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RESEARCH AND ANALYSIS

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Quantifying WEEE arising in scrap metal collections

Method development and application in Ireland

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Abstract

Quantifying waste electrical and electronic equipment (WEEE) not arising in documented and formal WEEE collection is a major challenge. This paper presents a method to characterize and estimate quantities of WEEE arising in scrap metal. Two European Catalogue List of Waste, codes 17 04 05, *construction and demolition wastes—iron and steel* and 20 01 40, *metals separated out from municipal, household, commercial, and industrial waste*, were analyzed on arrival to scrap metal sites. Metal scrap originated from household and business sources and excluded end-of-life vehicles and batteries. The point of sampling eliminated risks of double counting. Four representative sites across Ireland were surveyed over the course of 1 year. UNU-Keys were used to assign estimated masses based on identification of WEEE items as they arrived in loads entering scrap metal sites. In total, 415 tonnes of metal scrap were sampled and 747 individual WEEE items were identified. It is estimated that 3.91% ± 1.88% of the mass sampled was WEEE equating to 2.28 kg/capita. Although large equipment dominated the count and mass-based assessments of untreated WEEE in metal scrap, 35% of items identified were classified as small equipment. Professional equipment made up 29% of the estimated mass and 25% of WEEE items observed. Policy makers tasked with enhancing WEEE collection rates need to consider interventions targeting construction, demolition, and renovation, especially planning so that impending WEEE items such as photovoltaic panels are appropriately treated in the future. This article met the requirements for a gold–silver JIE data openness badge described in http://jie.click/badges.

KEYWORDS
substantiated estimate, waste electronics

1 | INTRODUCTION

Convenience electronics, uptake of photovoltaic technology, the rising prevalence of the "internet of things," and increased range of waste electrical and electronic equipment (WEEE) falling under "open scope," that is, all electrical and electronic equipment (EEE) are considered within the scope of the regulations unless they are specifically excluded or exempted; this means that WEEE quantities are expected to continue to grow (European Commission, DG Environmental, 2019; Parajuly et al., 2019). Globally, 53.6 million metric tonnes of e-waste or WEEE were generated in 2019

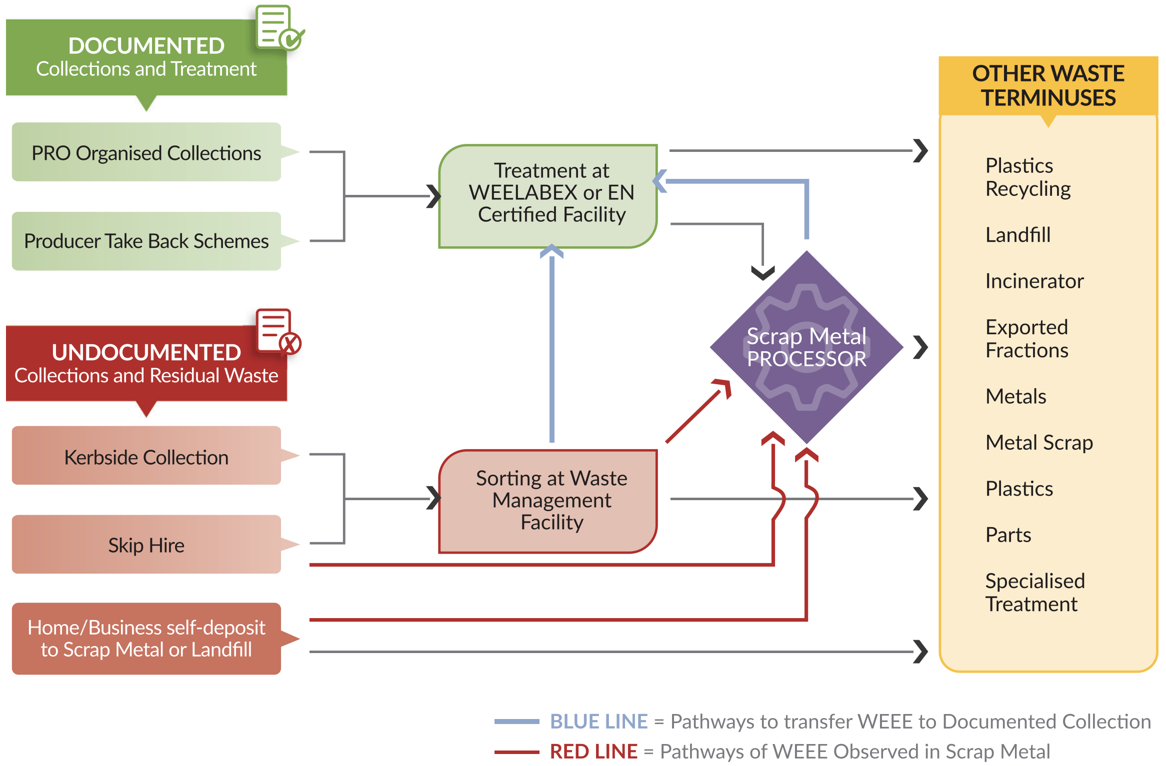

FIGURE 1 WEEE Flows from households to documented and undocumented waste collections and subsequent material flows

and only 17.4% were appropriately recycled (Forti, Baldé, Kuehr, & Bel, 2020). Inappropriately treated WEEE is hazardous to environmental and human health (European Commission, 2016). In 2019, 98 Mt of CO_2-equivalents, or 0.3% of global energy-related emissions were released into the atmosphere from fridges and air conditioners because of inadequate disposal. Approximately 50 tonnes of mercury and 71 kilo tonnes of brominated flame retardant plastics are found globally in undocumented flows of e-waste annually (Forti et al., 2020). It is therefore imperative that greater efforts are made to increase WEEE collection, depollution, and recycling (Parajuly et al., 2019). The "recast" *WEEE Directive 2012/19/EU* requires EU member states to transition to an annual target of either 65% of the average weight of EEE placed on market (POM) in the previous 3 years or 85% of WEEE arising (European Union, 2012). To aid in the estimation of WEEE generated and product POM a WEEE Calculation Tool was developed (Baldé, Meeuwissen, Magalini, & Wang, 2017) and disseminated to each member state.

