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Developing and Applying Circularity Indicators for the Electrical and Electronic Sector: A Product Lifecycle Approach

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Abstract: The adoption of circularity indicators in the electrical and electronic sector is understood to play a critical role in organisational decision making during the transition from a linear to a circular economy. Yet, it is widely recognised that there is no standardised method of measuring circularity performance. Additionally, the extent of literature uncovers a range of shortcomings of existing cross-sector circularity indicators, including a predominant focus on end-of-life, limited coverage of social measurements, a lack of sector specificity and limited capture of product functionality, durability or sharing. Furthermore, the current electrical and electronic sector-specific circularity indicators focus greatly on repair and recycling, failing to acknowledge the significant impact on circularity of the design and manufacturing, distribution and use phases. Therefore, this research set out to answer how electrical and electronic manufacturers can measure the circular economy performance of their products by developing and testing multidimensional circularity indicators for all products' life cycle stages. To achieve this, a two-fold qualitative approach was adopted. Firstly, a stakeholders' workshop aiming to generate, categorise and rate novel circularity indicators was held. Secondly, a focus group piloted the resulting workshop's circularity indicators. The findings highlight key factors that influence circularity indicators' applicability to electrical and electronic products, including product function, service arrangement, and customer type. The research has implications for electrical and electronic organisations seeking pathways to the circular economy by understanding, assessing, and measuring the circularity of their products.

Keywords: circularity indicators; electrical and electronic products; lifecycle phases; circular economy; circular economy business models

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Citation: Pollard, J.; Osmani, M.; Cole, C.; Grubnic, S.; Colwill, J.; Díaz, A.I. Developing and Applying Circularity Indicators for the Electrical and Electronic Sector: A Product Lifecycle Approach. *Sustainability* **2022**, *14*, 1154. https://doi.org/10.3390/su14031154

Academic Editors: Elena Cristina Rada and Lucian-Ionel Cioca

Received: 7 December 2021
Accepted: 18 January 2022
Published: 20 January 2022

1. Introduction

The circular economy (CE) has been gaining traction with consumers, industry stakeholders, researchers, and policymakers due to the promising opportunities to deliver benefits in line with the sustainability paradigm [1,2]. The transition from a linear economy to the CE relies on individual organisations adopting circular economy business models (CEBM) [3]. One sector that could benefit from greater adoption of CEBM is the electrical and electronic (E&E) sector [4].

The E&E sector has increasingly been the subject of CE research in recent years due to its unsustainable production, consumption, and waste practices [5]. As a trend, the product innovation process is speeding up, resulting in shortening of product lifecycles and early obsolescence [6]. The rate of growth of demand for E&E products is constantly increasing [7]. Often, E&E products are subjected to functional or technical obsolescence despite the potential for a reduction in overall lifecycle energy by extending their service life when compared to replacement with new models [8,9]. Furthermore, the rise of smart objects means that E&E functionality is being added to a growing number of products [10]. Unused E&E products are often hoarded instead of being passed on or disposed of [11]. There is currently a limited second-hand market for E&E products [12] and remanufacturing represents a market share of only 0.1% [13]. As a result, waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams globally [7]. The WEEE generation presents particularities due to the contained hazardous and toxic substances, as well as the valuable materials [10,14]. Additionally, over 53 million metric tons (Mt) of WEEE was generated globally in 2019 and the waste generation rate in the sector is increasing by approximately 2 Mt year-on-year [7]. Similarly, in Europe, WEEE is increasing 2% per annum [4]. The E&E sector still operates in a predominantly linear economy with limited instances of reuse and recycling [15], which results in the majority (60%) of the embodied resources being lost at end-of-life [7]. The adoption of CEBM by E&E organisations could help to address these sectorial pressures by intrinsically linking their business value to the CE, thereby improving resource efficiency and encouraging improved management of WEEE for value retention and closed-loop value chains [16]. However, research has shown that industry stakeholders are still unsure of the benefits of introducing circularity into their business practices [17].

The ability of E&E organisations to measure the circularity of their products is critical to the development of actionable, economically viable and sustainable CEBM with measurable results [18]. Currently, there is no standardised method of measuring circularity, which presents a key barrier to further CEBM implementation [19]. Circularity indicators (CIs) that can measure and monitor the impacts of CE performance and the impacts of CE-led interventions are required to support the adoption of CEBM in practice [20]. Research developing or reviewing CIs has been increasing over the last 5 years [21]; numerous CIs have been proposed to capture circularity or an aspect of it [22,23]. However, there is still much debate on the ability of existing CIs to capture the nuances and scope of the CE [24–26]. Furthermore, there is evidence that the majority of organisations do not employ CIs or formal measurement methods to measure the circularity of their products; and a lack of CI data and CE knowledge are the greatest obstacles to the implementation and measurement of CEBMs [27]. The development of sector-specific CEBM has been proposed as a method for reducing organizational knowledge gap regarding the CE and CEBM implementation [28]. Saidani et al. [20] highlighted the need for sector-specific CIs that account for the characteristics of sectorial activities to increase their use by organisations; hence, there is a requirement for further research to develop and test sector-specific CIs.

Thus far, there has been limited investigation of E&E sector-specific CIs [29,30], and no study has been identified that addresses the range of CEBM possibilities for E&E products with a view to capturing the circular performance throughout the E&E products' lifecycle. In response to the gap in the body of knowledge, this research seeks to answer the question: "How can E&E sector organisations measure and monitor the circularity of their products?" Answering this question, the aim of this paper is to develop and test a multidimensional set of CIs capable of measuring and monitoring the circularity of E&E products.

2. Circular Economy Business Models

CEBM build on the understanding of a business model (BM) as the way an organisation creates, captures, and delivers value [31]. Similarly, a CEBM has been defined as a way that an organisation can perform its business functions to create, capture, and deliver value whilst improving resource efficiencies and closing material loops via CE practices [16]. As such, a CEBM aims to deliver circular systems that are economically and commercially viable for an organisation [32]. Successful CEBM relies on the supply and value chain also integrating circular practices, and customers adopting behaviours that enable circularity [33].

Recently, researchers have increasingly adopted a dynamic view of CEBM by exploring how organisations transform their existing BM to CEBM by increasingly integrating CE principles [18,34]. Several generic CEBM archetypes have emerged as tools for this transformation process [35]. Pieroni et al. [34] described these archetypes as dynamic conceptual tools that support identification of CEBM opportunities. Several archetypes exist within the emerging body of knowledge, and varying terminology is used to describe them. The five CEBM archetypes that capture those most commonly appearing in the literature are shown in Table 1.

