghana.

In another case study, **Bob et al., 2017** considers the e-waste situation in South Africa. Here, e-waste is receiving considerable attention from the Department of Environmental Affairs (DEA) who view it as being one of the fastest growing and most complex waste streams. There is recognition that e-Waste provides both threats and opportunities. This article presents and discusses data collected from a survey-based and case study research (including key informant interviews) with representatives from various government departments and agencies. The findings reveal that there are substantial variations within the government sector in terms of e-waste responsibility, the amount of e-waste generated, policies and procedures that are in place, and how e-waste is managed. The results show that government departments and agencies have stockpiles of e-waste and there is substantial storing/hoarding of e-waste throughout the country. Furthermore, current practices of managing e-waste are unsustainable and undesirable. Based on the findings and literature review undertaken which includes an overview of the e-waste challenge and trends globally and in South Africa specifically, a model for the management of e-Waste in the government sector that drives broader economic revitalisation and sustainability imperatives is proposed that embraces a regional approach.

2.8 WEEE in Oceania

Finally, in Australia, **Golev et al., 2016** have considered the WEEE situation there at a national level. For almost two decades WEEE/e-waste has been considered a growing problem that has global consequences. The global rates for formal e-waste treatment are estimated to be below the 20% mark, with the majority of end-of-life (EoL) electronic devices still ending up in the landfills or processed through rudimentary means. Industrial confidentiality regarding device composition combined with insufficient reporting requirements has made the task of simply characterizing the problem difficult at a global scale. To address some of these problems and issues, the authors have presented a critical overview of existing statistics and estimations for e-waste in an Australia context, including potential value and environmental risks associated with metals recovery. From their findings, for example, Australians purchased 35 kg of EEE on average per person in 2014 while disposed of 25 kg of WEEE, with each person possessing approximately 320 kg of EEE. The total amount of WEEE was estimated at 587kt worth about US\$ 370 million if all major metals are fully recovered. These results are presented over the period 2010–2014, detailed for major EEE product categories and metals, and followed by 2015–2024 forecasts for Australia using national modelling. Future projection, with the base scenario fixing EEE sales at 35 kg per capita, predicts stabilization of e-waste generation in Australia at 28–29 kg per capita, with the total amount continuing to grow along with the population growth.

Also in Australia, **Lodhia et al., 2017** consider the Extended Producer Responsibility (EPR) legislation in the country, enacted in order to address the high annual volumes of television and computer waste presenting a challenge to Australian communities. Using a regulatory analysis, the results show that during the first 3 years of the scheme, over 130 liable parties joined co-regulatory arrangements each year to fund upstream recycling services for television and computer waste. In program terms, the scheme has been highly successful recycling over 130,000 tonnes of metals, leaded and non-leaded glass, plastics and other materials while limiting landfill transfers to approximately 6900 tonnes.

3. Calculating Historic WEEE in Ireland

The UNU “WEEE Generated Model” that was used in this project for the analysis of WEEE return rates and the prediction of future return streams was derived from the application of IOA methods, in order to improve the evaluation methods currently employed for quantifying WEEE/e-waste generation. Products typically enter such a system at the point of sales (EEE sales in this case). These products then accumulate in the built environment (in which they have become EEE stock). When these EEE products reach their end of their life after a certain period (i.e. lifespan), they leave the system as WEEE/e-waste (**Van der Voet et al., 2002**). IOA models attempt to quantitatively describe the dynamics and magnitude of, and the interconnection between, the product sales, stocks and lifespans of such a system (**Walk, 2004; Gregory et al., 2009; Lau et al. 2013**).

In the WEEE Generated Model, IOA techniques are employed to quantitatively evaluate the sources, pathways and final sinks of the EEE material flows (**Wang et al., 2013**). With data collected for all three IOA areas (sales, stock and lifespan of the product), the WEEE Generated Model applies a multivariate IOA called the “Sales–Stock–Lifespan Model” to determine the generation and associated WEEE parameters for that market.

Figure 1 shows the typical contributors to and relationship between these IOA variables and the available datasets. In this figure, the life cycle of EEE in society is modelled as the inflow, stock and outflow of a funnel. Information can be extracted from each dataset for any historical year, that is, for sales, stock size and age composition, lifespan profiles or disposal age distribution of the resulting WEEE. The relationship between these data points is also shown in Figure 1. The mathematical and logical functions applied in the model for the conservation of mass, IOA rules and algorithms are instrumental for filling in the data gaps and validating data quality in the model. For more detail on the laws, rules and algorithms employed in the implementation of this model, please refer to **Wang et al. (2013)**.

Within the EEE market, product lifespan varies among countries, owners and individuals, and usually takes the form of a probability distribution for a given population (**Murakami et al., 2010**). Because of factors such as social and technical development, product lifespan is a time-dependent model input, so parameters of lifespan distributions corresponding to each historical sales year are modelled. For the WEEE Generated Model and the underlying Sales–Stock–Lifespan Model, the Weibull distribution function was applied to model the lifespan profile of EEE. As opposed to other statistical distributions (e.g. normal, lognormal or beta distributions), it has been shown that the Weibull function is the best fit for the EEE market: it has higher analytical tractability than other models and produces the best fit curves for the lifespans of most EEE products (**Walk, 2004; Nordic Council of Ministers, 2009**).

Within the WEEE Generated Model, each data point contains not only information about its own representing variable, but also potential indications with regard to other variables. By applying all the formulas in the model, additional modelling data can be extracted from known data. This enables the maximum capture of all available data, which improves the estimation without losing the potential implications. Thus, the WEEE Generated Model/Sales–Stock–Lifespan Model adopts multivariate analysis by involving all three variables in IOAs and multiple data points to estimate WEEE generation.

Once the datasets have been identified and gathered, the WEEE Generated Model (Sales–Stock–Lifespan Model) may then be applied to a multivariate analysis based on available Irish data points. This is done to ensure reliable and continuous datasets for model calculation, either by filling in the data gaps or finding the most reliable available data source(s). Variables and datasets are used in conjunction here, as the variable(s) associated with the highest data quality are used to validate and consolidate any variables in the dataset that have a lower data quality. Empirical and logical constraints (such as market saturation figures) are also used to consolidate the available datasets at this point.

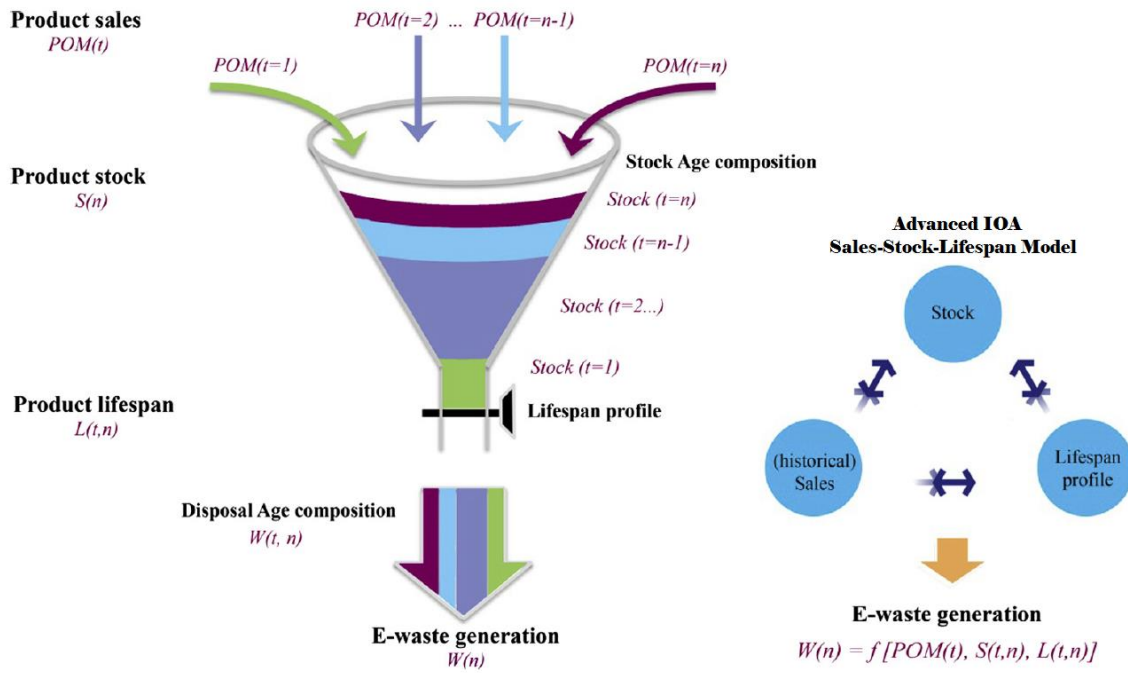


Figure 1 - WEEE Generated Model using the Sales-Stock-Lifespan Model to enhance WEEE estimates.

Once reliable sales and stock data have been garnered for the Irish market and validated/consolidated as described, the WEEE Generated Model can then be applied directly to calculate the WEEE generation figures for the period in question. Implementing the model in this fashion guarantees greater data consolidation and multivariate analysis, thereby improving the accuracy and generated results for the WEEE Generated Model, compared with other traditional or bespoke approaches. The results of the WEEE Generated Model for the Irish Market are presented in section 4 of this paper.

4. WEEE Generated Model Results

This section of the paper details the research outputs and findings. Specifically, the historic WEEE figures and predictions for the Irish EEE market are presented for the period 2000–2020. These figures were generated using the UNU WEEE Generated Model, in conjunction with the appropriate Irish datasets, as described in Section 3.

With the Irish EEE sales, life-cycle and model data used in conjunction with the UNU WEEE Generated Model, a set of predictions for the historic WEEE return rates were generated for the eight UNU-KEY categories of interest in this project. [Table 1](#) gives the historic WEEE prediction figures for all eight categories for the Irish market from 2000 until 2020 inclusive.