Annex VII of the WEEE Directive lists appropriate treatment pathways for various WEEE which includes, at a minimum, removal of hazardous materials, for example, flame retardants, refrigerant gases, mercury containing parts, and components such as batteries, printed circuit boards $> 10\ cm^2$, and radioactive containing components. Appropriate treatment of WEEE is essential to a viable circular economy as WEEE also represents a resource opportunity (European Commission, 2015). The value of raw materials present in WEEE arising in 2016 was estimated at approximately 55 billion Euros, greater than the 2016 GDP of most countries (Baldé, Forti, Gray, Kuehr, & Stegmann, 2017). Much EEE contain both precious metals and critical raw materials (CRMs). Appropriate WEEE recovery and treatment provides opportunity to recover CRMs (Chancerel, Marwede, Nissen, & Lang, 2015; Ueberschaar, Otto, & Rotter, 2017), further reduces overall environmental impacts associated with inappropriate disposal (Unger, Beigl, Höggerl, & Salhofer, 2017), and creates jobs (Forti et al., 2020; McMahon, Ryan-Fogarty, & Fitzpatrick, 2021). Across Europe challenges in meeting these new targets have been identified, the *Countering WEEE Illegal Trade* report (Huisman et al., 2015) noted that in 2012 only 35% of WEEE discarded in Europe ended up in official collection and recycling systems. The balance was either exported (16%), recycled under non-compliant conditions within Europe (33%), scavenged for valuable parts (8%), or thrown in waste bins (8%).

1.1 | WEEE management in Ireland

Ireland comfortably met the previous per-inhabitant-based WEEE collection target of 4 kg per year due to high consumption and turnover of EEE. In 2017, Ireland collected 10.88 kg/capita, however EEE POM was 22.5 kg/capita, therefore meeting the new targets is expected to be challenging (Environmental Protection Agency, 2020). Figure 1 depicts WEEE flows in Ireland into documented WEEE collection systems (civic amenity sites, retailer collection, and special collection events) and undocumented collections. The lines in red represent where metal scrap analyzed during this study originated.

Ireland is among several EU member states including Belgium, Italy, France, Portugal, and the Netherlands who adopt an "all actors report" model (European Commission, DG & DIGITALEUROPE, 2017). This involves collating data from metal scrap traders, recyclers operating outside the producer compliance programs, refurbishing, and second-hand shops to register volumes (Baldé et al., 2017). Ireland has two business to consumer (B2C) producer responsibility organizations (PROs), who are responsible for collection of WEEE from retailers and the public on behalf of registered producers. These producers are then exempt from reporting and meeting recovery and recycling targets. Self-complying B2C and business to business (B2B) producers are required to report directly to the Irish Environmental Protection Agency (EPA) (Environmental Protection Agency, 2015a). The EPA conducts National Waste Data Surveys on all waste collectors including specialized WEEE treatment facilities in order to ascertain collection rates for treatment, preparation for reuse, recycling, recovery, and export of WEEE. Data returns from waste collectors and waste collection facilities collated by the National Waste Collection Permit Office (NWCPO) are also used for reporting purposes.

It is known that WEEE ends up outside the PRO organized collections and other appropriate treatment, reuse, and recycling avenues in Ireland. This is a worldwide phenomenon; significant quantities of domestic and commercial WEEE are mixed with residual waste collections, plastics recycling, metal scrap and are even illegally dumped (European Commission, DG & DIGITALEUROPE, 2017; Forti et al., 2020). For Ireland, some estimations of WEEE arising in household and commercial waste have been made particularly through the EPA commissioned *Household Waste Characterization Campaign* and the *Non-household Waste Characterization Campaigns* (RPS & Clean Technology Centre, 2018). A more detailed summary is provided in Supporting Information S1. Applying these results to the 2016 National Waste Profile figure shows that household and non-household kerbside waste collections contained 6,943 and 3,061 tonnes of WEEE, respectively. This represents 2.0 kg per capita (1.4 kg from households and 0.2 kg per capita from non-household) or 19% of the reported WEEE collected in 2016. However, it is unclear if this WEEE eventually ends up being treated at certified facilities as per Figure 1. The Waste Characterization Reports provide an incomplete picture of WEEE arising in residual waste since the analysis is carried out on kerbside and continual waste collection only and excludes waste brought directly to landfill, scrap metal processors, waste collected by small operators for occasional waste clearances, and through skip hire (see Figure 1). The *EPA Non-household Waste Characterization Campaign* surveyed certain sectors excluding industry and primary producers. Studies surrounding the fates of WEEE from B2B have been less to the fore in literature. Peagam, McIntyre, Basson, and France (2013) contest that B2B WEEE collection has been under-researched, whilst Huisman et al. (2012) suggested that almost all WEEE originating from business sources enter metal or plastics recycling, incineration, or landfill without having undergone appropriate treatment.

Informal consultations were carried out by the authors with domestic and commercial waste management contractors as well as the EPA and local authority waste inspectorate, a WEEELABEX[1] certified recycling facility and representatives of PROs. These consultations revealed that WEEE were observed in almost all waste collections from homes and businesses. Large WEEE items were often hidden amongst waste in skip hire[2] returns, contrary to consumer guidance. Waste contractors sorted metal containing items including WEEE into "good" and "bad" scrap piles; that is, items that have a high metal content, for example, washing machines were placed into the "good" scrap pile and small WEEE comprised of plastics such as small household appliances, for example, vacuum cleaners were considered "bad" scrap. Scrap metal processors paid waste contractor rates according to the grade and weight of metals. Some domestic and commercial waste contractors exported scrap directly to processors outside the state.

The terms and conditions of scrap metal processors Waste Facility Permits state that "WEEE shall be subject to appropriate treatment and recovery....prior to acceptance at the scrap metal facility." In the case of non-household WEEE, the final owner should ensure that it was "treated in accordance with the WEEELABEX normative requirements or any other equivalent EN treatment standards" (European Union (Waste Electrical and Electronic Equipment) Regulations, 2014, 2014) and documentation should be available to confirm treatment. These WEEE should be reported as collected and treated. Some WEEELABEX/EN treatment certified facilities provide WEEE collection cages (pictures are supplied in Figure S1A in Supporting Information S1) to scrap metal processing sites in order to facilitate collection and treatment of WEEE arising in mixed metal collections, since the majority of these sites are not accredited to the necessary standards to treat WEEE in accordance with Irish legislation. Removal of WEEE to these or other ways of returning WEEE to accredited recycling are represented by the dotted line from scrap metal recyclers to WEEE recyclers in Figure 1. Accredited WEEE recyclers and representatives of the PROs reported that they receive lower than anticipated volumes of WEEE from scrap metal processors.