Table 1. Five circular economy archetypes proposed by Pollard et al. [18].

CEBM Archetype	Description
Circular Supply Chain	Embedding circular thinking into the management of the supply chain.
Recycling and Recovery	Optimising material value by recovering secondary raw materials or by-products for recycling.
Product life extension	Designing products to be durable for a longer use period or multiple use periods.
Sharing economy	Services of sharing, lending, or collaborative use of underutilised products.
Product service systems (PSS)	Services of tangible, intangible or virtual offerings and alternative ownership models to meet customer needs.

Sector-specific processes were deemed crucial to increase CEBM adoption and address practitioner uncertainties [28]. Pollard et al. [18] proposed a process framework for developing CEBM expressly adapted to the specificities of the E&E sector. The proposed framework identifies five key, interrelated layers, including (1) business strategy; (2) CEBM canvas; (3) CEBM challenges and enablers; (4) policy; and (5) CIs. The stages of the process framework represent decision-making steps for E&E manufacturers leading to the development of measurable CE implementation strategies (CEIS). The individual CEIS represent actions for the E&E manufacturers which, together for an implementation action, plan for the CEBM. The inclusion of CIs within the framework highlights circularity measurement as a core stage.

3. Circularity Indicators

The broad scope of the CE makes the development of CIs that capture the system difficult [36]. However, CIs offer the opportunity to provide clarity to the complex system through the simplified presentation of information [20]. In this way, measurable CIs can increase confidence in CEIS decision-making processes to address the lack of knowledge of the CE and CEBM amongst industry stakeholders [17,37].

To date, there are no widely accepted or adopted standard CIs, and numerous, complimentary or competing CIs are proposed in both academic and grey literatures. Yet, most are incapable of addressing all five of the CEBM archetypes [26]. Additionally, CIs established in academic literature have been criticised for not being verified through testing with their intended user group, resulting in a limited uptake [27]. De Pascale et al. [22] reviewed 61 CIs published between 2000 and 2019, from the perspective of the 3Rs (reduce, reuse, and recycle) and the three sustainability dimensions, finding that few CIs cover all three sustainability dimensions, and that recycling is the most considered of the 3Rs. In a review of 63 CE metrics published between 2007 and 2017, Parchomenko et al. [23] took a wider approach by considering 24 elements of the CE and found a greater representation of metrics addressing circularity at a material level than at product and system levels, and a lack of metrics to capture value maintenance and longevity. Both studies made the distinction between CIs at the three systemic levels: macro- (national or regional), meso- (industrial parks or cities) and micro-level (organisations or products), as defined by Ghisellini et al. [1]. Kristensen and Mosgaard [38] stated that micro- and meso-level CIs are less prevalent than macrolevel CIs in the literature up to 2019. Contrarily, Saidani et al. [20] argued there has been a marked increase in research of CIs at all three scales (micro, meso and macro) between 2010 and 2018, with most studies on macrolevel indicators originating from China and microlevel indicators originating from Europe. However, they agreed that microlevel CIs lack maturity, which limits their uptake in practice.

In response to the research question and the identified lack of E&E sector-specific CIs, this research is concerned with microlevel CIs that capture circularity at an E&E organisational product level. Currently, organisations most commonly use informal, unstructured methods to assimilate the impacts of their CEBM [27]. Of the cross-sectorial, microlevel CIs proposed in the literature, Kristensen and Mosgaard [38] identified the key themes and these are presented in Table 2. Few micro-level CIs jointly consider all three pillars of sustainable development, and De Pascale et al. [22] presented this as a gap for future research. Saidani et al. [20] concluded, in a review of the 20 cross-sectorial, microlevel CIs, that recycling or remanufacturing activities were the most commonly considered, and only three address the specificities of a particular sector. In another review of cross-sectorial, microlevel CIs, Moraga et al. [26] highlighted that none of the existing CIs addressed product functionality or sharing, therefore were unable to capture the circularity of alternative ownership or use business models. Equally, Elia et al. [25] noted that very few of the existing cross-sector, microlevel CIs and evaluation methods consider product durability, which is key in the E&E sector due to the prevalence of planned obsolescence, echoing the point raised by Parchomenko et al. [23].

Table 2. Key themes addressed by existing microlevel CIs. Data adapted from Kristensen and Mosgaard [38].

Theme	Description
Recycling	Indicators to measure the recycled content or the recyclability of a product, or the extent to which recycling activities support circularity. Indicators measuring recycling also commonly address waste management, remanufacturing and reuse.
Reuse	Indicators to measure the potential for reuse of a product.
Remanufacturing	Indicators to measure the extent to which refurbishment, reconditioning and repurposing activities support circularity.
Resource efficiency	Indicators to measure the extent to which the consumption of resources can be reduced and mitigated.
Product-life extension	Indicators to measure the extent to which material or product's usable life can be extended.
Disassembly	Indicators to measure the extent to which the ease of disassembly facilitates the conduct of circular strategies (recycling, remanufacturing, etc.).
Waste management	Indicators to measure the extent to which waste generation can be reduced and mitigated.
End-of-life management	Indicators developed to support decision making at product's end-of-life by providing a comparison of different strategies.

Rossi et al. [39] proposed requirements for the development of microlevel CIs, which they argued must facilitate the achievement of CE principles and be aligned to an organisation's CEBM while addressing the triple bottom line (environmental, economic, and social performance). Predominantly, the existing literature draws alignment between the CIs and sustainable development [22,24,38]. Although, there is currently limited alignment between existing CIs and the social dimension of sustainability, as most fail to capture the social impacts of circularity [40]. The European Environmental Agency [41] called for measurements of circularity to be aligned to product lifecycle phases (e.g., achievements made at material input, design, production, consumption, and end-of-life). Likewise, Pollard et al. [18] also aligned CIs to the lifecycle phases of E&E products. The design, manufacturing, distribution and use, and end-of-life lifecycle phases are all critical for the circularity of E&E products [1,32,42,43].