Year	Dish washers	Ovens	Washing machines	Dryers	Fridges	Freezers	Flat-panel TVs
	UNU-KEY 0102	UNU-KEY 0103	UNU-KEY 0104	UNU-KEY 0105	UNU-KEY 0108	UNU-KEY 0109	UNU-KEY 0408
2000	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	
2001	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	
2002	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
2003	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
2004	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
2005	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
2006	97.46%	99.85%	98.32%	99.84%	99.61%	99.98%	84.84%
2007	92.45%	99.03%	94.61%	98.90%	98.18%	99.82%	59.62%
2008	86.52%	97.38%	89.76%	96.92%	95.72%	99.45%	38.97%
2009	80.75%	94.95%	84.41%	93.96%	92.47%	98.84%	26.31%
2010	75.37%	91.89%	78.87%	90.27%	88.68%	97.95%	18.41%
2011	70.45%	88.39%	73.29%	86.08%	84.50%	96.77%	12.80%
2012	66.02%	84.57%	67.77%	81.55%	79.99%	95.28%	8.99%
2013	62.00%	80.57%	62.35%	76.84%	75.21%	93.47%	6.57%
2014	58.26%	76.52%	57.00%	72.06%	70.32%	91.36%	4.96%
2015	54.57%	72.45%	51.68%	67.28%	65.32%	88.93%	3.81%
2016	50.85%	68.40%	46.44%	62.50%	60.23%	86.18%	2.95%
2017	47.13%	64.39%	41.36%	57.74%	55.13%	83.10%	2.30%
2018	43.44%	60.40%	36.52%	53.01%	50.09%	79.69%	1.80%
2019	39.80%	56.44%	31.97%	48.32%	45.14%	75.98%	1.40%
2020	36.24%	52.49%	27.75%	43.68%	40.35%	71.99%	1.10%

Table 1 - Irish Historic WEEE figures for 2000–2020 using the WEEE Generated Model

The following figures show the historic WEEE return rate(s), graphed as a function of the same timescale as in Table 1, plotted against EEE POM and WEEE figures for each of the corresponding UNU-KEY categories. For each data point, EEE sales (POM) data, WEEE (collected material) and historic WEEE as a percentage of this overall total for the corresponding categories are shown. These figures are presented in ascending order of UNU-KEY.

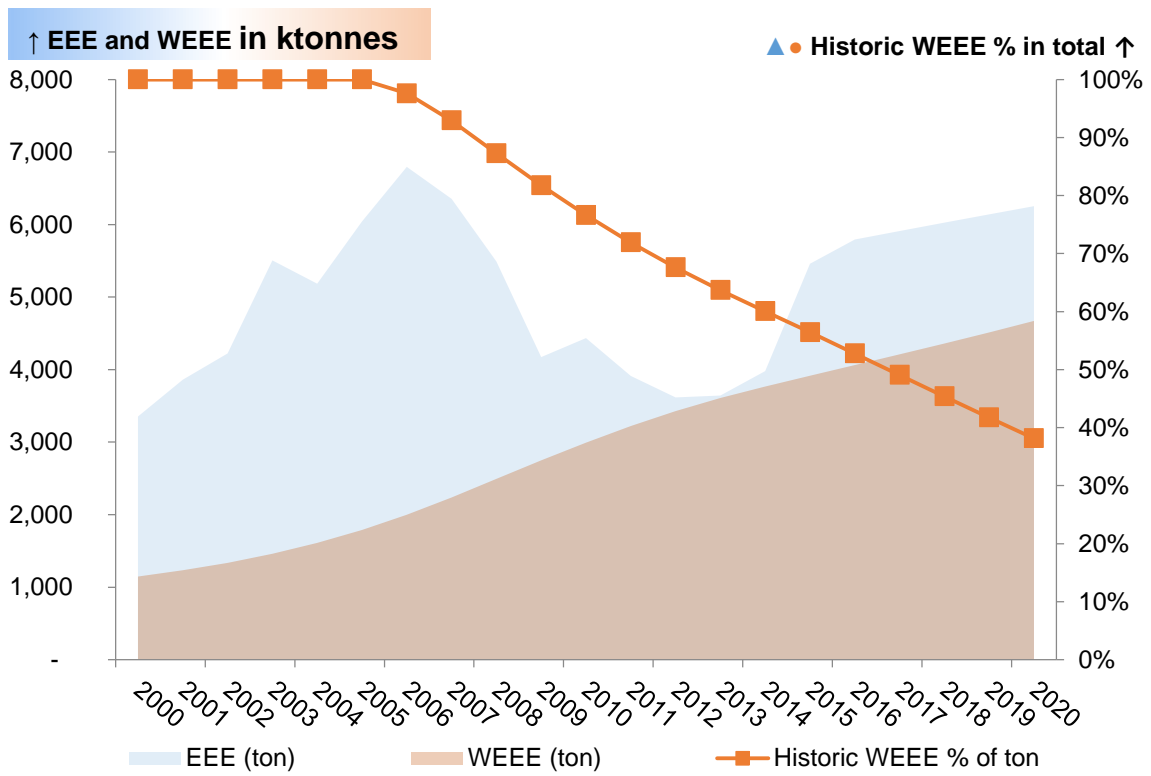


Figure 2 - EEE, WEEE and historic WEEE for Category 0102 – Dishwashers.

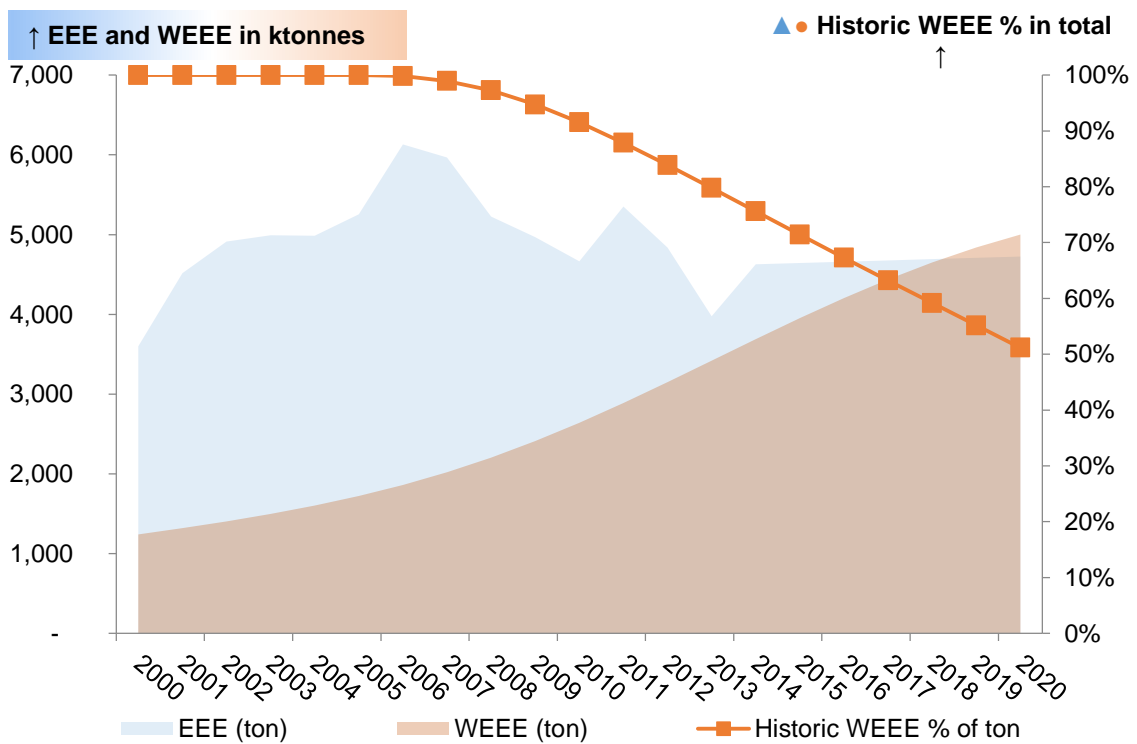


Figure 3 - EEE, WEEE and historic WEEE for Category 0103 – Ovens.

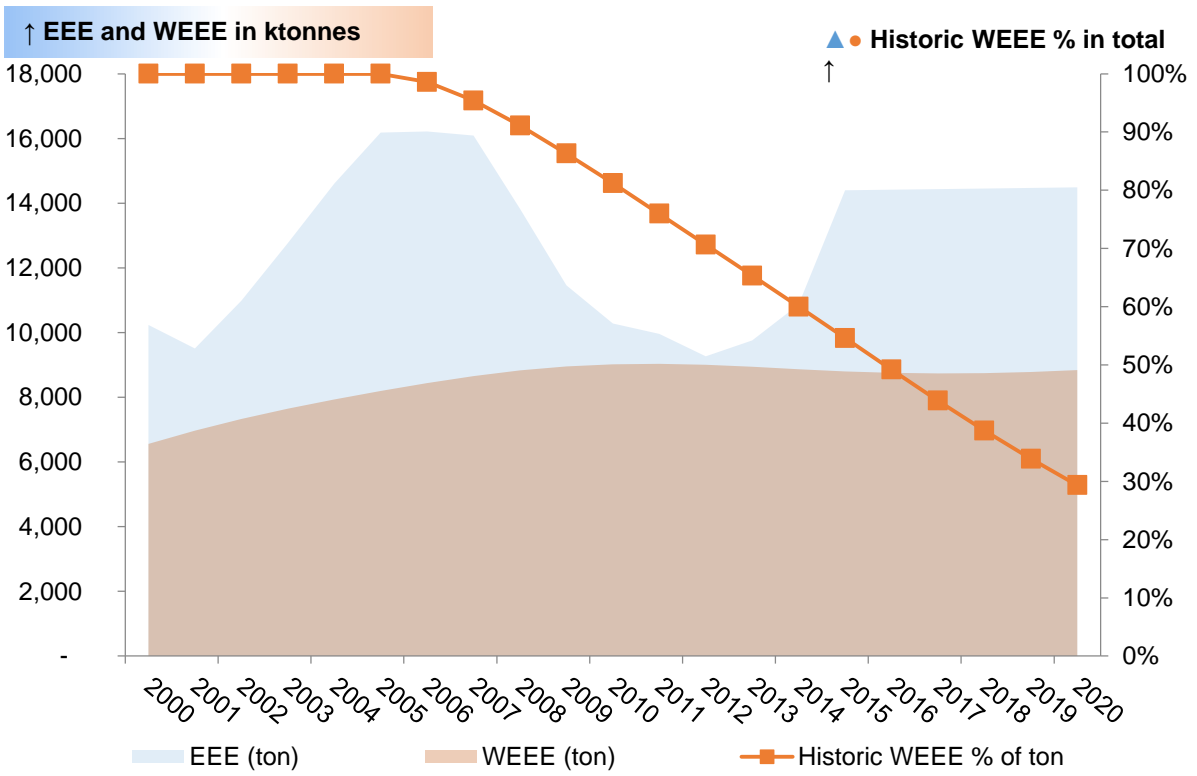


Figure 4 - EEE, WEEE and historic WEEE for Category 0104 – Washing Machines.