1.2 | WEEE in metal scrap

Across Europe, numerous studies have informed that WEEE is found in substantial quantities in scrap metal collections (ADEME, 2013; Huisman, 2013; Huisman et al., 2012; Magalini et al., 2014; Smith, Peagam, & Hennig, 2014). It is believed that the vast majority are not appropriately treated beforehand, missing the key instructions provided by Annex VII of the WEEE directive (Magalini et al., 2014). An FAQ document on the WEEE

[1] The WEEELABEX project lays down "*a set of European standards with respect to the collection, sorting, storage, transportation, preparation for re-use, treatment, processing and disposal of all kinds of WEEE, and, additionally, a harmonised set of rules and procedures that will provide for conformity verification*" (Leroy, 2012).

[2] A skip (British English, Australian English, Hiberno-English, and New Zealand English) is a large open-topped waste container designed for loading onto a special type of lorry. Instead of being emptied into a bin lorry on site, as a wheelie bin is, a skip is removed, or replaced by an empty skip, and then tipped at a landfill site or transfer station (waste management) ("Skip (Container)," 2020).

TABLE 1 Belgian, Dutch, and French WEEE in metal scrap summary (ADEME, 2013; Huisman, 2013; Huisman et al., 2012)

Study	% WEEE in scrap metal	kg/Inhabitant	Tonnes
Belgium	2	1.4	15,000
France	10	3.1	200,000
The Netherlands	3.5–7	Up to 6.6	88,000–110,000

Directive (European Commission, DG Environmental, 2014) acknowledges the complexity of WEEE flows and the difficulties presented by higher collection targets. In order to help member states to demonstrate achievement of collection targets, substantiated estimates which are "supported by independent scientific methodologies and be based as far as possible on real market data" may be used (European Commission, DG Environmental, 2014). If a member state can establish a mechanism to estimate the quantity of WEEE that is collected and treated outside of the operation of the current regulations and not recorded, then these substantiated estimates of WEEE can be counted toward the average percentage of recycled and recovered materials originating from WEEE and of components of WEEE under Article 16(4) of the recast directive (European Commission, 2019). The European Electronics Recyclers Association (EERA) has cautioned that the use of substantiated estimates affect "the proper collection, logistics and treatment of WEEE" (EERA, 2019). Nevertheless, material flow analyses of untreated WEEE arising in metal scrap may provide further insight into WEEE flows, locating blind spots, identifying key intervention points and ultimately improving WEEE collection through compliant channels (Magalini et al., 2014). The data could also be used to further the case for jobs creation through improved collection and appropriate treatment (McMahon et al., 2021).

Quantification of WEEE arising in scrap metal collections have featured in countrywide WEEE mass balance reports such as those conducted in Belgium (Huisman, 2013), Denmark (Gilberg, 2017), France (ADEME, 2013), the Netherlands (Huisman et al., 2012), and the United Kingdom (Smith et al., 2014). Assessments of WEEE in metal scrap in both Belgium and the Netherlands were based on interviews and surveys of scrap metal sites. The percentage of WEEE was determined by operator estimates (Huisman, 2013; Huisman et al., 2012). In France, site visits and interviews were used to determine WEEE in metal scrap content (ADEME, 2013). The UK's assessment sampled light iron collections and sought out large domestic appliances (LDA) only. These were separated from sampled loads, identified, recorded, counted, and weighed directly using weighbridges on sites (Smith et al., 2014). The *Countering WEEE Illegal Trade* study (Huisman et al., 2015) estimated that in the EU-28+2, 2.2 million tonnes of WEEE were mixed with metal scrap in 2012. In the United Kingdom, the estimated LDA content of light iron was found to be 10.87% $\pm$ 2.4%. (Smith et al., 2014). The higher figure in the UK study points to a key difference in the structure of their compliance system, which lacks a mandatory retailer take-back scheme. Denmark estimates that 12,500 tonnes of WEEE are lost to unauthorized scrap dealers (Gilberg, 2017). The Belgian, Dutch, and French studies are summarized in Table 1.

All studies acknowledged difficulties in tracking WEEE in metal scrap, particularly issues around double counting as wastes are transferred between collectors and processors.

1.3 | Aims of the study

There are no formal documented or standardized methods to quantify WEEE arising in metal scrap. The primary aim of this research was to devise a rapid assessment method that was minimal, reliable, replicable, and low cost. This is reflective of the conditions in which the EPA and Local Authority Inspectorate operate and was also essential in securing voluntary participation of the scrap metal processors. Quantifying WEEE in metal scrap was part of a broader research agenda examining WEEE flows in Ireland and encompassed both qualitative and quantitative analyses of WEEE arising and not arising (Casey, Lichrou, & Fitzpatrick, 2019; Ryan-Fogarty et al., 2020). WEEE in metal scrap data were used to identify WEEE composition to uncover reasons why untreated WEEE ended up in scrap metal. This knowledge was used to present recommendations to prevent and regularize these flows.

2 | METHODS

In developing the sampling method four scrap metal processing sites were visited and observed, and discussions were held with representatives from each of the sites. A sampling method was piloted on two sites in January 2019 before refining further for sampling on four sites across Ireland. The overall research had an advisory committee consisting of various sections of the EPA (waste statistics, inspectorate and enforcement, and policy development) and PRO representatives. The methods were developed in consultation with the advisory committee.

2.1 | Systems analysis

Scrap metal processors accept waste metal from waste management contractors, commercial and industry sources, small waste removal firms, other waste collection permit holders, and members of the public. Profit margins are reported to be small depending on markets, therefore physical