Kristensen and Mosgaard [38], when publishing an analysis of 30 existing cross-sectorial, microlevel CIs, found there are three overarching types of CIs: (1) single, quantitative CIs; (2) analytical guidelines, tools and models; and (3) composite, multiple CI sets. Several authors noted the benefit of using multidimensional CIs which they argue are able better capture the complexities of the CE [25,44]. Linder et al. [45] suggested that a generic, microlevel CI is preferable to allow for comparisons between products across sectors. Conversely, Saidani et al. [20] argued that existing, generic, microlevel CIs could form the basis for the development of sector-specific CIs tailored to a specific context, and that this specificity could further encourage adoption. This is echoed by Kravchenko et al. [36], who contended that developing CIs tailored to sectorial specificities facilitates their implementation by ensuring the resulting measurements are contextually appropriate to support informed CEBM decision making.

By and large, two CIs have been developed to specifically address E&E sector activities: the WEEE Recycling Indicator Set [30]; and Repairability Indicators for E&E products [29]. However, both focus greatly on repairing and recycling associated with the end-of-life phase, disregarding the other opportunities and other E&E products' lifecycle phases. Additionally, Rossi et al. [39] proposed a set of 18 generic, microlevel CIs and applied them to a case study from the E&E sector, however they did not highlight how the specificities of the sector impacted the suitability of the CIs. In other instances, the Lifecycle Assessment (LCA) method has been employed to compare the suitability of multiple CEBM for E&E products [9]. Studies in other sectors (e.g., building [46] and agri-food [47]) have identified similar knowledge gaps, and in response sought to identify sector-specific CIs. However, no study was found that proposed multidimensional CIs that addressed the specificities of E&E products.

Furthermore, there are numerous shortcomings in the ability of the existing, cross-sectorial CIs to address all of the CE practices and CEBM pertinent to the E&E sector, including the lack of coverage of product sharing and diverse ownership models [26]; product durability [25]; social sustainability issues [40]; and implementation of CEIS across E&E product lifecycle phases [38].

4. Methods

The research adopted a qualitative approach to conduct exploratory research to address the research aim of developing a multidimensional set of microlevel CIs capable of measuring and monitoring the circularity of E&E products. The sectorial specificity of the developed CIs will enable them to better address the key CE practices and CEBM which are pertinent to the E&E sector and be adapted to the operational requirements of E&E organisations. They will therefore be of greater relevance to their decision-making processes.

Exploratory research aims to explore and collect open-ended data on a subject for the discovery of new concepts through inductive reasoning [48]. The research was exploratory in nature due to the emerging topic of research and the limited existing knowledge on CIs for the E&E sector. The data collection comprised two methods: (1) a stakeholder workshop aimed to generate a novel set of CIs and rate their relevance to the E&E sector, then (2) the generated and categorised CIs were validated via a focus group with a printers' manufacturer and their partners. Thus, this research is exploratory, as CIs were developed based on the findings of the workshops and then tested through application to empirical case studies. The workshop and focus group sampling, design, and results are laid out in the sections below.

4.1. Workshop

4.1.1. Workshop Participants

The sampling frame for the workshop aimed to identify a variety of E&E sector stakeholders using purposive sampling to represent the key phases of the E&E product lifecycle. This sampling approach is pertinent for exploratory research in an emerging field. The 14 organisations presented in Table 3 were selected for their involvement in implementing or facilitating the implementation of CEBM in the E&E supply chain; up to two participants from each organisation were present, totalling 17 workshop participants. The participating organisations selected representatives who were chosen for their organisational management and decision-making responsibilities associated with sustainability and/or business development. The rationale for the sampling frame was to ensure a large coverage of E&E products' typologies and sector services, and therefore a diverse range of potential users for the CIs.

Table 3. Research sample for stakeholder workshop.

Organisation	Expertise/Business Focus	Participant
E&E manufacturers	Design and manufacture of printers and cartridges	2
	Design and manufacture of telecommunications equipment	2
	Design and manufacture of television sets	1
	Design and manufacture of washing machines	1
WEEE recyclers (SME)	WEEE management through social enterprise	1
	WEEE management, logistics and recycling services	1
	WEEE management and treatment	1
WEEE industry association	WEEE producer responsibility	1
Consultancies	Sociocultural analysis of business models	1
	Development of manufacturing services based on 3D printing	1
ICT developer	Information exchange throughout the E&E value chain	1
Research organisations	Recyclability and sustainability of thermoplastic and thermosetting plastics	1
	Sustainable technological development, including product testing	2
	Research, development, and technology transfer for resource efficiency	1

4.1.2. Workshop Design and Data Analysis

The workshop was divided into two main activities: (1) the generation of a set of CIs for E&E products; (2) the ranking of the individual CIs and categorisation into associated lifecycle phases. Prior to the workshop activities, a presentation was given to the participants to introduce the topic of CIs and summarize the associated knowledge gaps emanating from literature. In the first activity, the participants were asked to take part in a collaborative discussion to generate a list of the key microlevel CIs relevant to the E&E sector. Where proposed CIs were contentious, participants were invited to debate their appropriateness for the E&E sector and to reach a consensus about their inclusion. In the second activity, participants were asked to individually rate the relevance of each of the generated CIs to E&E products according to low, medium, or high relevance. The participant's ratings were then compared and any disagreements between participants over the ratings were again discussed to reach a consensus. Additionally, the participants were asked to categorise the CIs under the E&E products' lifecycle phases to which they applied.

The data during the workshop were recorded by the workshop moderator. The transcript was then analysed based on participants' final responses to the CIs, their categorisation and ratings.

4.2. Focus Group

The set of E&E products' CIs generated during the workshop were then piloted in a focus group with a manufacturer of printer (PRINT-MAN) and their partners shown in Table 4. The focus group aimed to validate the use of the CIs to measure the outcomes of CEIS (Circular Economy Implementation Strategies) deriving from the PRINT-MAN's CEBM. The PRINT-MAN undertook a process to develop their CEBM, following the CEBM canvas developed by Pollard et al. [18] and with the support of the researchers and focus group participants. This activity helped with defining CEBM, expressed through the resulting CEIS, to be measured by the CIs being piloted.

Table 4. Focus group participants.