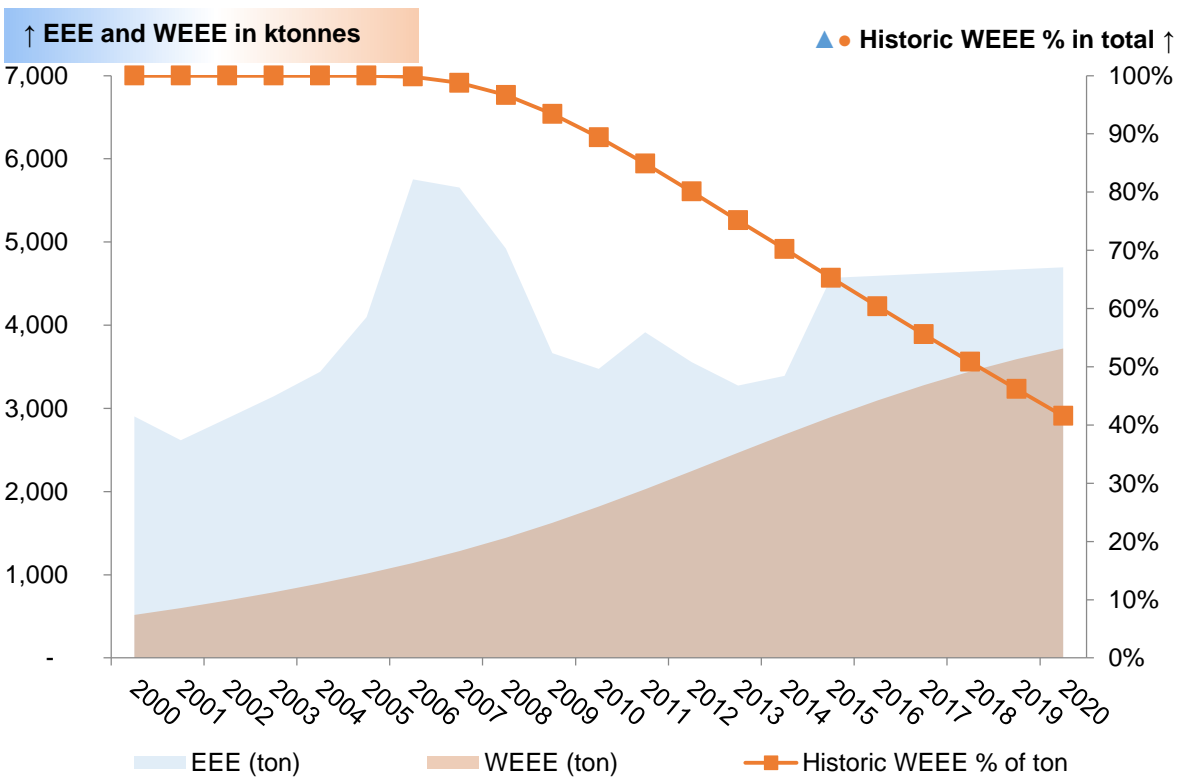


Figure 5 - EEE, WEEE and historic WEEE for Category 0105 – Dryers.

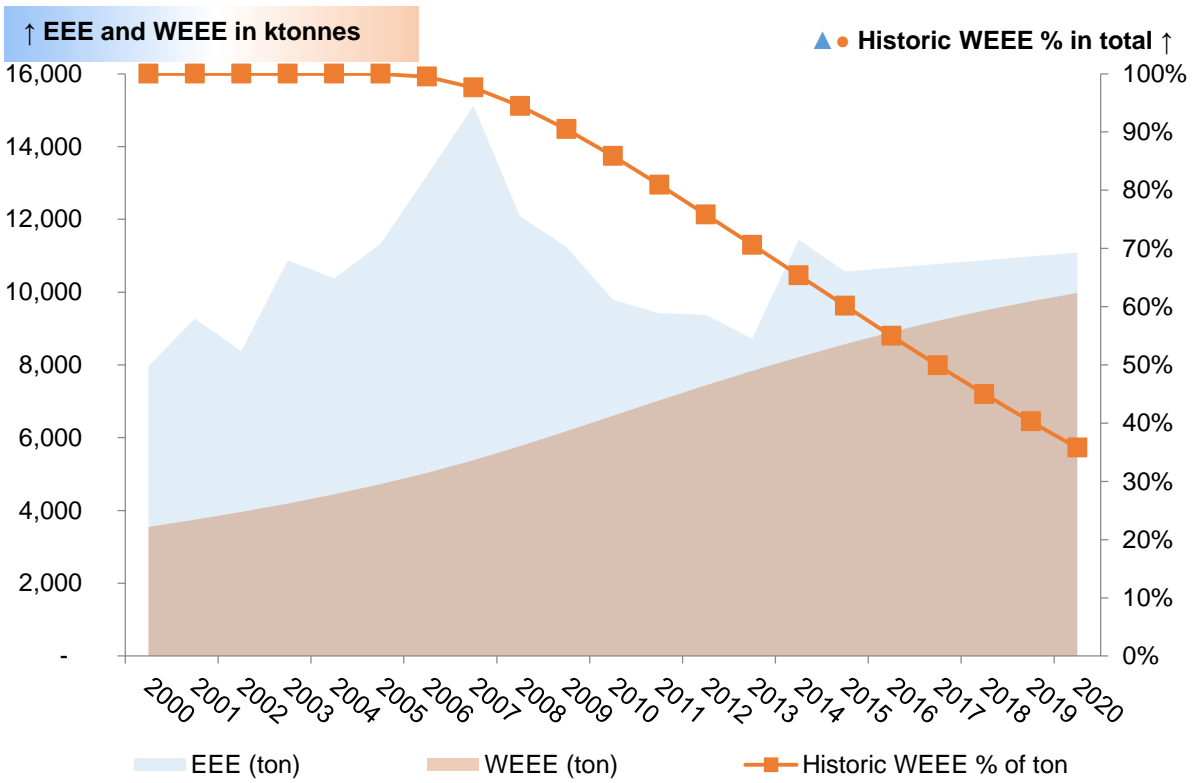


Figure 6 - EEE, WEEE and historic WEEE for Category 0108 – Fridges.

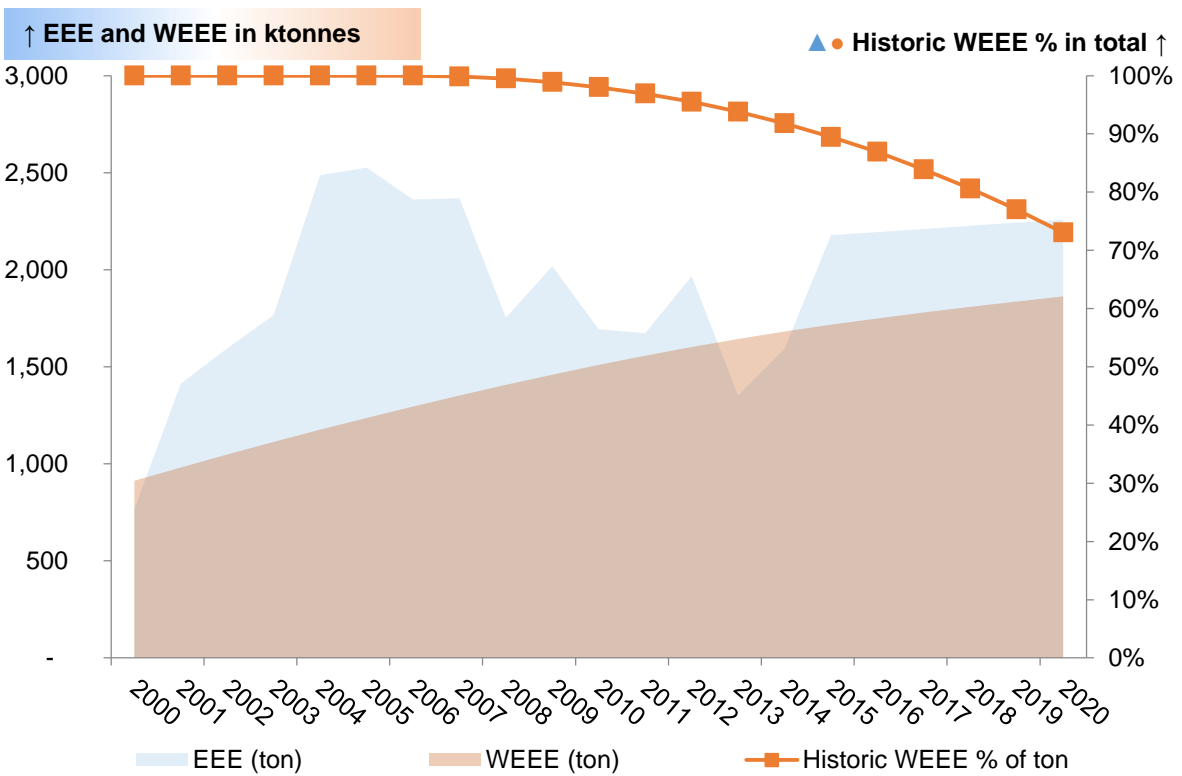


Figure 7 - EEE, WEEE and historic WEEE for Category 0109 – Freezers.