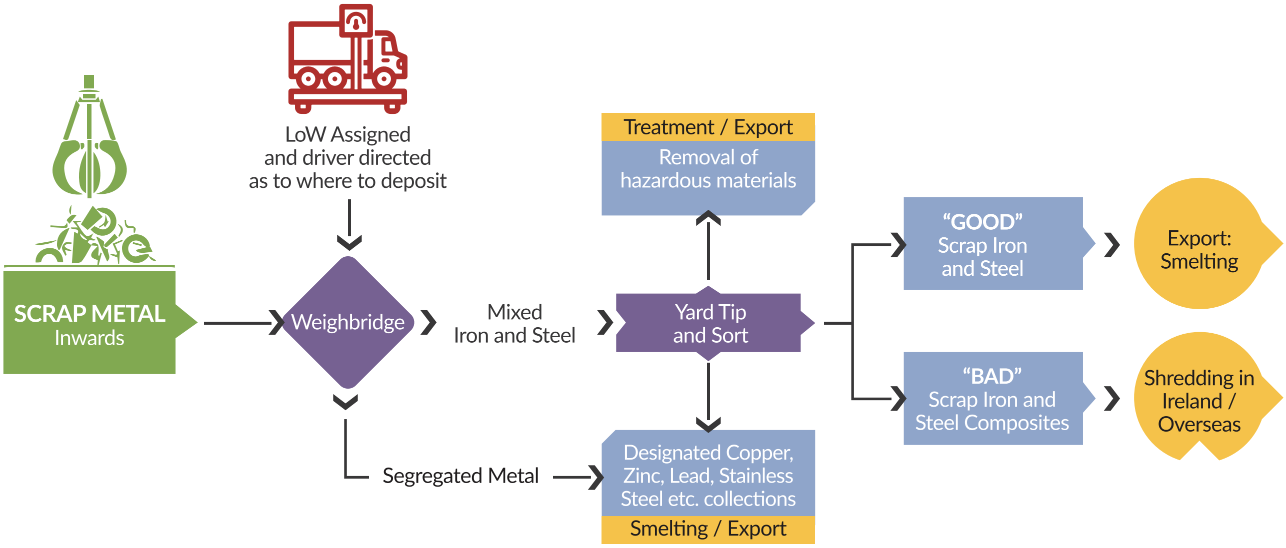

FIGURE 2 Flow of scrap metal through scrap metal processing sites

space, personnel time, and equipment used tend to be optimized. Scrap metal processors are reliant on a steady supply of waste collected and customers do not appreciate delays in depositing material and want competitive prices for scrap collected. Scrap metal arriving on site is weighed by weighbridge and assigned a List of Waste (LoW) Code from the European Waste Catalogue (Environmental Protection Agency, 2015b). During piloting it was observed that most of the incoming waste to scrap metal processors are recorded as 17 04 05 (*Construction and demolition wastes: iron and steel*) or 20 01 40 (*Municipal wastes (household waste and similar commercial, industrial and institutional wastes): metals separated out from municipal, household, commercial and industrial waste*). Both are similar in composition and were used interchangeably by sites, often determined by the type of operator delivering the waste as opposed to the waste origin itself—that is, if a small waste removal firm or member of the public delivered metal, it was coded as 20 01 40, if a skip hire company delivered, it was deemed 17 04 05.

Figure 2 provides a simplified flow chart of the throughput of metals on a typical scrap processing site.

Loads are tipped and spread using a mechanical grab. Priority is given to removal of dangerous materials, for example, gas canisters, which could cause an explosion. Only occasionally are problematic WEEE, for example, fridges, freezers, screens, etc. placed in WEEE collection cages (see Supporting Information S1 for images). Sorting then focuses on separating higher value materials, for example, copper and stainless steel. Then, iron and steel left are separated into two piles: "good scrap" and "shredder/frag feed." "Good scrap" is relatively clean iron and steel, requiring minimal further processing prior to export. Metals fused to other materials (e.g., plastics, wood, fabrics) are placed in the "shredder" or "frag feed" pile. These are sent to a mechanical shredder, (also called hammer mills or fragmentizers) for further processing. Some scrap metal processors had multiple sites including port-based operations for export. In addition, some scrap processors diverted materials inward based on the probability of the load being more suitable for shredding or export. The merits of a sampling method based solely on counting untreated/undocumented WEEE destroyed through mechanical shredding was considered and a comparison of proposed sampling methods is provided in Supporting Information S1.

In summary, from the systems analysis, site visits, and piloting, several considerations had to be built into the sampling method:

- Scrap metal processors expressed safety concerns, risk assessments, safety training, and site-specific inductions were completed.
- Sites needed to be assessed in advance of sampling to ensure representativeness of sampled materials.
- Separate WEEE collection and using on-site weighbridges would not be possible due to physical space restrictions and delay and downtime incurred by sites and customers.

2.2 | Sampling method

Google Maps were used to identify the geographic spread of scrap metal processors, then large sites and end processors were identified through NCPWO data. These sites were contacted, informed of the research, and invited to participate. Participation was entirely voluntary; it was not possible to compensate sites for participation in the research. Nine sites were assessed, of these four sites were found to be suitable for sampling. Sites were deemed unsuitable for sampling due to types of waste accepted, low volumes, site layouts that were inhospitable to sampling, and representativeness of loads accepted. The chosen sites were in the East (Dublin), Midlands, Mid-West, and South of the country. All the metal processors surveyed were amongst the largest in the state, each having multiple sites across the country.

The four sites were sampled during a 12-month period from March 2019 to March 2020. Sampling occurred over 17 days. Seasonality in the scrap metal business meant that December is typically a busy month and as a result early January tends to be quiet, these times were avoided. Loads for sampling were not pre-selected, every load assigned LoW Codes 17 04 05 and 20 01 40 were examined until the quota of 100 tonnes per site was met (see Section 2.3: Calculations). On one site, Site B, volumes were uncharacteristically low and it would have taken many days to meet the quota. Due to the proximity of the site to Dublin, the remaining quota was obtained at that site instead.

It was necessary for on-site staff to operate as normal and not separate out WEEE that they would not have, if the research team were not present. During the sampling period no observations of WEEE removal to WEEE collection cages were made. Each site had weighbridges that were calibrated in accordance with their waste collection permit conditions. The vehicle carrying each load entered the weighbridge. At this point the vehicle registration number, producer or collector information (name, permit number, where applicable), origin of the waste and LoW Code assigned were noted by the sites' weighbridge software system. Once the gross weight of the vehicle was recorded, the vehicle driver was instructed to tip the load in the designated tipping bay. The grab operator then sorted the load into different material bays. The empty vehicle proceeds back to the weighbridge and the weight of the load is established.

At the point where the load was tipped and spread for sorting, researchers identified and counted WEEE items within the incoming loads. The time of arrival of the load and vehicle registration numbers were noted so that the weight of the load and LoW Code assigned could be recorded. This was important as sometimes wastes arrived that were not of interest, for example, 15 01 04 metallic packaging. Items were photographed for later verification if they were not immediately identifiable. A spreadsheet was used to record site location, sample number, LoW Code assigned, load weight, items observed (e.g., LCD TV, microwave, fridge), and the number of items observed.