Organisation	Expertise/Business Focus	Participants
E&E manufacturer	Design and manufacture of printers and cartridges	2
WEEE recyclers	WEEE management, logistics and recycling services	1
	WEEE management and treatment	1
WEEE industry association	WEEE producer responsibility	1
ICT developer	Information exchange throughout the E&E value and supply chains	1
Research organisations	Sustainable technological development, including product testing	2
	Research, development, and technology transfer for resource efficiency	1

The focus group had two main activities: (1) the development of CEIS in line with the PRINT-MAN's CEBM canvas and further identification of the short-term CEIS and associated E&E product lifecycle phases; and (2) for the short-term CEIS, association with the CIs. The first activity resulted in the identification of CEIS to be implemented by the PRINT-MAN as part of their newly developed CEBM. The participants then identified the CEIS implementation timeframe (short-, medium-, or long-term) and prioritised the CEIS for implementation in the short-term. The participants also categorised the CEIS according to the E&E product lifecycle phases. In the second activity, the participants linked the CIs, from a shortlist of the complete set, that were relevant to measure each of the CEIS. The CI shortlist was generated from the developed CIs for their relevance to the PRINT-MAN's CEBM.

5. Results

The following section presents the results of the qualitative workshop and the focus group. The presentation of the workshop results is divided into the two activities: first, the generation of the set of CIs for E&E products; and secondly, the rating of the relevance of the CIs to the E&E products and assigning them to three E&E product lifecycle phases as determined by the workshop participants: design and production, distribution and use, and end-of-life CIs. Finally, the results of the focus group are presented to validate the developed CIs.

5.1. Generation of Circularity Indicators

A total of 40 microlevel CIs were generated and refined in the workshop. Participants discussed the need for the generated CIs "to be flexible and pragmatic" to allow them to "be adopted at a generic level and product level for very different E&E products". They also noted the challenge of differing "methods of data collection making direct comparison of performance difficult". Furthermore, the CIs were proposed to address the key CEBM archetypes identified. The CIs alone do not ensure circularity and are designed to be used in combination with the other CIs in the list.

5.1.1. Environmental Circularity Indicators

Of the generated CIs, 25 are aligned with the environmental sustainability pillar (Env CIs), with great emphasis on product material content, reuse and WEEE management. The 25 Env CIs are shown in Table 5.

Table 5. Environmental CIs for E&E products.

Env CI	Description
Env CI1	Proportion of recycled content in a product
Env CI2	Proportion of recyclable materials in a product
Env CI3	Proportion of material content suitable for recycling in current recycling infrastructure
Env CI4	Proportion of virgin materials in a product
Env CI5	Proportion of sustainably certified materials in a product
Env CI6	Proportion of hazardous material/chemical content in a product
Env CI7	Proportion of reused components in manufacturing process
Env CI8	Resources embodied in a product or a service
Env CI9	Technical lifetime of products (under standard conditions)
Env CI10	Time taken to disassemble product
Env CI11	Degree of repairability of product
Env CI12	Percentage of product lines that follow ecodesign principles
Env CI13	Percentage of waste generation
Env CI14	Recycling rates for end-of-life products
Env CI15	Percentage of reused, recycled and recovered parts and materials that go through end-of-life processes
Env CI16	Percentage of collected or taken-back end-of-life products prepared for reuse, refurbishment, remanufactured and recycled compared to sales of new products.
Env CI17	Proportion of materials recovered through recycling processes
Env CI18	Percentage of critical materials recovered through end-of-life processes
Env CI19	Quality of materials recovered from recycling processes
Env CI20	Energy use in manufacturing processes
Env CI21	Percentage of total energy use sourced from renewable energy sources in manufacturing processes
Env CI22	Water use in manufacturing processes
Env CI23	Energy recovery at end-of-life
Env CI24	Average lifetime of products (use time)
Env CI25	Percentage of products produced that have a Bill of Materials (BOM)

Participants suggested that Env CI2 should relate to the "techno-economic viability of recycling, which depends not only on the recyclability of materials, but also on the product design and recycling infrastructure"; to address this, Env CI3 was proposed by the workshop participants. It was felt that there was some overlap between Env CI4 and the other Env CIs capturing the alternative material inputs. It was also noted in the case of Env

CI5 that, while the use of certified sustainable materials supports circularity, use practices must be monitored to ensure the materials are not used in a linear manner. Participants showed varying opinions on the inclusion of Env CI6, with some resistance to its inclusion due to the necessity of certain hazardous materials for E&E product functionality. However, it was argued that it is relevant in the case that "real alternatives exist for a hazardous material, e.g., non-halogenated rather than brominated flame retardants".

Ecodesign was seen as a key activity in CEBM implementation, therefore justifying the need for an Env CI to capture the effort made to comply with circular design guidelines and improve product design factors. Additionally, reuse was recognised as being one of the core principles of the CE, with preparation for reuse also recognised as being important in offering an opportunity to retain product value. The issue of energy recovery, captured by Env CI23, was contentious amongst the participants with a great variance in the considered relevance to circularity. It was argued by a few of the participants that energy recovery should be considered on a par with landfill, and therefore, not encouraged by the presence of an CI. While the majority of participants felt that though it was not the most preferable circular practice, it was still preferable to landfill in enabling resources to be recovered from waste.

5.1.2. Social Circularity Indicators

Nine of the generated CIs align with the social sustainability pillar (Soc CIs), as are shown in Table 6.

Table 6. Social CIs for E&E products.

Soc CI	Description
Soc CI1	Measure of the level of supply chain collaboration
Soc CI2	Measure of an organisation's involvement in circular networks
Soc CI3	Degree of availability of product service system options
Soc CI4	Intensity of use of product (compared to industry average)
Soc CI5	Consumer awareness of circularity employment in repair and reuse activities
Soc CI6	Degree of accessibility to repair services/spare parts/repair instructions
Soc CI7	Presence of collection systems for recycling end-of-life products
Soc CI8	Presence of take-back schemes for reuse and remanufacturing
Soc CI9	Percentage of products operating in sharing networks

There was some uncertainty about the definition of Soc CI1 and CI2; some participants perceived that there was overlap between the two CIs. It was observed that the measurement of an organisation's involvement in circular networks was a complex issue and that "while an organisation's involvement in circular networks demonstrates a level of commitment, it does not ensure good practice". It was noted that an organisation must instead have circularity at the core of its business strategy. However, there was an agreement among workshop participants that "without stakeholders' cooperation and commitment" a CE is unlikely.

5.1.3. Economic Circularity Indicators

Six CIs align to the economic sustainability pillar (Eco CIs), as are shown in Table 7.

For the economic CIs relating to renting and leasing (e.g., Eco CI4), the participants reported that the CIs should refer to the market for "use instead of ownership, otherwise leasing or renting is only an alternative finance model" without strict alignment to the CE concept. It was proposed that the economic CIs referring to the market share or size (Eco CI4 and CI5) should be related to the company's market for a product type and not the absolute market.