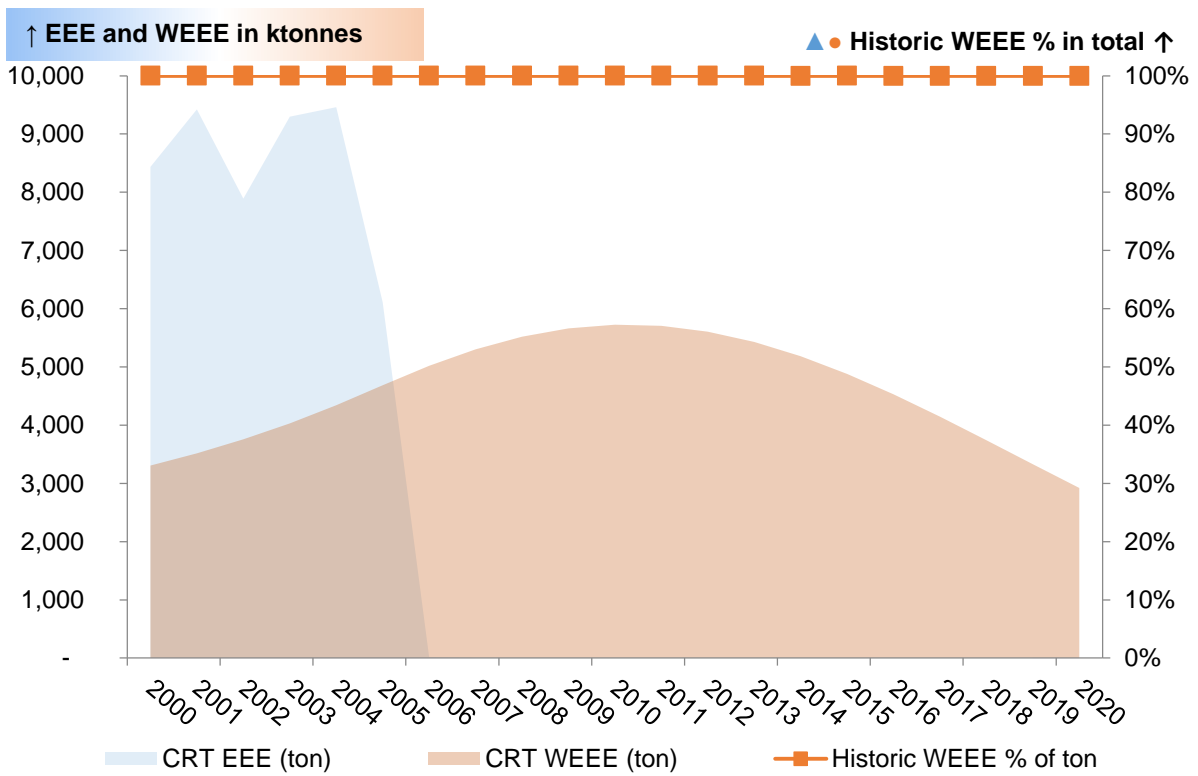


Figure 8 - EEE, WEEE and historic WEEE for Category 0407 – CRT TVs.

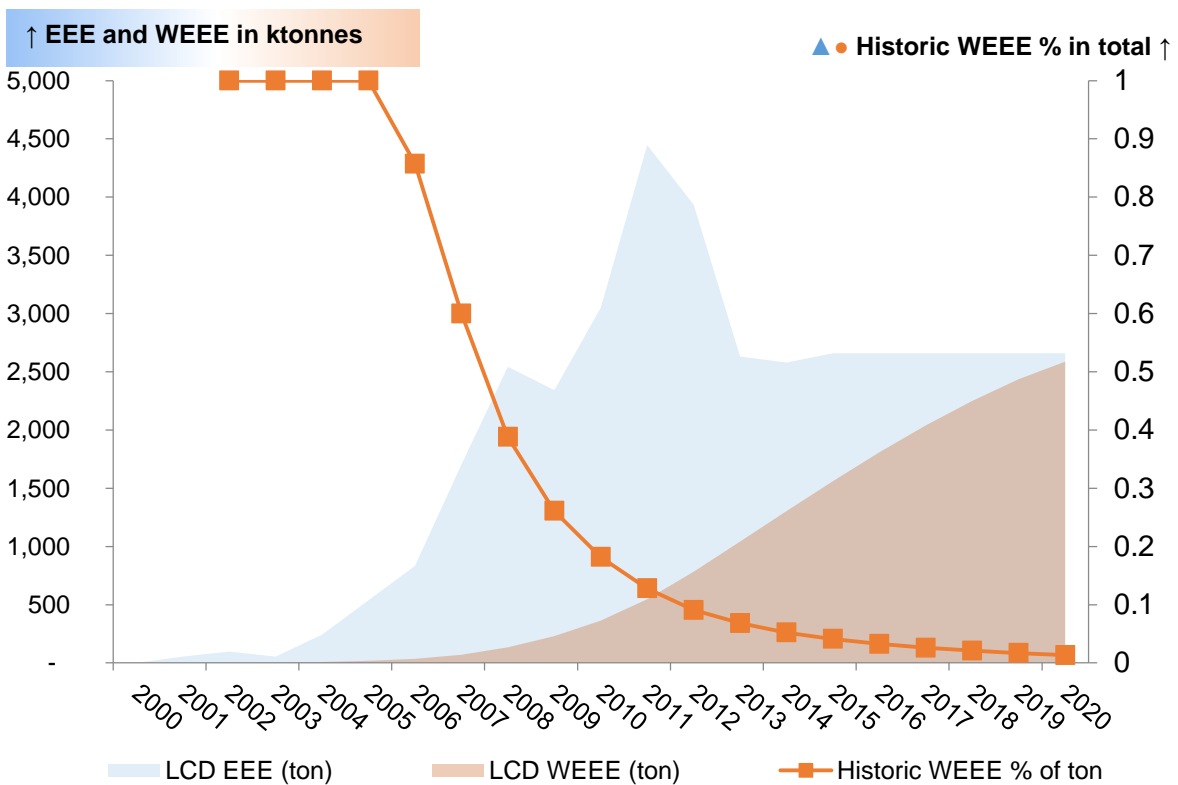


Figure 9 - EEE, WEEE and historic WEEE for Category 0408 – LCD TVs. LCD, liquid crystal display.

The eight UNU-KEYS presented as the outputs of the WEEE Generated Model may be mapped to their equivalent Irish counterparts as follows: cold EEE (PRL Categories 1.1 and 1.2) comprises UNU-KEYS 0108 (Fridges) and 0109 (Freezers); LHA (PRL Category 1.3) is mapped to the sum of UNU-KEYS 0102 (Dishwashers), 0103 (Ovens), 0104 (Washing Machines) and 0105 (Dryers); while TV (PRL Category 4) is equivalent to the total of UNU-KEYS 0407 (CRT TVs) and 0408 (Flat-Panel TVs)..

Table 2 summarises the WEEE Generated Model outputs for these three categories: cold, LHA and TV. Both the WEEE (in tonnes) and historic WEEE (as percentages) are given in the table for the years 2000–2020 for these categories. In addition, **Figure 10** shows the WEEE and the per cent historic WEEE figures for all “cold” EEE (PRL Categories 1.1 and 1.2) in Ireland; **Figure 11** presents the comparable situation for all LHA EEE (PRL Category 1.3) in Ireland; and **Figure 12** gives the WEEE and per cent historic WEEE data for all TVs (PRL Category 4) in Ireland.

Year	Cold WEEE (tonnes)	Cold historic WEEE (%)	LHA WEEE (tonnes)	LHA historic WEEE (%)	TV WEEE (tonnes)	TV historic WEEE (%)
2000	4461	100	9463	100	3306	100
2001	4728	100	10,120	100	3516	100
2002	5008	100	10,757	100	3759	100
2003	5304	100	11,394	100	4034	100
2004	5622	100	12,041	100	4350	100
2005	5960	100	12,719	100	4703	100
2006	6328	100	13,438	99	5054	100
2007	6733	99	14,195	95	5372	99
2008	7175	96	14,973	91	5653	99
2009	7638	94	15,738	86	5892	97
2010	8112	90	16,472	82	6088	95
2011	8583	87	17,172	77	6253	92
2012	9042	83	17,829	72	6388	89
2013	9480	78	18,439	68	6471	85
2014	9895	74	19,007	63	6488	81
2015	10,288	69	19,564	59	6441	77
2016	10,654	64	20,118	54	6339	72
2017	10,994	60	20,666	50	6186	68
2018	11,305	55	21,202	46	5991	63
2019	11,585	50	21,725	42	5766	58
2020	11,840	45	22,234	38	5508	54

Table 2 - WEEE and historic WEEE figures for cold, LHA and TV EEE categories in Ireland

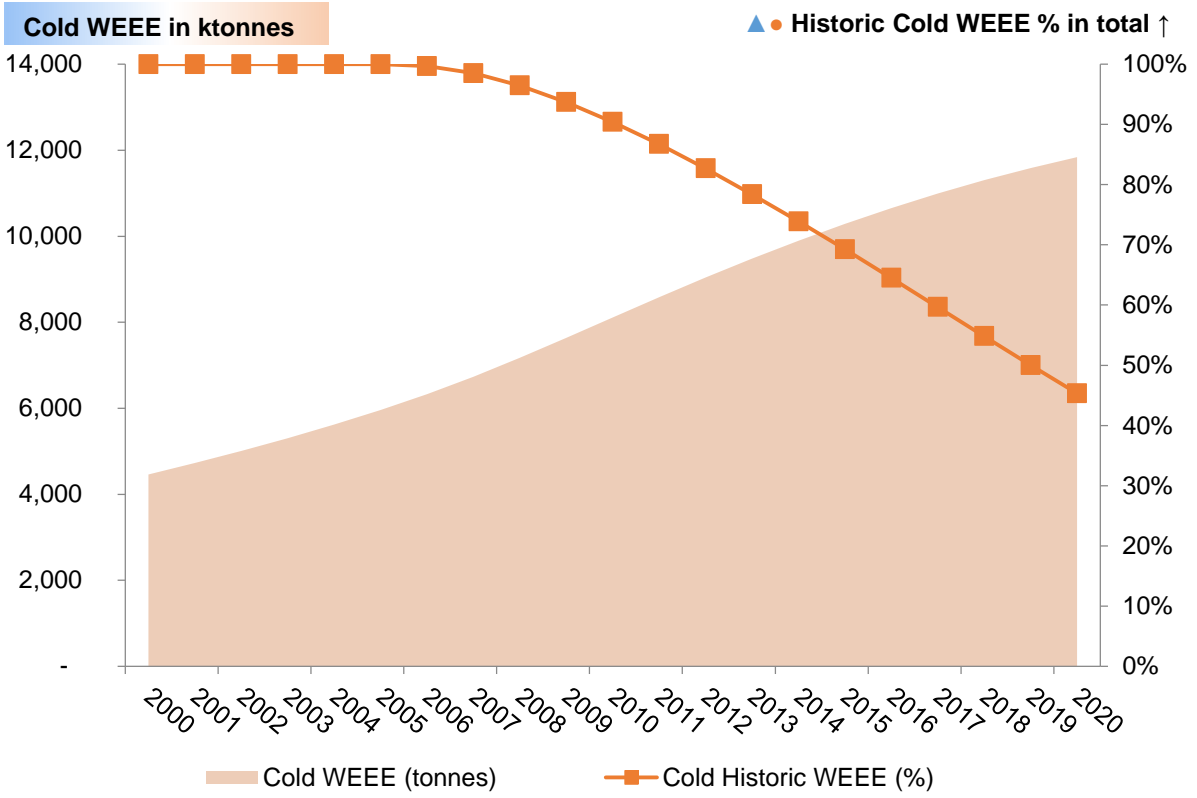


Figure 10 - WEEE and historic WEEE for Cold EEE in Ireland.