Since it was not possible to collect WEEE and weigh on site, each item observed was classified by a "UNU-Key." Fifty-four UNU-Keys were developed by UNU to categorize products by similarities in function, and material composition (e.g., hazardous materials and precious metals). Products in the same category share homogeneous average weights and similar life-time distributions (i.e., when an item would be expected to become waste). They also serve as the common methodology to calculate WEEE collection targets as part of the WEEE Calculation Tool (Baldé et al., 2017; Forti et al., 2020). UNU-Keys were used to convert identified WEEE items to estimated weight by applying the average Put on Market kilogram per unit weights—this is the average weight of the items in each UNU-Key when at time of sale within the EU-28. A full list of average weights spanning years 1995, 2000, 2005, 2010, 2015, and 2016 are listed in Annex 3 of Forti, Baldé, and Kuehr (2018). The year 2000 was chosen as the average POM year for WEEE arising in metal scrap at the time of the study since previous studies on Irish WEEE arising (Johnson, Fitzpatrick, Wagner, & Huisman, 2018) determined that in 2020 almost half of large WEEE items expected to arise would be "historic," that is, pre-2005 POM. Pictures of the conditions on scrap metal sites and some examples of the presentations of WEEE encountered in metal scrap are provided in Figure S1B in Supporting Information S1.

2.3 | Calculations

Scrap metal populations observed were LoW Codes 17 04 05 and 20 01 40. An average of total quantities of both LoW Codes from annual returns for previous years was obtained from the NWCPO. The totals consist of waste collected by waste collection permit holders, plus waste brought by members of the public to waste collection permit holder sites. Total quantities were projected to be in the range of 200,000—300,000 tonnes per annum for 2018 and 2019 based on available data. Because the population was expected to be large, Cochran's formula (see Equation 1), as described by (Israel, 1992) was used to determine the sample size (n_0).

$$\mathbf{n_0} = \frac{\mathbf{Z^2pq}}{\mathbf{e^2}} \tag{1}$$

The Z value was found in statistical tables (1.96 for 95% confidence level), p is the estimated proportion of an attribute that is present in the population, we assumed maximum variability and set $p = 0.5$, q is $1 - p$ (0.5) and e is the desired level of precision, in this case ±5%, so 0.05, the sample size required was found to be 384 tonnes.

$$\mathbf{n_0} = \frac{1.96^2\,(0.5)\,(0.5)}{0.05^2} \tag{2}$$

A sampling quota of 100 tonnes was set for each site and sampling continued until the quota was met. A final sample size of 415 tonnes was recorded. Annual data returns were not available for 2019 at the time of writing therefore 2018 data were used. In 2018 the NWCPO recorded 280,062 tonnes of LoW Codes 17 04 05 and 20 01 40 combined.

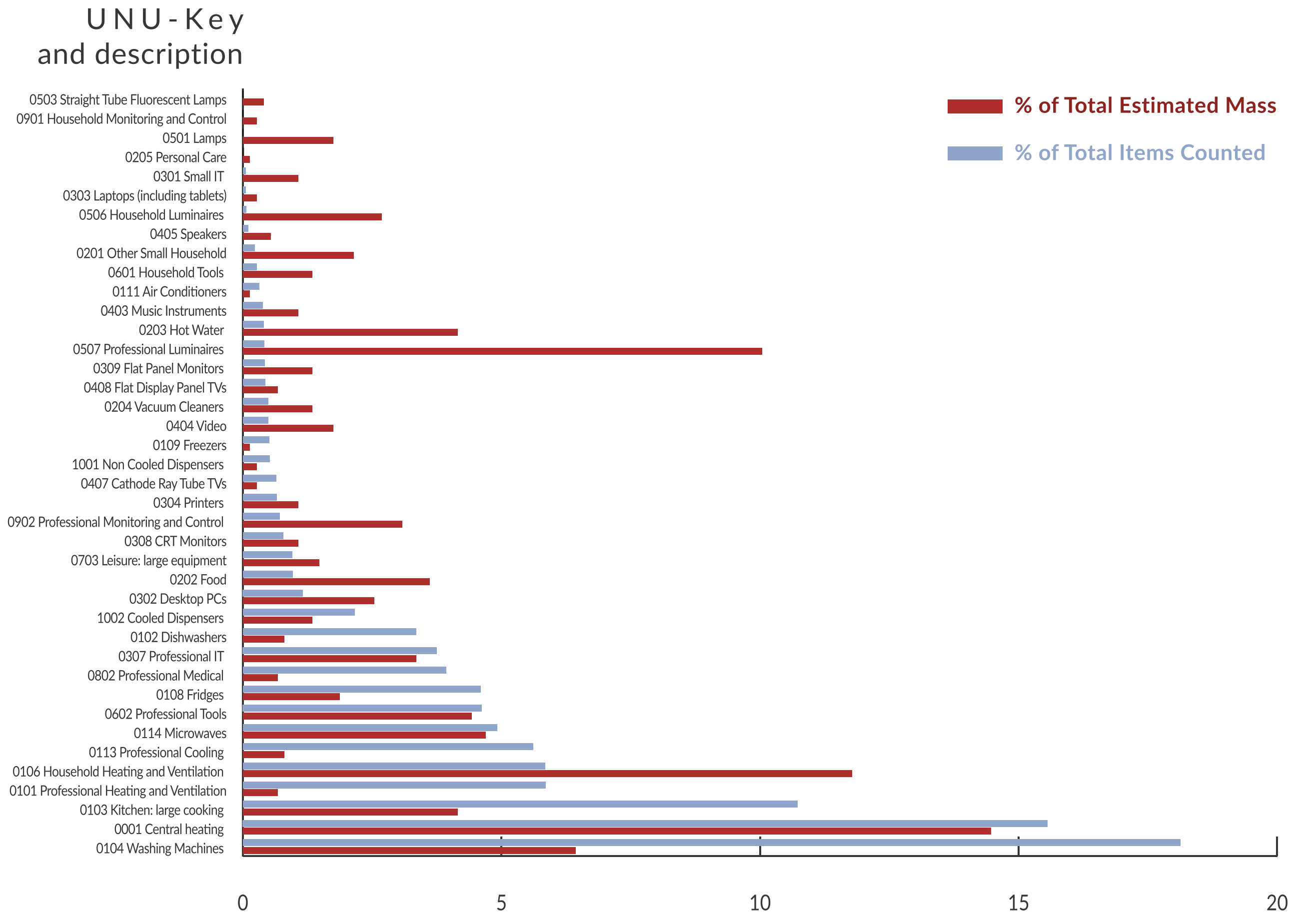

FIGURE 3 UNU-Keys as percentage of total mass recorded and percentage of total items counted. Underlying data used to create this figure can be found in Supporting Information S2

3 | RESULTS

Of the 415 tonnes of scrap metal sampled 3.91% ± 1.86% of this were estimated to be WEEE. This puts WEEE in the range of 2.05–5.77% with a confidence level of 95%. Scaling this for 2018 data for the LoW Codes sampled gives an estimated figure of 10,950 tonnes which translates to an estimated range of 5,741–16,160 tonnes. If this WEEE were to be collected through compliance schemes, an estimated potential 2.28 kg/capita could be added to Ireland's collection rates. In identifying individual WEEE items, 747 out of 764 items observed were categorized. Items that were not identifiable were fragments or extremely specialized WEEE of which there were multiple similar items.