Table 7. Economic CIs for E&E products.

Eco CI	Description
Eco CI1	Proportion of products reused compared to direct sales
Eco CI2	Percentage of products remanufactured compared to total manufactured products
Eco CI3	Percentage of product lines offering use- or result-oriented product service systems compared to direct sales
Eco CI4	Size of the market for rental/leasing goods
Eco CI5	Market share of repair and reuse services compared to sales of new products
Eco CI6	Percentage of household income spent on services rather than goods

5.2. *Relevance to E&E Product Lifecycle Phases*

In the second workshop activity, participants were asked to assess the CIs relevance to E&E products and to determine the lifecycle phase to which they were applicable. Of the 40 CIs generated in the first activity, the stakeholder review process identified 20 CIs that were deemed to be highly relevant to E&E products, 15 CIs of medium relevance and 5 CIs of low relevance.

The participants identified and grouped three lifecycle phases: design and production, distribution and use, and end-of-life. Additionally, the participants assigned some indicators to "strategy" outside of the E&E product lifecycle phases; it was suggested that these CIs monitor and measure the impacts of decisions made at an organisation's strategic level. Participants categorised four CIs as applying to strategy, as shown in Table 8: two of high relevance (Env CI12 and CI25) and two of medium relevance (Soc CI1 and CI2).

Table 8. Strategy CIs and their relevance for E&E products.

CI	Description	Relevance
Env CI12	Percentage of product lines that follow ecodesign principles	High
Env CI25	Percentage of products produced that have a Bill of Materials (BOM)	High
Soc CI1	Measure of the level of supply chain collaboration	Medium
Soc CI2	Measure of an organisation's involvement in circular networks	Medium

5.2.1. Design and Production

Participants categorised 11 CIs as applying to the design and production phases of E&E products' lifecycle, as shown in Table 9. Design and production were grouped by the participants as they argued that the two phases are closely related and that impacts of decisions made at the design phase were realised through the outcomes during the production phase, therefore similar CIs were required for the phases to capture the results of those decisions.

Overall, the design and production CIs related to the materiality of E&E products were seen as highly to mediumly relevant to E&E products. The majority of the highly relevant CIs related to recycling or reuse. Energy use (renewable and total) also featured in the high and medium CIs, respectively. It was suggested that "the energy use during manufacturing should also be related to a functional unit (e.g., energy per kg of product)". Participants noted that the CI could be relevant to the product's use phase if normalised for the industry average for product type. Most mediumly relevant CIs referred to the materials content of the E&E product.

Env CI22, referring to the water consumption in the manufacturing processes, was deemed less relevant to E&E products; water use during the manufacturing phase was argued to have a relatively low impact. The technical lifetime of products (Env CI9) was also considered of low relevance to E&E products, due to the net-negative impacts that can occur from extending the lifetime of energy-using products. Additionally, participants felt that the average lifetime of the E&E products was a more relevant CI than their technical lifetime.

Table 9. Design and production phase CIs for E&E products.

CI	Description	Relevance
Env CI1	Proportion of recycled content in a product	High
Env CI2	Proportion of recyclable materials in a product	High
Env CI7	Proportion of reused components in manufacturing process	High
Env CI21	Percentage of total energy use sourced from renewable energy	High
Env CI4	Proportion of virgin materials in a product	Medium
Env CI5	Proportion of sustainably certified materials in a product	Medium
Env CI6	Proportion of hazardous material/chemical content in a product	Medium
Env CI20	Energy use in manufacturing processes	Medium
Env CI8	Resources embodied in a product or a service	Low
Env CI9	Technical lifetime of products (under standard conditions)	Low
Env CI22	Water use in manufacturing processes	Low

5.2.2. Distribution and Use

Participants identified 11 CIs from the list that applied to the distribution and use phase of the E&E product lifecycle, as shown in Table 10. All the distribution and use CIs were rated either highly or mediumly relevant.

Table 10. Use and distribution phase CIs for E&E products.

CI	Description	Relevance
Env CI11	Degree of repairability of product	High
Soc CI3	Degree of availability of product service system options	High
Soc CI6	Degree of accessibility to repair services, spare parts, repair instructions	High
Eco CI3	Percentage of product lines offering use- or result-oriented product service systems compared to direct sales	High
Eco CI4	Size of the market for rental or leasing goods	High
Eco CI5	Market share of repair and reuse services compared to sales of new products	High
Env CI24	Average lifetime of products (use time)	Medium
Soc CI4	Intensity of use of product (compared to industry average)	Medium
Soc CI5	Consumer awareness of circularity employment in repair and reuse activities	Medium
Soc CI9	Percentage of products operating in sharing networks	Medium
Eco CI6	Percentage of household income spent on services rather than goods	Medium

The CIs related to the repair and reuse of products (Env CI11, Soc CI6 & Eco CI5) were considered highly relevant by participants. It was recognised that there were two key issues that need to be measured: product repairability and access to repair services. The repairability of E&E products was considered dependent on product typology. Access to repair service, spare parts, and repair instructions (Soc CI6) was argued to be more relevant to business-to-customer business models as often business-to-business business models include maintenance and repairs in a PSS contract agreement. Additionally, three CIs related to PSS (Soc CI3, Eco CI3 & CI4) were regarded as highly relevant.

The CIs relating to sharing CEBM were considered of medium relevance by the participants, who recognised sharing platforms for E&E products as important "to improve access to products and encourage relevant circular end-of-life practices". The intensity of product use (Soc CI4) was considered of medium relevance to E&E products to encourage the adoption of PSS or sharing business models. Although, it was noted that the relevance of this CI is dependent on the product type and usage patterns, with the nature of some E&E products "already requiring 24/7 operation".

There was initial variance in participants' responses to Env CI24, but they concluded that it is of medium relevance to E&E products to enable planned obsolescence to be addressed. Additionally, the comparison with Env CI9 would enable the impact of consumer behaviours to be assessed. In the case of energy-using products, it was suggested that Env

CI24 must be considered alongside a lifecycle assessment to determine the optimal lifetime for the product.

5.2.3. End-of-Life

A total of 14 CIs were categorised as related to the end-of-life lifecycle phase, as shown in Table 11.

Table 11. End-of-life phase CIs for E&E products.