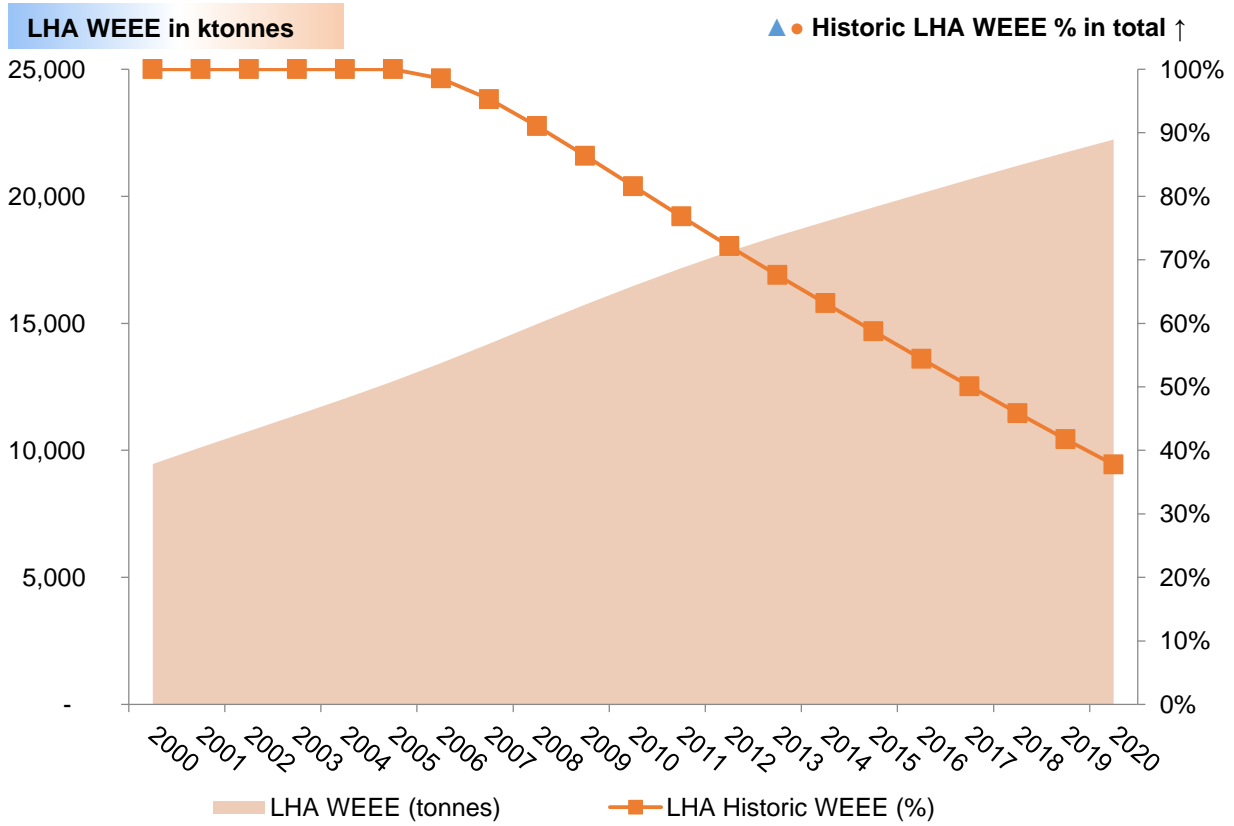


Figure 11 - WEEE and historic WEEE for LHA EEE in Ireland.

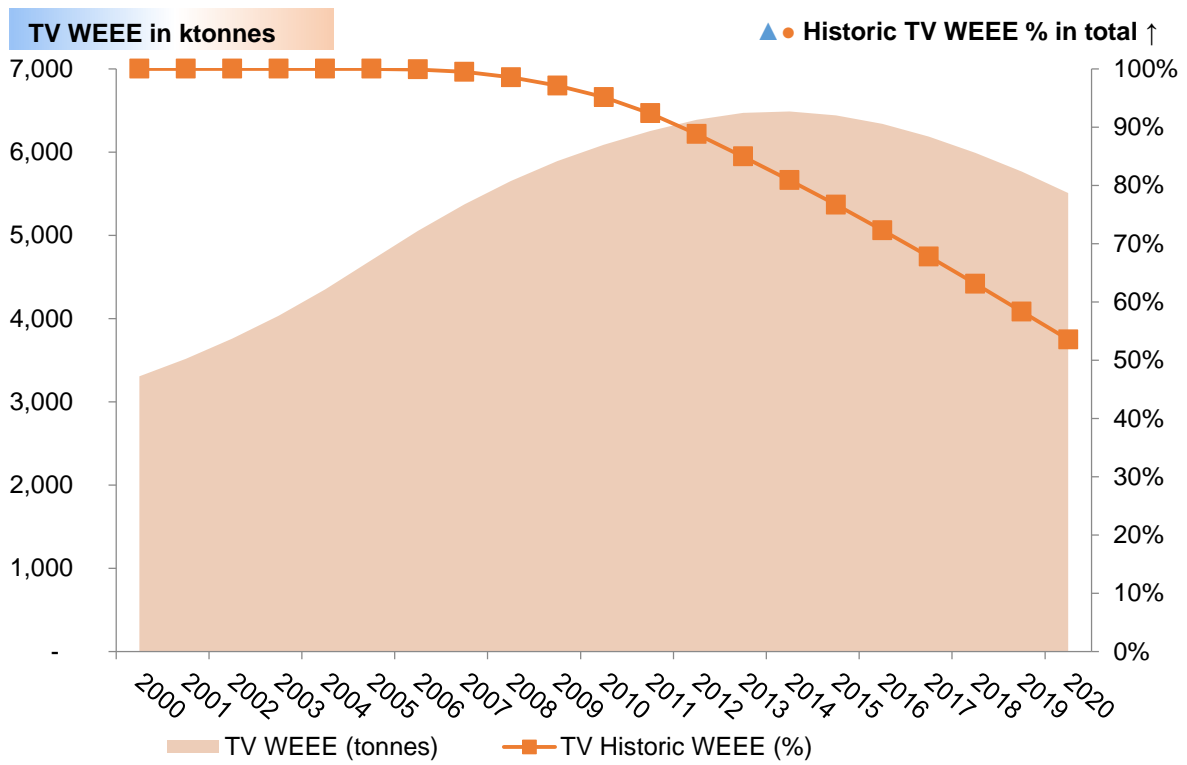


Figure 12 - WEEE and historic WEEE for TV EEE in Ireland.

For the TV category data (PRL Category 4 or UNU-KEY 407/408), Figure 13 shows the cumulative prediction for CRT (Cathode-Ray Tube) and FDP (Flat Display Products) for the years 2000-2020 in Ireland. Figure 14 shows the complimentary situation with stock(s) of TVs in the Irish market for the same timeframe.