In total, 257 individual loads were examined. Individual loads ranged in weight from 20 to 20,670 kg. Only 11% of loads did not contain WEEE, while 21% contained 5 WEEE items or more, and one load contained 32 individual WEEE items. No correlation was found between load weight and number of WEEE items.

A comparison of percentages of UNU-Keys by estimated WEEE mass and number of WEEE items are presented in Figure 3. The estimated mass of WEEE and items counted were sorted into the EU-6 Categorizations as shown in Figure 4.

Of the 54 UNU-Keys defined only 14 UNU-Keys were not observed in the two LoW Codes sampled on scrap metal sites, these are listed in Table 2.

Although the recast directive brought all EEE into scope including B2B, it was possible to isolate UNU-Keys assigned to "professional," that is, B2B WEEE in observed WEEE. Automatic dispensers were included as those found in scrap were sourced from commercial applications. This analysis revealed that almost 29% of the estimated mass and 25% of WEEE items observed were B2B. The proportions of these are presented in Figure 5.

4 | DISCUSSION

Methods to establish WEEE arising in metal scrap vary considerably by scrap metal observed and underlying WEEE management systems employed so that identifying comparable studies to ours is difficult. However, the method presented here tackles an important aspect of WEEE estimation

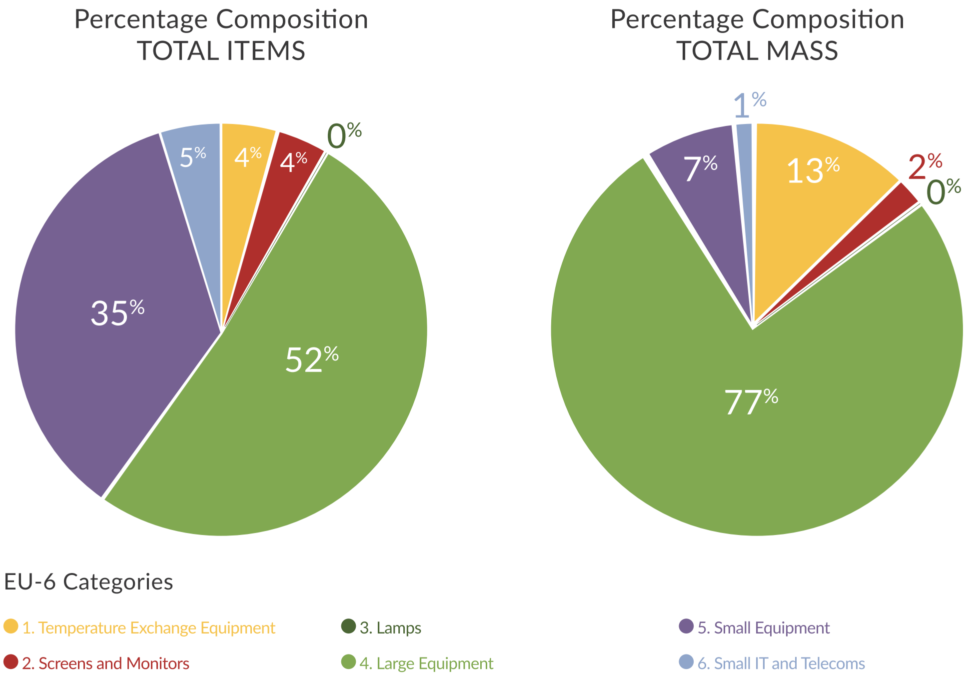

FIGURE 4 Percentage composition by (a) total number of items and (b) by estimated mass of WEEE observed in metal scrap by EU-6 category. Underlying data used to create this figure can be found in Supporting Information S2

TABLE 2 Items not observed during sampling by UNU-Key

UNU-Key	Description
0002	Photovoltaic panels (including converters)
0105	Dryers (wash dryers, centrifuges)
0112	Other cooling (e.g., dehumidifiers, heat pump dryers)
0305	Telecom (e.g., [cordless] phones, answering machines)
0306	Mobile phones (including smartphones, pagers)
0401	Small consumer electronics (e.g., headphones, remote controls)
0402	Portable audio and video (e.g., MP3, e-readers, car navigation)
0406	Cameras (e.g., camcorders, photo and digital still cameras)
0502	Compact fluorescent lamps (including retrofit and non-retrofit)
0504	Special lamps (e.g., professional mercury, high and low pressure sodium)
0505	LED lamps (including retrofit LED lamps and household LED luminaires)
0701	Toys (e.g., car racing sets, electric trains, music toys, biking computers)
0702	Game consoles
0801	Household medical (e.g., thermometers, blood pressure meters)

in metal scrap, that of double counting through the focus on specific LoW Codes. We did not sample shredder feed directly; duplication would have occurred as fractions of the waste incoming to sites assigned LoW Codes 17 04 05 and 20 01 40 make their way into shredders eventually (see Figure 2). The population sampled excludes direct input to shredders and wastes that were directly exported. The estimates and quantities presented are therefore conservative estimates. In addition, there were some loads that had to be discounted during sampling as they were too small for their weight to be recorded by the weighbridge (tolerances varied, one site was unable to record weights below 100 kg), these were mainly small loads from householders.