CI	Description	Relevance
Env CI3	Proportion of material content suitable for recycling in current recycling infrastructure	High
Env CI10	Time taken to disassemble product	High
Env CI14	Recycling rates for end-of-life products	High
Env CI15	Percentage of reused, recycled and recovered parts and materials that go through end-of-life processes	High
Env CI16	Percentage of collected or taken-back end-of-life products prepared for reuse, refurbishment, remanufacture and recycle compared to sales of new products.	High
Env CI18	Percentage of critical materials recovered through end-of-life processes	High
Env CI19	Quality of materials recovered from recycling processes	High
Eco CI2	Percentage of products remanufactured compared to total manufactured products	High
Env CI17	Proportion of materials recovered through recycling processes	Medium
Env CI23	Energy recovery at end-of-life	Medium
Soc CI8	Presence of take-back schemes for reuse and remanufacturing	Medium
Eco CI1	Proportion of products reused compared to direct sales	Medium
Env CI13	Percentage of waste generation	Low
Soc CI7	Presence of collection systems for recycling end-of-life products	Low

Of the eight CIs rated highly relevant, the majority related to recycling and associated activities. Reuse, remanufacture and refurbishment were also key themes in the highly relevant CIs. It was argued that Env CI10 was highly relevant to E&E products' end-of-life activities, and that it was relevant for not only repair but also recycling activities where "manual disassembly leads to better yields but is often economically not viable due to duration of disassembly and the associated cost". Additionally, Env CI14 was seen as highly relevant, especially in the case of E&E products where life-extension opportunities are limited but the distinction between the quality materials recovered, notably for critical raw materials, was also seen as highly relevant (Env CI18 and CI19).

Despite concern from participants in the first activity regarding its inclusion, Env CI23 was rated of medium relevance. Other CIs of medium relevance related to reuse and recycling. Two CIs were of low relevance (Env CI13 & Soc CI7), potentially due to the ambiguity of these CIs which addressed similar issues as some of the more highly rated CIs.

5.3. Focus Group: Manufacturer of Printers

Following the workshop, the developed set of CIs were then piloted in the focus group to validate their applicability for E&E sector organisations and their effectiveness for measuring and monitoring CEBM. To pilot and validate the CIs, it was first necessary to identify the PRINT-MAN's CEBM in the form of the CEIS to be measured. Therefore, the focus group comprised two activities: first, the development of PRINT-MAN's CEBM Canvas and related CEIS; and second, the association of the latter with the CIs.

5.3.1. Printers Manufacturer's CEBM Canvas

During the first activity of the focus group, the participants applied a systematic process to develop a CEBM for the PRINT-MAN. The PRINT-MAN's CEBM was expressed in terms of CEIS to be realised. Discussions between the focus group participants led to the development of 68 possible CEIS across the nine components of the CEBM Canvas. The CEIS proposed were seen as advantageous and feasible for the PRINT-MAN's business, according to their product, service offerings and customer profile. The CEIS represent the implementation plan of PRINT-MAN's CEBM which are to be measured via the CIs.

The participants then categorised their potential CEIS according to their implementation timeframes: short-, medium-, and long-term. This was determined according to the PRINT-MAN's actual business constraints and their readiness to conduct the CEIS. The short-term CEIS were defined as actions that could be fully realised within the next two years, whereas medium-to-long-term CEIS were defined as requiring a longer implementation timeline. The participants identified a total of 19 short-term CEIS (1–19) to be implemented from their developed CEBM, seen in Table 12. The short-term CEIS were then categorised by their related E&E product lifecycle phase; of the 19 short-term CEIS, 7 actions were to be implemented in the design and production phase, 15 actions were to be implemented the distribution and use phase, and 6 actions were to be implemented in the end-of-life phase. Some of the actions overlapped in two phases and so were listed twice.

Table 12. PRINT-MAN's CEIS.

CEIS	Description	Lifecycle Stage Design and Production	Distribution and Use	End-of-Life
1	Expand collecting and refurbishing programs for whole printers and key components	X		X
2	Identify levers to reduce dismantling and refurbishing costs by setting various operating models	X	X	
3	Provide information about printers to recycling partners	X		X
4	Use materials that recyclers can easily and profitably recycle	X		
5	Learn from recyclers what materials can be recycled better or more profitably to use more of them instead of low-value or low-efficiency materials	X		X
6	Use ICT to support information sharing across the supply chain related to recycled content	X	X	X
7	Devise an ecodesign strategy for printers during dismantling activities	X		X
8	Reduce the number of unnecessary and incorrect shipments		X	
9	Salvage working and repairable parts from collected/return printers and use on E2N (Equal to New) printers			X
10	Explore competitiveness of 3D printing for smaller plastic parts for repair	X	X	
11	Increase the flow of returned end-of-life printers by reducing the associated time and cost		X	
12	Assess options to reuse material from EOL/WEEE printers			X
13	Engage with key customers to understand their needs and requirements as it relates to refurbished products		X	
14	Active lobbying at the EU and/or national level for wider acceptance and promotion of circular business models		X	
15	Active media/PR campaign on refurbished printers		X	
16	Promote refurbished printers		X	
17	Use QR code to inform customers about options to return their unused products to the manufacturer		X	X
18	Investigate economics of more CE-suitable materials coming from end-of-life cartridges or printers			X
19	Maintain highest levels of data security by ensuring that customers' documents are erased from refurbished (E2N) printers			X

5.3.2. Measuring the Printers' Manufacturer's CEIS

In the second activity, the focus group participants were asked to associate CEIS 1–19 to the relevant CIs from the generated list. Of the 35 highly or mediumly relevant CIs from the workshop, the participants selected a shortlist of nine CIs to measure the outcomes of their CEIS: Env CI2, CI12, CI15, CI16, CI19 and CI25, Soc CI9, and Eco CI3, and CI5. The nine selected CIs covered all four of the lifecycle phases identified by the workshop participants and all three of the sustainability pillars. The results of the final activity associating the CEIS 1–19 to the nine CIs can be seen in Table 13. The results demonstrated that the CEIS could be captured by the nine selected CIs.

Table 13. PRINT-MAN's CEBM Implementation Plan and associated CIs.