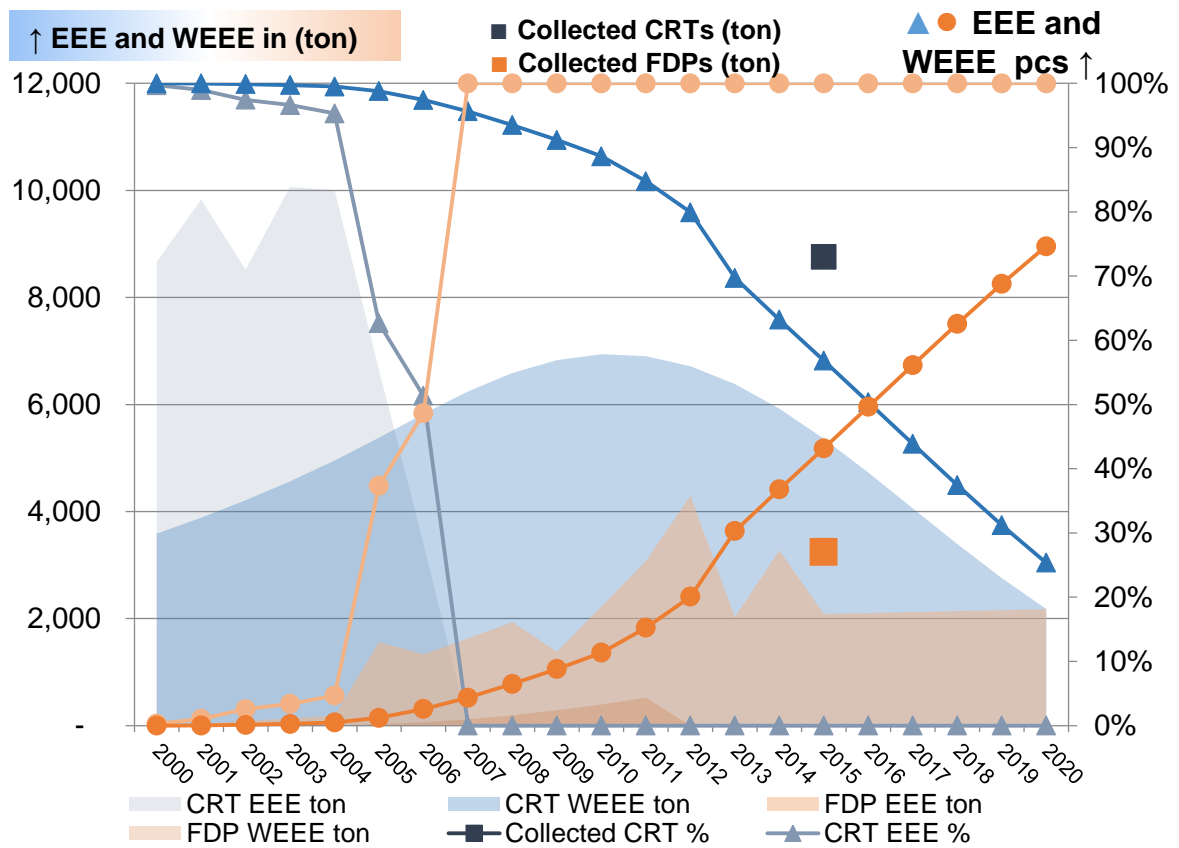


Figure 13- Model Predictions of CRT and FDP EEE and WEEE for Ireland, 2000-2020

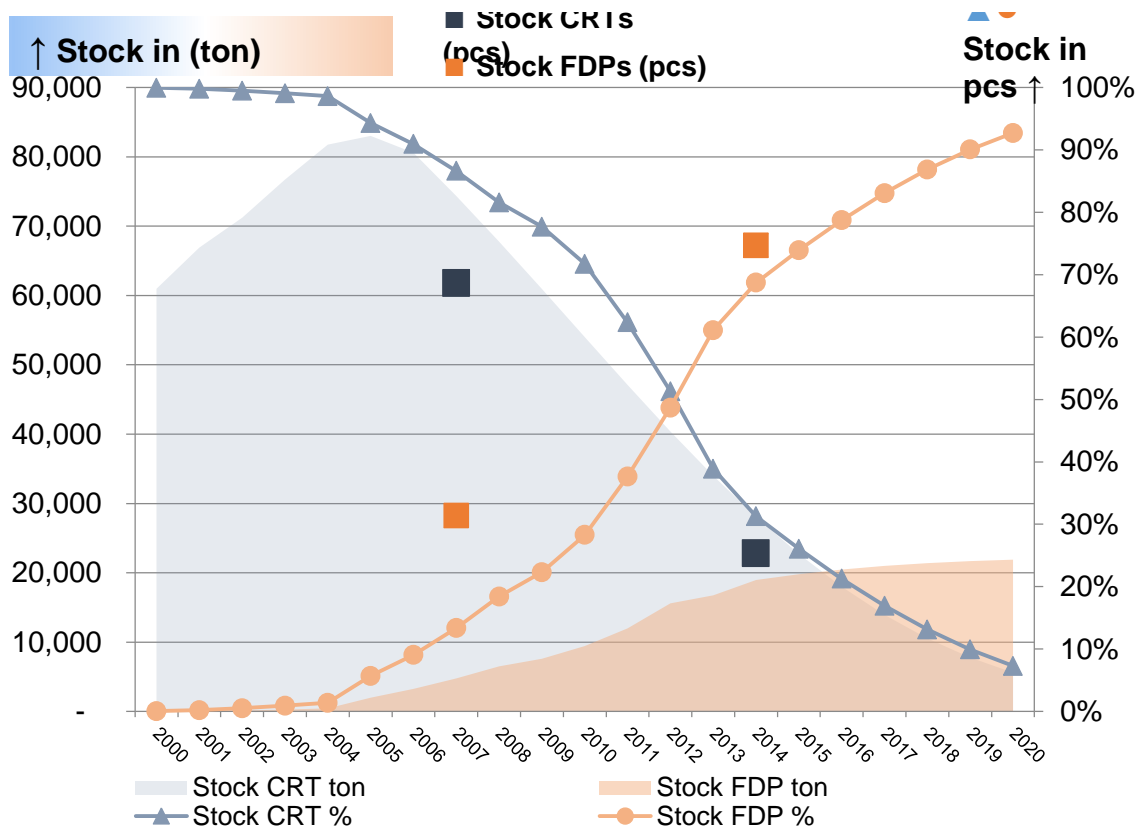


Figure 14 - Cumulative Stock of Televisions in Ireland as predicted by the model, 2000-2020.

5. Validation with Irish WEEE Sampling

The Irish WEEE return stream was sampled across a number of different categories and at a number of different locations around the country. This was then used as a means of validation for the outputs of the WEEE Generated Model described in Chapter 4. There were three main EEE categories sampled during the course of this work, namely:

- Category 1 (“cold”): this category consisted of sampling fridges and freezers in the return stream;
- Category 1 (“LHA”): dishwashers, washing machines, dryers and ovens were sampled in this return stream;
- Category 4 (“TVs”): both CRT and flat-panel TVs were considered in this category.

For each category sampled, the main goal of the sampling exercise was to determine whether the individual WEEE was historic or non-historic in nature. To accomplish this, the WEEE was examined for the presence or absence of the crossed-out wheelie bin symbol. This symbol has been in use since the WEEE Directive came into force as a special logo [in addition to the CE (*Conformité Européene*) logo] to show that the equipment should not be disposed of in the normal waste stream. In this way, it is a clear indication of the nature of the WEEE, that is, whether it is historic or non-historic. There are two variations of the crossed-out wheelie bin symbol, as shown in [Figure 17](#) and [Figure 18](#).



Figure 15 - Crossed-out wheelie bin logo version 1

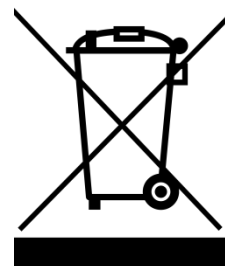


Figure 16 - Crossed-out wheelie bin logo version 2

The number of samples required for the cold, LHA and TV WEEE category sampling requirements were calculated as shown in [Table 3](#).

Sampling category	Population size	Confidence Interval	Confidence level	Number of samples required
Cold	26,633	6%	95%	265
LHA	70,000	5%	95%	382
TV	95,000	5%	95%	383

Table 3. Sampling requirements for Irish historic WEEE categories

[Table 4](#) summarises the quantity of EEE stock sampled over the course of the project for all of the sampled sites, according to the three sample categories of interest (cold, LHA and TV).

Sampling type	WEEE sampled	Sample totals
Cold	Fridges, freezers	268
LHA	Washing machines, dishwashers, dryers, ovens	472
TV	CRT, flat-panel	486

Table 4. Summary of sampled WEEE types and quantities

For all of the goods sampled during the course of this project, **Table 5** summarises the breakdown of historic versus non-historic WEEE for the three main product categories in 2015.

Type of EEE	Total sampled	Historic WEEE	Non-historic WEEE	Historic WEEE (%)	Non-historic WEEE (%)
Cold	268	180	88	67.2	32.8
LHA	472	256	216	54.2	45.8
TV	486	353	133	72.6	27.4

Table 5. WEEE sample results for the Irish return stream in 2015

The comparison of these results with the WEEE Generated Model output(s) described in Chapter 4 of this report is best achieved by displaying the historic WEEE predictions from the WEEE Generated Model versus the percentage historic WEEE figures from the sampling activities above as graphs. **Table 6** shows the results of the WEEE sampled data after they had been processed and the percentage of historic WEEE extracted for the three different WEEE categories, contrasted with the WEEE Generated Model predictions for the same categories and timeframe.

Year/dataset	Cold historic WEEE (%)	LHA historic WEEE (%)	TV historic WEEE (%)
2015 sampled data	72	54	73
2015 model predictions	69	59	77

Table 6. Results of the WEEE sampling for the Irish return stream in 2015

These graphs are presented in this section of the report. **Figure 17** shows the cold WEEE model predictions versus the 2015 sampled cold WEEE data, **Figure 18** shows the situation for the LHA category and, finally, **Figure 19** presents the percentage historic WEEE prediction(s) versus the sampled values for the TV category.

As shown in the graphs presented in Figures 5.3, 5.4 and 5.5, the sampled data from the various WEEE categories are presented with SE and 95% CIs. These data points and associated error bars correlate very well with the expected (predicted) values for the cold, LHA and TV EEE categories. For each of the WEEE categories, there is a strong correlation between the model predicted data for 2015 and the sample data. Therefore, the sampled data corroborate the model predictions very well across the cold, LHA and TV WEEE classes considered, especially given the constraints of the sampling process, etc. Further sampling is recommended on an annual basis to corroborate these findings and allow continuous improvement and refinement of the model predictions as newer data become available.

It should be noted that the representativeness of these WEEE samples can be affected by the inclusion or exclusion of other WEEE streams, such as newer/richer products which may get traded away as opposed to being recycled.

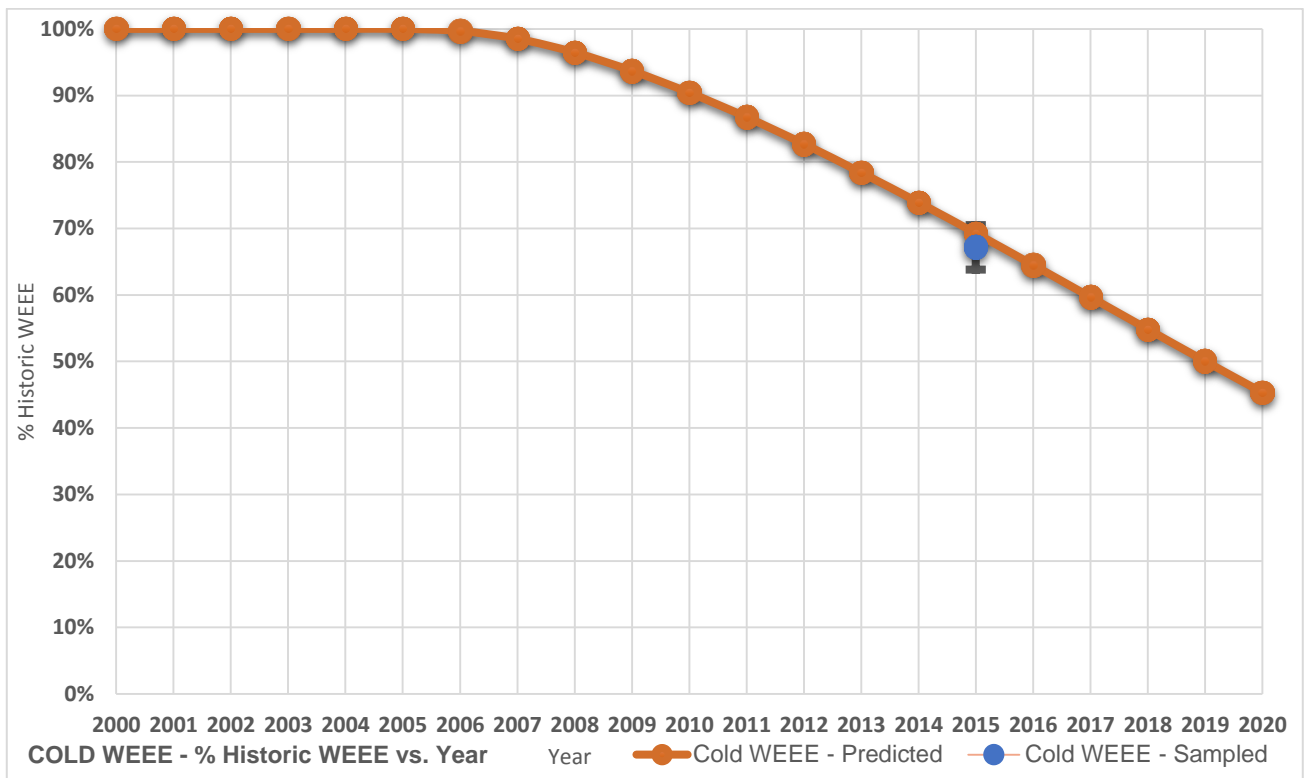


Figure 17 - Percentage historic WEEE for the cold category – predicted vs sampled data.