In determining the sampling method as part of this research, scrap metal sites reported that WEEE arises in other metal containing streams, Table 3 provides a list of these. None were observed during the sampling period as quantities of these LoW Codes arising on scrap metal sites

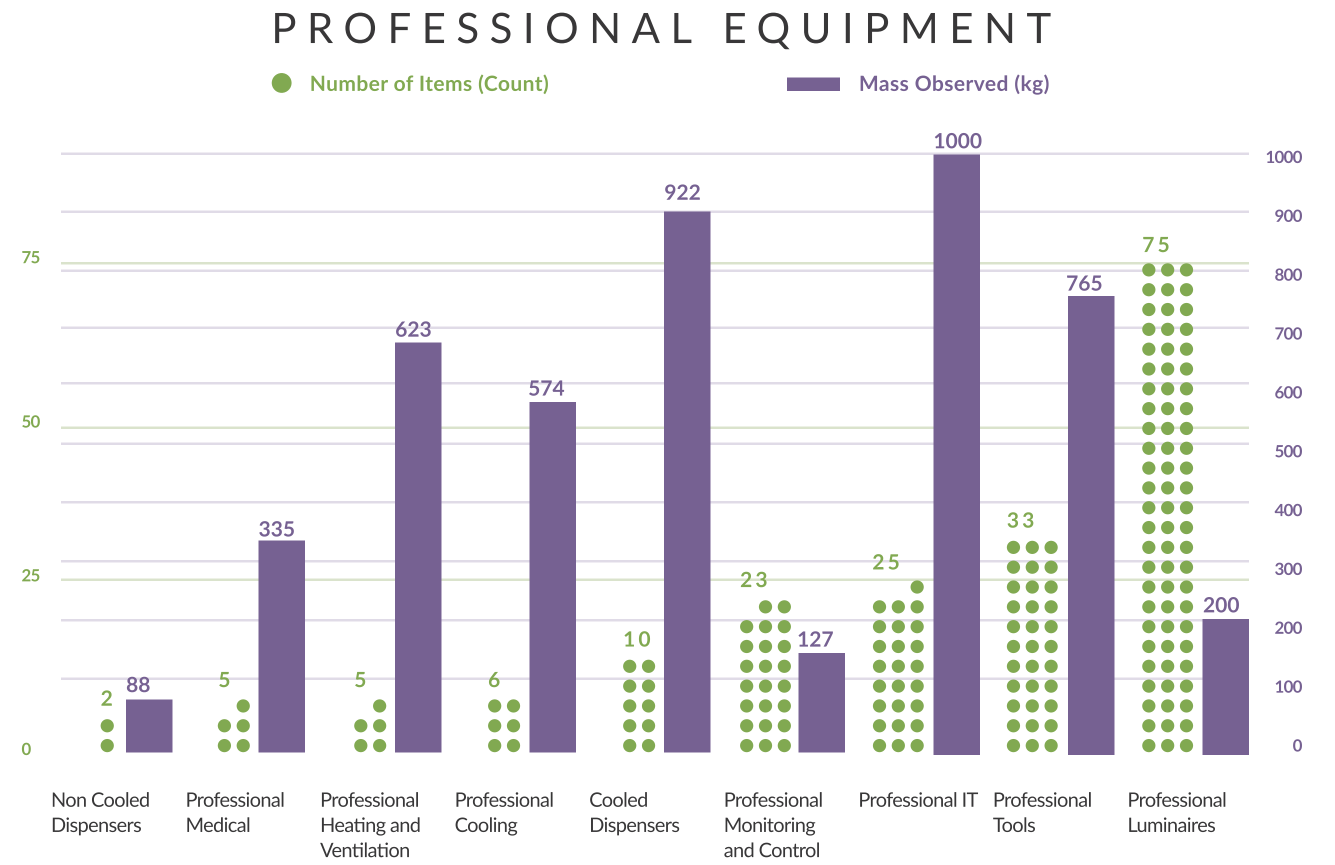

FIGURE 5 Professional equipment WEEE: Number of items and estimated kilograms observed in metal scrap. Underlying data used to create this figure can be found in Supporting Information S2

TABLE 3 Other LoW codes where WEEE is found incoming to scrap metal processors

LoW code	Waste description
17 04 07	Construction and demolition wastes:
	Mixed metals
19 12 02	Wastes from waste management facilities…12—wastes from the mechanical treatment of waste (e.g., sorting, crushing, compacting, pelletizing)
	Ferrous metals
19 12 03	Wastes from waste management facilities…12—wastes from the mechanical treatment of waste (e.g., sorting, crushing, compacting, pelletizing)
	Non-ferrous metals

were low, however a longer study, aided by self-reporting from metal sites may have the potential to capture data regarding WEEE arising in these remaining LoW Codes.

WEEE that is lost from the official accounting system for target setting has an impact on meeting collection targets. Based on 2017 figures, Ireland's collection rate was 57% of the average of the previous 3 years POM. Ireland would comfortably reach the collection target of 65% of the average of EEE POM for previous 3 years if WEEE in metal scrap were included. However, this WEEE has not been subject to appropriate treatment as defined by the WEEE directive Annex VII. Observations on scrap metal sites established that they were not actively soliciting WEEE, most WEEE were "hidden" in larger loads and would have been very difficult for processors to detect. Preventative measures are required to divert WEEE away from scrap metal collections, and into appropriate recycling, reuse, and recovery operations (Johnson, McMahon, & Fitzpatrick, 2020; Parajuly, Fitzpatrick, Muldoon, & Kuehr, 2020).

Figures 3 and 4 demonstrate the differences between estimated mass versus number of WEEE items. Scrap processors and domestic/commercial waste collectors both indicated that large WEEE items were not uncommon in skip collections, the dominance of large equipment (EU-4) in mass-based estimates was anticipated. In order to understand the dominance of large equipment, WEEE observed were also categorized based on EU-10 categories. LDA comprised 73% of the estimated mass of WEEE observed in metal scrap. When extrapolated and compared to POM and "Waste Collected" data from Eurostat for 2017 (available data), LDA in metal scrap were estimated to be 10% of the total LDA collected on 2017 and 7% of the total POM. Although it seems from Figure 3 that estimated masses were similar for both boilers and washing machines, on a per-item basis there were 108 boilers (~3.3 tonnes) and 48 washing machines (~3.4 tonnes).

Ireland has a well-established, free-to-consumer retailer take-back system and free public access to civic amenity WEEE collection. The difference in estimated mass versus quantity between central heating and washing machines shows that the retailer take-back system works well for shop bought LDA when replacing like-for-like appliances. However, there are clearly times where this scheme fails. This points to the source of this WEEE; LDA arising at a time of construction or demolition may not be immediately replaced and therefore are not recovered at the point of sale. If a member of the public is themselves carrying out the demolition or home renovation, then they can return WEEE to an electrical retailer or civic amenity site. This depends on the customers knowledge of WEEE disposal systems and ability to mobilize and transport waste LDA. If the renovation is carried out by a company, then, as a commercial operator, they are not permitted to use civic amenity sites, leaving disposal through construction and demolition waste as the only available option.