Printers' Lifecycle Phase	**CEIS**	**Description**					**CI**				
			Env CI2	**Env CI12**	**Env CI15**	**Env CI16**	**Env CI19**	**Env CI25**	**Soc CI9**	**Eco CI3**	**Eco CI5**
Design and Production	1	Expand collecting and refurbishing programs for whole printers and key components			X	X					
	2	Identify levers to reduce dismantling and refurbishing costs by setting various operating models			X	X	X				X
	3	Provide information about printers to recycling partners			X		X				
	4	Use materials that recyclers can easily and profitably recycle					X				
	5	Learn from recyclers what materials can be recycled better or more profitably to use more of them instead of low value or efficiency materials	X								
	6	Use ICT to support information sharing across the supply chain related to recycled content			X						
	7	Devise an ecodesign strategy for printers during dismantling activities	X	X				X			X
Distribution and Use	8	Reduce the number of unnecessary and incorrect shipments			X	X					
	9	Salvage working and repairable parts from collected/return printers and use on E2N (Equal to New) printers			X	X	X				X
	10	Explore competitiveness of 3D printing for smaller plastic parts for repair	X		X	X					X
	11	Increase the flow of returned end-of-life printers by reducing the associated time and cost						X			
	12	Assess options to reuse material from EOL/WEEE printers	X								
	13	Engage with key customer to understand their needs and requirements as it relates to refurbished products				X				X	X
	14	Active lobbying at the EU and/or national level for wider acceptance and promotion of circular business models	X	X	X	X	X	X	X	X	X
	15	Active media/PR campaign on refurbished printers				X			X	X	
	16	Promote refurbished printers				X			X	X	

Table 13. *Cont.*

Printers' Lifecycle Phase	CEIS	Description					CI				
			Env CI2	Env CI12	Env CI15	Env CI16	Env CI19	Env CI25	Soc CI9	Eco CI3	Eco CI5
	17	Use QR code to inform customers about options to return their unused products to the manufacturer							X	X	X
	18	Investigate economics of more CE suitable materials coming from end-of-life cartridges or printers	X	X	X		X				
	2	Identify levers to reduce dismantling and refurbishing costs by setting various operating models			X	X	X				X
	3	Provide information about printers to recycling partners			X		X				
	6	Use ICT to support information sharing across the supply chain related to recycled content			X						
	7	Devise an ecodesign strategy for printers during dismantling activities	X	X				X			X
End-of-Life	19	Maintain highest levels of data security by ensuring that customers' documents are erased from refurbished (E2N) printers			X				X	X	X
	1	Expand collecting and refurbishing programs for whole printers and key components			X	X					
	9	Salvage working and repairable parts from collected/return printers and use on E2N printers			X	X	X				X
	14	Active lobbying at the EU and/or national level for wider acceptance and promotion of circular business models	X	X	X	X	X	X	X	X	X
	15	Active media/PR campaign on refurbished printers				X			X	X	
	17	Use QR code to inform customers about options to return their unused products to the manufacturer							X	X	X

6. Discussion

The key research findings can be summarised into three central themes, to examine the significance of the results within the context of existing knowledge in the field of circular economy measurement. These core themes are CIs and their relevance to the E&E sector; the applicability of the CIs to the E&E products and their lifecycle; and the measurement of CEIS via CIs.

6.1. Generation of CIs and Their Relevance to the E&E Sector

The findings of this research contribute to the body of existing knowledge through the identification and evaluation of a novel set of multidimensional, microlevel CIs tailored to the specific characteristics of the E&E sector. The developed CIs are differentiated from previous cross-sector, microlevel CIs due to their intended specificity for the E&E sector [20,36], which is anticipated to encourage greater use by E&E sector organisations by ensuring the data are relevant and useful in the adoption of their CEBM, cited as a challenge of existing CIs [36]. By conducting exploratory research to generate the CIs with stakeholders from the E&E sector, this research addresses the previous lack of stakeholder engagement in the design process of CI development, as identified by Wisse [49].

The developed CIs go beyond the key themes currently addressed by existing microlevel CIs (e.g., recycling, reuse, etc.) as identified by Kristensen and Mosgaard [38], to incorporate the measurement of an E&E organisation's potential CEIS related to all five CEBM archetypes, as proposed by Pollard et al. [18]. Notably, the developed CIs address the potential for CEIS related to sharing economy and PSS CEBM, which were previously not comprehensively captured by microlevel CIs [26]. The generated CIs cover each of the three sustainability pillars (environmental, social, and economic). This should enable those using the developed CIs to report against the environmental, social, and economic impacts of their CEBM for their corporate responsibility reporting, seen as a key advantage for E&E organisations [17]. Under the social pillar, the developed indicators cover employment, supply chain participation and networks, access to tangible and intangible resources, product responsibility and the sharing economy; however, the participants did not propose indicators to address human rights or labour practices which have been proposed as important social themes for indicators [40].

CIs associated with recovery, recycling, reuse, refurbishment, and PSS activities were in general considered to be of high relevance to the E&E products. Some of the low-rated CIs by the workshop participants contrasted with the conclusions of previous, cross-sector research. For example, Rincón-Moreno et al. [44] demonstrated a high applicability of CIs related to natural resource inputs for cross-sector manufacturing companies, such as water consumption and energy productivity. Whereas similar CIs in this research were identified by the workshop participants to have a low relevance to E&E products. Similarly, CIs related to product lifetime (technical and actual) were only considered to be of low and medium relevance by the workshop participants. However, product-life extension is a key CEBM archetype, and the measurement of resource durability has been supported by previous cross-sector, microlevel CIs [50,51]. This demonstrates the importance of considering sectoral specificities in the development of CIs.

6.2. Applicability of CIs to E&E Products and Their Lifecycle

The workshop findings highlighted key factors that influence the applicability of CIs to E&E products, which include intended product function, service arrangement and customer type. Given the wide-ranging functionality and delivery of E&E products and services, the applicability of the developed CIs varies for different product groups. For example, a communication network device, which must operate continuously, cannot operate in sharing networks, therefore the associated CI is unsuitable for that product type. Similarly, the suitability of the CIs and ability to collect data may vary according to the customer and service type. Therefore, when selecting CIs, E&E organisations are advised to consider a customised shortlist of CIs from the overall list to best align to their CEBM and sustainability reporting, as was carried out by the participants in the focus group. The reduced number of CIs in the selected shortlist decreases the burden of data collection for E&E organisations, while still enabling all their CEBM performance to be measured. However, the need for organisations to further customise their CIs from the developed CIs is a potential limitation to their applicability, which the findings show is somewhat overcome by the sectorial specificity [36]. Additionally, a lack of organisational resources or knowledge could have a bearing on an organisation's selection of CIs [17]. This, in turn, would have a direct consequence on the usefulness of the measurements to the transition to a CEBM.