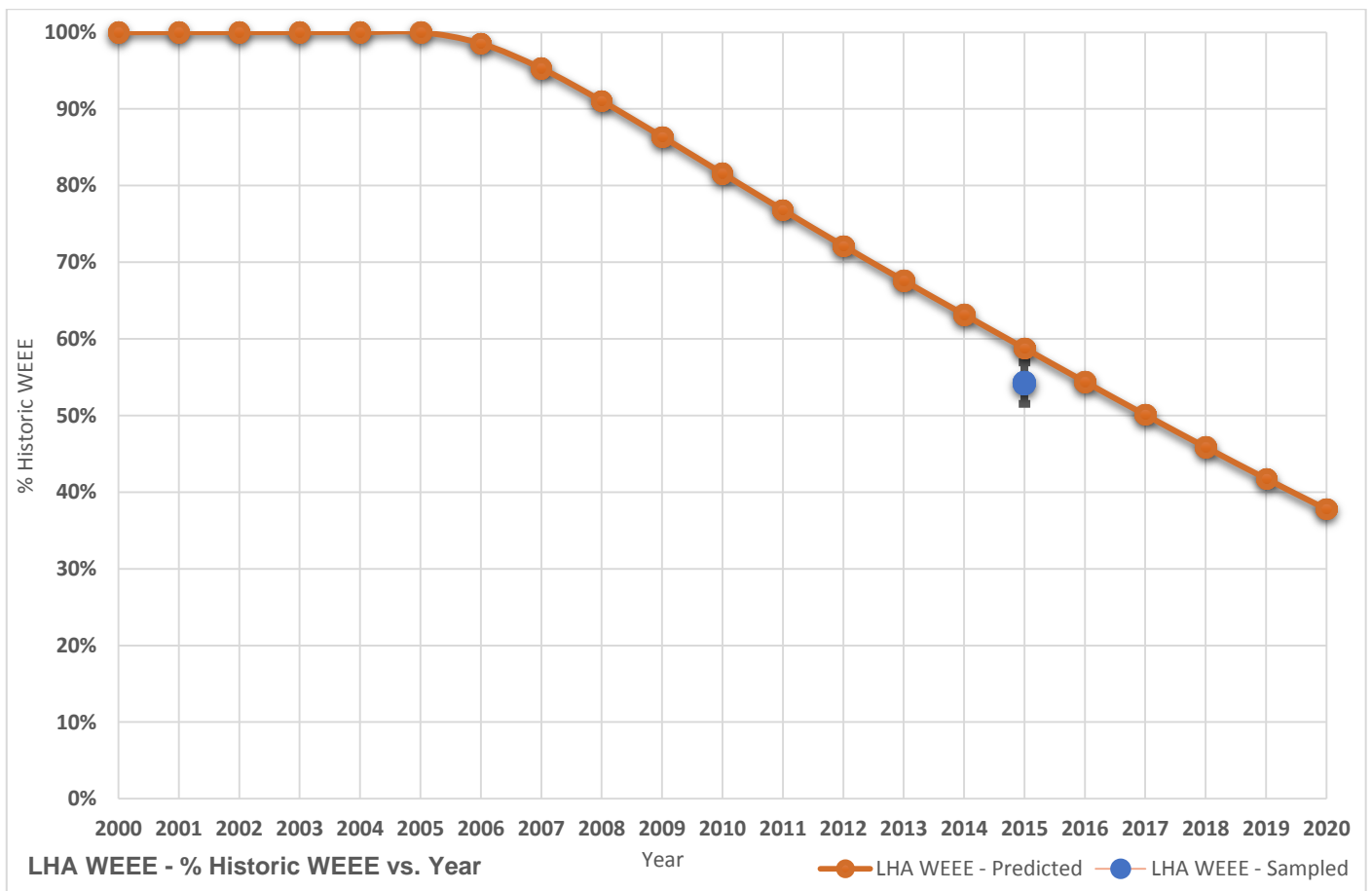


Figure 18 - Percentage historic WEEE for the LHA category – predicted vs sampled data.

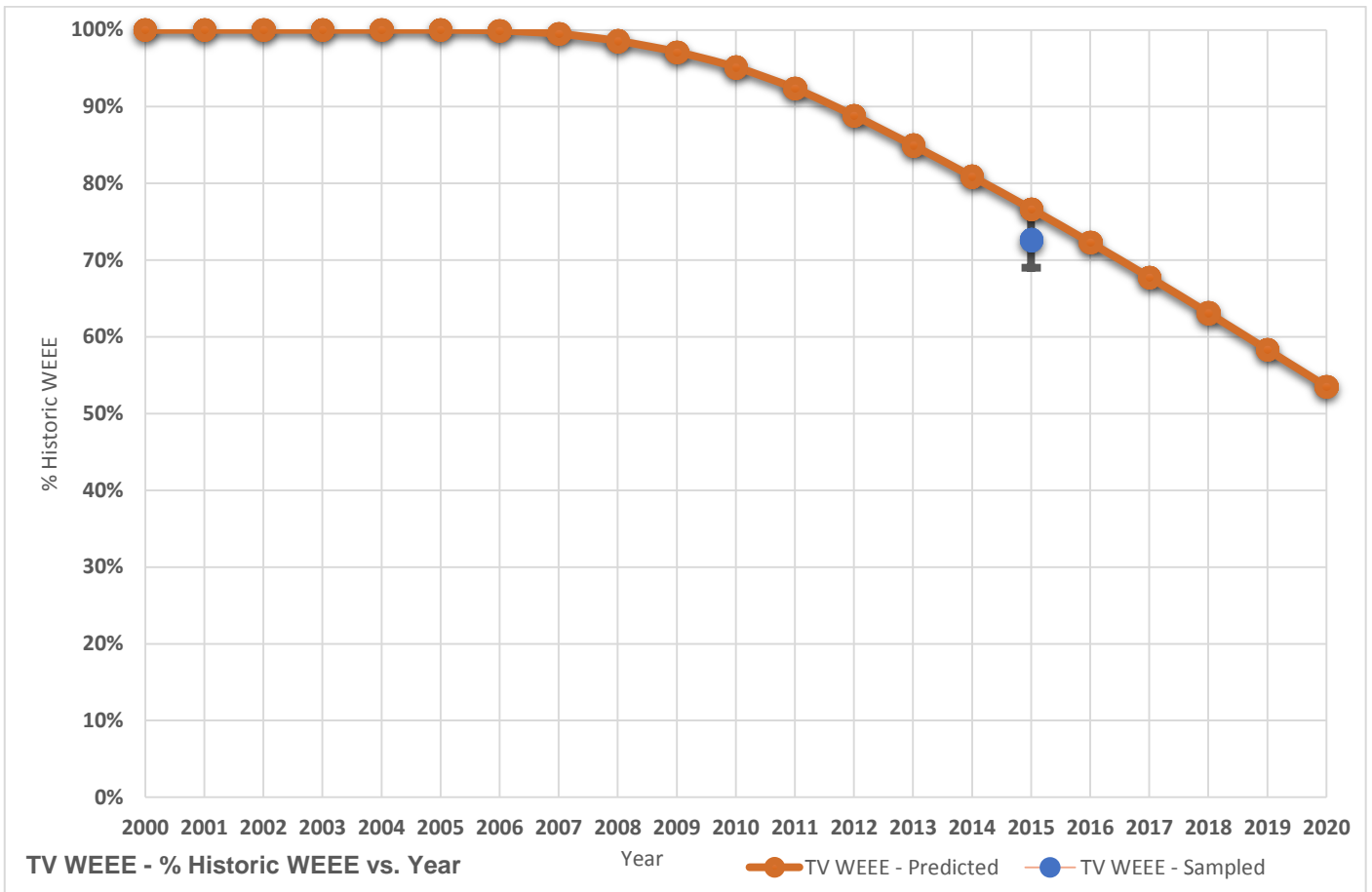


Figure 19 - Percentage historic WEEE for the TV category – predicted vs sampled data.

6. Conclusion and Recommendations

This paper has documented the development and validation of a model for the prediction of historic WEEE for Ireland and the results of this model have been applied to the Irish WEEE sector. It considers the specifics of the Irish EEE and WEEE sectors and utilises a model that had been validated across other EU countries to obtain specific EEE, WEEE and historic WEEE figures and projections for Ireland for the 20-year period 2000–2020. The model has been empirically validated for Irish WEEE using first-hand sampled recycling data across the distinct categories of interest in this project, namely cold WEEE, LHA WEEE and displays/TV WEEE.

According to the model, historic WEEE as a percentage of total WEEE across the three categories of interest are currently 69% for the cold category, 59% for the LHA category and 77% for the TV category. Therefore, there are still substantial quantities of historic WEEE in the return stream, even 10 years after the implementation of the WEEE Directive in Ireland. Over the course of the next 5 years, the model predicts that these levels will reduce to 45%, 38% and 54%, respectively, by the year 2020. While this is a noticeable reduction in historic WEEE levels, the model predictions would seem to suggest that historic WEEE will still arise in Ireland in the cold, LHA and TV return streams for the next 10 or more years.