The estimated mass of *Category 1: Temperature Exchange Equipment* is concerning as these items contain greenhouse gases and components that require specialist treatment and failure to do so results in direct environmental damage. In general, scrap metal processors are not appropriate to the task of treating highly complex WEEE, which are often sources of rare and other hazardous trace elements and materials (Chancerel, Meskers, Hagelüken, & Rotter, 2009). Pre-processing is a key step that is required in the treatment of WEEE, as shredding is the most ineffective method to recover precious metals (Chancerel et al., 2009; J. G. Johansson & Björklund, 2010). Isolating products and components for appropriate treatment (Ueberschaar, Jalalpoor, Korf, & Rotter, 2017) provides the best chance to recover CRMs through effective materials management and "material hygiene" (J. Johansson & Luttropp, 2009). Scrap metal processors are not strangers to this concept, it is practiced on sites, materials are routinely sorted to maximize material homogeny and purity as this directly impacts profits. Some go further to ensure that where possible the separation of clean iron and steel is so attuned that it can be graded, certified to end of waste standard then sold as products. In order to move WEEE out of metal scrap and ensure appropriate treatment, incentives need to be provided where informal collections occur (Step Initiative, 2016).

Interestingly, 35% of all items observed were classified as *Small Equipment*, and by mass this represented 7% of the estimated total. Without a count-based analysis small equipment in scrap metal collections may be overlooked due to their lower contribution to mass-based target setting, for example, Smith et al. (2014) focused on LDA only. However, with collection targets set for each category, further analysis of small WEEE arising in non-compliant flows is warranted, particularly in plastic waste recycling.

In terms of WEEE not observed during sampling, it is perhaps too early to see flows of photovoltaic panels become WEEE as they are relatively new to the Irish market, whilst some items are not commonly used in Ireland (e.g., dehumidifiers and answering machines). The trends identified, specifically regarding WEEE arising as a result of construction or demolition prompts concern for the fate of waste photovoltaic panels into the future. In this way analysis of WEEE arising in specific LoW Codes has proved beneficial by flagging current and raising potential future issues regarding WEEE collection from consumers and businesses.

The lack of specialist lamps and compact fluorescent lamps could be explained by difficulties in identifying these as opposed to regular lamps and light fittings. Small WEEE such as household appliances, toys, tools, consumer electronics, and IT equipment's high plastic content (Maisel et al., 2020) might make them more likely to arise in plastic recycling streams. Most notable is the lack of small WEEE pertaining to data storage such as mobile phones and tablet computers. These items are of interest due to their conflict and CRM content (Fitzpatrick, Olivetti, Miller, Roth, & Kirchain, 2015). Research suggests that data storing small EEE such as mobile phones are more likely to be stored for long periods in households (Speake & Yangke, 2015; Wilson et al., 2017; Ylä-Mella, Keiski, & Pongrácz, 2015). Consumers are concerned for the safety of their data, keeping small WEEE like this is also seen as useful to have as a backup or the consumer does not know how to appropriately dispose of them (Casey et al., 2019; Speake & Yangke, 2015; Wilson et al., 2017). These findings verify that such WEEE is unlikely to arise in metal scrap.

Other categories of WEEE not observed in scrap metal included toys, games consoles, household medical devices, telecom, and small consumer electronics like headphones and remote controls. Small items are particularly easy to dispose of in household waste collections. Because these tend to have a high plastics content, most of these items would not arise in a metal collection and may end up in waste that is taken directly to shredding facilities, landfill, plastics recycling, or incineration.

Professional or B2B WEEE was a significant proportion of both the mass-based estimate (29%) and count of WEEE items (25%). As others have noted B2B WEEE arising outside of formal collection is under researched (Smith et al., 2014). The significant volumes in construction and demolition waste are logical, if a business fails or a business premises is leased to a new tenant, removal of equipment is completed by agents other than the original purchasers of equipment. Take-back schemes become defunct and WEEE is subsequently disposed of together with other wastes as part of renovations and clear outs.

Using UNU-keys facilitated a rich insight into electrical and electronic items arising in metal scrap, for example, 98% of items observed could be categorized. The non-invasive aspects of this method made participation in this research easier for scrap metal sites and permitted access to privileged information and observations on these sites. The method developed is low cost, minimally invasive, and replicable. However, it is not without error. Using the UNU-Keys can only provide an *estimate* of WEEE masses and the authors decided the set of weight values to use based on likely POM year of WEEE likely to be observed. There can be huge variance of weights within categories and assumptions implicated therein.

Yet, UNU-Keys and their corresponding HS codes are used to populate the WEEE Calculation Tool, upon which estimations of WEEE Generated for collection target setting are based.

A further cautionary tale in the use of UNU-Keys is that attention needs to be paid to the evolving nature of WEEE. Dryers were not recorded in the waste sampled; however, they may have been misidentified as washing machines since the categorization allows for combined dryers. One explanation is that the proportion of dryers to washing machines in households is low—a UK study revealed that 98% of household owned a washing machine, but just 58% a dryer (Statista, 2019). Evolving technology means that more energy efficient dryers require condensers (like refrigeration) thereby increasing the need for appropriate treatment of such items as they reach end of life. It is important to classify items by treatment need as well as weight and use and further highlights the need for appropriate treatment of all WEEE. The analysis of UNU-Keys pertaining to professional equipment will need expansion and further refinement as more WEEE comes into scope.

5 | CONCLUSIONS

A method for estimating WEEE in metal scrap was developed that is replicable and can be used by researchers and inspectorate. It is rapid, low cost, causes minimal disruption and may convince otherwise unwilling sectors to facilitate sampling and data retrieval.

Analysis based on the European Waste Catalogue LoW Codes permits future comparisons across member states and the point of use eliminates the risk of double counting. Demolition and renovation of households and businesses were the main sources of WEEE reviewed in this analysis. Interventions to divert WEEE into documented treatment and collection need increased focus on these events.

Using an identification and classification system such as the UNU-Keys facilitated both compositional and estimated mass analyses. Large equipment dominates the WEEE observed, however small equipment was more prevalent in metal scrap than has been previously reported. This has impacts on meeting collection targets per category. B2B waste needs further analysis and diversified classification as more WEEE comes under scope.

Items not observed point to likely future issues regarding WEEE collection. The prevalence of boilers shows that photovoltaic panels are likely to meet the same fate as their end-of-life approaches if targeted intervention is not implemented.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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