CIs assigned to an organisation's strategy, as proposed by the workshop participants, are often not identified by researchers [5] but highlight the internal process necessary to define E&E organisations' circular business strategy, which has a bearing on the E&E products' circularity. The strategy represents a shift from linear to circular business objectives, which is core to driving the transition from linear BM to CEBM [18].

CIs for the E&E sector in existing literature focus predominantly on the end-of-life phase [29,30], whereas the CIs proposed by this research present CIs for all three E&E products' lifecycle phases. The identification of CIs for each of the identified lifecycle phases provides reassurance that the generated CIs can capture the circularity of E&E products throughout their lifecycle. Surprisingly, the same number of CIs were categorised under distribution and use as design and production (11 CIs); the use lifecycle phase of E&E products has had greater coverage in literature compared to design and production phases [5], however the research demonstrates the importance CIs for the design and production phase which can greatly influence the circularity performance of the other E&E product lifecycle phases [32]. End-of-life was the most represented lifecycle phase within the CIs, which may be explained by the current focus within the sector on end-of-life waste management practices (e.g., recycling) [52]. Of the 14 CIs related to the end-of-life phase, eight referred in some way to recycling activities.

6.3. Measuring CEIS through CIs

The focus group findings demonstrated the application of the CIs to measure the circularity of an E&E product-specific CEBM. Measuring the performance of the CEIS enables the PRINT-MAN to internally monitor the circularity of their printers and accumulate data for dissemination in their corporate reporting. By increasing the communication of their circularity measurements, E&E organisations can increase trust with their customer base and increase awareness of the CE [17,53]. Additionally, the increasing availability of circularity data is expected to lower the barriers to adoption of CEBM by providing demonstrative evidence of their implementation [54].

The product functionality of printers, the PRINT-MAN's service arrangement and the business-to-business customer segment have an influence on the suitability and applicability of the CIs, therefore requiring a customised list of CIs. For example, some of the CIs relate exclusively to business-to-customer, and therefore were excluded from the PRINT-MAN's shortlist of CIs. The nine CIs chosen by the focus group participants cover all five CEBM archetypes [18]. Whereas the short-term CEIS identified are largely aligned to four of the five CEBM archetypes: circular supply chain; recovery and recycling; product life extension; and PSS. However, the inclusion of the CI "Soc CI9: Percentage of products operating in sharing networks" enables the PRINT-MAN to measure and understand the current baseline for their involvement in sharing economy models with a view to improvements in the future, while also addressing the social sustainability pillar [55].

Of the nine shortlisted CIs by the focus group participants, only one was categorised under the social sustainability pillar, all others deriving from the environmental or economic pillars. As previously discussed, the generated CIs aimed to address the gap with regard to a lack of CIs capturing the social pillar [40], therefore it is interesting that few of these were chosen by the focus group participants despite being available for selection. The reporting of the social impacts of CEBM is an underdeveloped aspect of the CE discourse, and currently the division between what constitutes social and economic CIs is unclear, however, reporting against social CIs presents an opportunity to improve public perception of the organisation's reputation [56].

This research presents a methodological approach employed in the piloting the CIs that benefited from the involvement of E&E stakeholders, capitalising on the interactions between the PRINT-MAN and their partners. The inclusion of the partners reflects the notion that CEBM development is collaborative, to maximise the identification of opportunities for value creation [57]. Conducting pilot testing with the PRINT-MAN and their partners also addresses the lack of stakeholder testing seen as a limitation to existing CIs [27].

7. Conclusions

The research set out to answer how E&E sector organisations can measure and monitor the circularity of their products. In response, the research aimed to generate, rate, and validate microlevel CIs relevant to E&E sector products. The adoption of CIs is understood to be key to providing organisations with the data required for CEIS decision making during the transition from linear to CEBMs. However, thus far there is still great discussion over what constitutes the most suitable method for measuring circularity and whether existing microlevel CIs can effectively measure the circularity of E&E products.

This research is the first to provide E&E organisations with CIs that are associated with the key lifecycle phases of their products, therefore contributing to the advancement of knowledge in circularity measurement and monitoring within the E&E sector. Implications can be drawn from the findings for E&E sector organisations wishing to measure the circularity of their products and apply associated CIs. The resulting CIs are intended to provide E&E organisations with a way of assessing the impacts of products on their transition to the CE through the implementation of CEBMs. E&E manufacturers using the developed CIs to measure the circular performance of their products should first establish their ability to reliably collect the required data, which may lead to a customisation of the CIs to be considered. Where data are not available for key CIs related to their CEBMs, such as those rated as highly relevant, E&E manufacturers should be encouraged to develop procedures internally and with their supply chain partners to collect the required data.

Due to the exploratory nature of this research, standardised calculation metrics have not been offered for the developed CIs, which could be seen as a potential limitation. Future research should look at establishing standard calculation metrics for the CIs, especially those with high relevance to the E&E sector, with the aim of ensuring the comparability of the data between organisations.

It was not possible to represent all of the wide-ranging E&E product types in the data collection process. Building on this research, future research could aim to validate the CIs by collecting data for the 20 high and 15 medium CIs during the realisation of the CEIS for additional case studies of different E&E products (such as computers, televisions, refrigerators, washing machines, etc.). By doing so, the studies could aim to establish the availability and usefulness of the derived data to the E&E organisations in evaluating the circularity performance of their products, acknowledging the importance of application to real-world case studies to further strengthen the research findings.

Author Contributions: Conceptualization, M.O., C.C., S.G., J.C. and A.I.D.; Formal analysis, J.P.; Funding acquisition, M.O.; Investigation, M.O., C.C., S.G., J.C. and A.I.D.; Methodology, C.C. and A.I.D.; Project administration, J.P. and C.C.; Supervision, M.O.; Visualization, J.P.; Writing—original draft, J.P.; Writing—review and editing, J.P., M.O., S.G. and A.I.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission, grant number 776714.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Loughborough University Ethics Committee (Ref No. ABCE 2567 and 22 October 2018).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to inclusion of proprietary information.

Acknowledgments: This paper is derived from data collected as part of Activating Circular Services in the Electric and Electronic Sector (C-SERVEES) project, funded by the European Commission [Grant Agreement Number: 776714]. The authors are grateful to the participants of the workshop and focus group who gave up their time and expertise to help us with this study.

Conflicts of Interest: The authors declare no conflict of interest.

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