References

- Araújo, M.G., Magrini, A., Mahler, C.F. and Bilitewski, B., 2012. A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. *Waste Management* 32: 335–342.
- Awasthi, A.K. and Li, J., 2017. Management of electrical and electronic waste: A comparative evaluation of China and India. *Renewable and Sustainable Energy Reviews*, 76, pp.434-447.
- Bahers, J.B. and Kim, J., 2017. Regional approach of waste electrical and electronic equipment (WEEE) management in France. *Resources, Conservation and Recycling*, 129, pp.45-55.
- Baldé, C.P., Wang, F., Kuehr, R. and Huisman, J. 2015. *The Global E-Waste Monitor – 2014*. United Nations University, IAS – SCYCLE, Bonn, Germany. Available online: <http://i.unu.edu/media/unu.edu/news/52624/UNU-1stGlobal-E-Waste-Monitor-2014-small.pdf>.
- Beigl, P., Wassermann, G., Schneider, F. and Salhofer, S., 2003. Municipal waste generation trends in European countries and cities. In *Proceedings of the Ninth International Waste Management and Landfill Symposium Sardinia*.
- Bob, U., Padayachee, A., Gordon, M. and Moutlana, I., 2017. Enhancing Innovation and Technological Capabilities in the Management of E-Waste: Case Study of South African Government Sector. *Science, Technology and Society*, p.0971721817702293.
- Borthakur, A. and Govind, M., 2016. Emerging trends in consumers' E-waste disposal behaviour and awareness: A worldwide overview with special focus on India. *Resources, Conservation and Recycling*.
- Chung, S.S., 2011. Projection of waste quantities: the case of e-waste of the People's Republic of China. *Waste Management and Research* 30: 1130–1137.
- Chung, S.S., Lau, K.Y. and Zhang, C., 2011. Generation of and control measures for, e-waste in Hong Kong. *Waste management* 31: 544–554.
- Duan, H., Miller, T.R., Gregory, J. and Kirchain, R., 2014. Quantifying export flows of used electronics: Advanced methods to resolve used goods within trade data. *Environmental science & technology*, 48(6), pp.3263-3271.
- Dwivedy, M. and Mittal, R.K., 2010. Future trends in computer waste generation in India. *Waste management* 30: 2265–2277.
- Egeonu, N. and Herat, S., 2016. E-waste: a problem or an opportunity? Review of issues, challenges and solutions in African countries. *International Journal of Environment and Waste Management*, 17(3-4), pp.318-339.
- Elshkaki, A., van der Voet, E., Timmermans, V. and Van Holderbeke, M., 2005. Dynamic stock modelling: A method for the identification and estimation of future waste streams and emissions based on past production and product stock characteristics. *Energy* 30: 1353–1363.
- Gregory, J.R., Nadeau, M.C. and Kirchain, R.E., 2009. Evaluating the economic viability of a material recovery system: the case of cathode ray tube glass. *Environmental Science & Technology* 43: 9245–9251.
- Golev, A., Schmeda-Lopez, D.R., Smart, S.K., Corder, G.D. and McFarland, E.W., 2016. Where next on e-waste in Australia?. *Waste Management*, 58, pp.348-358.
- Haig, S., Morrish, E. and Morton, R. 2011. *Market Flows of Electronic Products & WEEE Materials*. WRAP Publication MDD036.
- He, W., Li, G., Ma, X. et al., 2006. WEEE recovery strategies and the WEEE treatment status in China. *Journal of Hazardous Materials* 136: 502–512.
- Hilty, L.M., Schluep, M., Widmer, R. and Faulstich, M., 2017. Service Lifetime, Storage Time, and Disposal Pathways of Electronic Equipment: A Swiss Case Study. *Journal of Industrial Ecology*.
- Hötl, A., Brandtweiner, R. and Müller, R., 2017. Approach To Solving The E-waste Problem—Case Study Ghana. *International Journal of Sustainable Development and Planning*, 12(6), pp.1050-1060.
- Huisman, J., 2010. *WEEE Recast: from 4 kg to 65%: the Compliance Consequences*. United Nations University, Bonn, Germany.
- Huisman, J., Magalini, F., Kuehr, R. et al., 2008. *Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE)*. United Nations University, Bonn, Germany.
- Huisman, J., Van der Maesen, M., Eijsbouts, R.J.J. et al., 2012. *The Dutch WEEE Flows*. United Nations University, ISP–SCYCLE, Bonn, Germany.
- Imran, M., Haydar, S., Kim, J., Awan, M.R. and Bhatti, A.A., 2017. E-waste flows, resource recovery and improvement of legal framework in Pakistan. *Resources, Conservation and Recycling*, 125, pp.131-138.
- Jang, Y.C. and Kim, M., 2010. Management of used & end-of-life mobile phones in Korea: a review. *Resources, Conservation and Recycling* 55: 11–19.
- Kang, H.Y. and Schoenung, J.M., 2006a. Economic analysis of electronic waste recycling: modeling the cost and revenue of a materials recovery facility in California. *Environmental Science & Technology* 40: 1672–1680.
- Kang, H.Y. and Schoenung, J.M., 2006b. Estimation of future outflows and infrastructure needed to recycle personal computer systems in California. *Journal of Hazardous Materials* 137: 1165–1174.
- Kim, S., Oguchi, M., Yoshida, A. and Terazono, A., 2013. Estimating the amount of WEEE generated in South Korea by using the population balance model. *Waste Management* 33: 474–483.
- Kumar, A., Holuszko, M. and Espinosa, D.C.R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. *Resources, Conservation and Recycling*, 122, pp.32-42.
- Lau, W.K.Y., Chung, S.S. and Zhang, C., 2013. A material flow analysis on current electrical and electronic waste disposal from Hong Kong households. *Waste Management* 33: 714–721.
- Lee, J.C., Song, H.T. and Yoo, J.M., 2007. Present status of the recycling of waste electrical and electronic equipment in Korea. *Resources, Conservation and Recycling* 50: 380–397.
- Lodhia, S., Martin, N. and Rice, J., 2017. Extended Producer Responsibility for waste televisions and computers: A regulatory evaluation of the Australian experience. *Journal of Cleaner Production*, 164, pp.927-938.
- Magalini, F., Baldé, C.P., Habib, H., 2015. Quantifying waste of Electric and Electronic Equipment in Romania. *United Nations University, ISP – SCYCLE*, Bonn, Germany.

- Magalini, F. Wang, F., Huisman, J., Kuehr, R., Baldé, K., van Straalen, V., Hestin, M., Lecerf, L., Sayman, U., Akpulat, O., 2016. Study On Collection Rates Of Waste Electrical And Electronic Equipment (WEEE), possible measures to be initiated by the Commission as required by Article 7(4), 7(5), 7(6) and 7(7) of Directive 2012/19/EU On Waste Electrical And Electronic Equipment (WEEE). *European Commission DG ENV*.
- Moura, J.M.B.M., Pinheiro, I.G., Lischeski, D. and Valle, J.A.B., 2017. Relation of Brazilian institutional users and technical assistances with electronics and their waste: What has changed?. *Resources, Conservation and Recycling*, 127, pp.68-75.
- Nordic Council of Ministers, 2009. *Method to Measure the Amount of WEEE Generated: Report to Nordic Council's subgroup on EEA waste*.
- Oguchi, M., Kameya, T., Tasaki, T. et al., 2006. Estimation of lifetime distribution and waste numbers of 23 types of electrical and electronic equipment. *Journal of the Japan Society of Waste Management Experts* 17: 50–60.
- Oguchi, M., Kameya, T., Yagi, S. and Urano, K., 2008. Product flow analysis of various consumer durables in Japan. *Resources, Conservation and Recycling* 52: 463–480.
- Ongondo, F.O., Williams, I.D. and Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Management* 31: 714–730.
- Pannuzzo, B., 2014. Material flow analysis on domestic high value WEEE generation and collection in Finland. MSc thesis. Department of Civil and Environmental Engineering, Aalto University, Finland. Available online: http://civil.aalto.fi/en/midcom-serveattachmentguid-1e3d76821a596a0d76811e38f2b0fdc795bf879f879/materials_theses_bruno_pannuzzo (accessed 5 July 2016).
- Parajuly, K., Habib, K. and Liu, G., 2016. Waste electrical and electronic equipment (WEEE) in Denmark: Flows, quantities and management. *Resources, Conservation and Recycling*.
- Peralta, G.L. and Fontanos, P.M., 2006. E-waste issues and measures in the Philippines. *Journal of Material Cycles and Waste Management* 8: 34–39.
- Pérez Ríos, J., 2010. Models of organizational cybernetics for diagnosis and design. *Kybernetes* 39: 1529–1550.
- Polák, M. and Drápalová, L., 2012. Estimation of end of life mobile phones generation: the case study of the Czech Republic. *Waste Management* 32: 1583–1591.
- Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. *Science of the Total Environment* 408: 183–191.
- Spatari, S., Bertram, M., Gordon, R.B. et al., 2005. Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics* 54: 37–51.
- Tansel, B., 2017. From electronic consumer products to e-wastes: Global outlook, waste quantities, recycling challenges. *Environment international*, 98, pp.35-45.
- Van der Voet, E., Kleijn, R., Huele, R. et al., 2002. Predicting future emissions based on characteristics of stocks. *Ecological Economics* 41: 223–234.
- Walk, W., 2004. Approaches to estimate future quantities of waste electrical and electronic equipment (WEEE). In *Driving Forces for Future Electronics, Joint International Conference and Exhibition and Electronic Goes Green 2004+*. Fraunhofer, Stuttgart, 263–268.
- Wang, F., Huisman, J., Stevels, A. and Baldé, C.P., 2013. Enhancing e-waste estimates: Improving data quality by multivariate input–output analysis. *Waste Management* 33: 2397–2407
- Wen, L., Lin, C.H. and Lee, S.C., 2009. Review of recycling performance indicators: A study on collection rate in Taiwan. *Waste Management* 29: 2248–2256.
- Wielenga, K., Huisman, J. and Baldé, K., 2013. EEE Mass Balance and market structure in Belgium. *Final report commissioned by Recupel. United Nations University*.
- Yamasue, E., Numata, T., Okumura, H. and Ishihara, K.N., 2009. Impact evaluation of rare metals in waste mobile phone and personal computer. *Journal of the Japan Institute of Metals* 73: 198–204.
- Yang, J., Lu, B. and Xu, C., 2008. WEEE flow and mitigating measures in China. *Waste Management* 28: 1589–1597.
- Yoshida, A., Tasaki, T. and Terazono, A., 2009. Material flow analysis of used personal computers in Japan. *Waste Management* 29: 1602–1614.
- Yu, J., Williams, E., Ju, M. and Yang, Y., 2010. Forecasting global generation of obsolete personal computers. *Environmental Science & Technology* 44: 3232–3237.
- Zhang, L., Yuan, Z. and Bi, J., 2011. Predicting future quantities of obsolete household appliances in Nanjing by a stock-based model. *Resources, Conservation and Recycling* 55: 1087–1094.
- Zeng, X., Duan, H., Wang, F. and Li, J., 2017. Examining environmental management of e-waste: China's experience and lessons. *Renewable and Sustainable Energy Reviews*, 72, pp.1076-1082.