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Review

Circulating the E-Waste Recovery from the Construction and Demolition Industries: A Review

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Abstract: E-waste or electronic waste uses electrical power from a power cord/plug/battery. Construction and demolition (C&D) industries use various electronic components such as cables, switches, sockets, electrical heat pumps, air conditioning systems, and solar panels, which become e-waste at the end-of-life-cycle stages. E-waste contains valuable metals/non-metals/plastics that are recoverable and recyclable. E-waste disposal is banned from landfills in Victoria (Australia), because of their toxic components that require an additional waste separation process to avoid considerable environmental emissions and costs of separation and safe disposal. This paper aims to review the alternative circularity scenarios for recoverable materials from e-waste the C&D industries. Alternative scenarios for e-waste handling and management originating from the C&D industries are assessed in the current study. We identify and assess the important circularity indicators and waste management steps that would drive towards the identification of future initiatives or policy development to increase the resource recovery from e-waste. The policies would help to advocate for policy development for the C&D industries' e-wastes.

Keywords: material flow analysis; circular economy; e-wastes; construction and demolition industries; policy recommendations

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1. Introduction

E-waste from the construction and demolition (C&D) industries is waste in the form of electrical or electronic equipment, or devices that are no longer working/not required after the end-of-life construction of buildings [1]. E-waste usually contains hazardous materials that must be separated to avoid environmental emissions for safe disposal. E-waste is not only harmful to the environment but also to human health and resources [2]. Hence, e-waste and materials derived from the processing of e-waste should be handled and stored with care to avoid hazardous material leakage into the air, water, or soil [3]. The lack of e-waste management from C&D wastes can lead to air emissions, dust, ground contamination, or fire risk. To avoid contamination and ensure the safe handling and management of e-waste from the construction industries, it is essential to understand the risks of impact on the environment from the e-waste [4]. E-waste collection and separation, handling, storage, and transportation stages should be customised based on their risks or hazards and on the key supply chain indicators to improve resource recovery efficiency. Considering the wide range of possible e-waste, it is essential to gather a comprehensive understanding of their types from the construction industry. The next step should identify suitable waste management stages and their key performance indicators (KPIs). These processes should also be analysed to understand their environmental consequences to strategically design their safe handling and management processes, for the development of policies for multi-level stakeholders. It is also crucial to understand how to recirculate reusable e-waste. Assessment is necessary to understand whether recovery of the materials from the e-waste is better than the safe disposal or reuse of this e-waste whenever possible. Reducing environmental burdens from the C&D e-wastes, increasing the recovery of the resources, and supporting economic growth are essential to optimise the waste management supply chain to support policy development [5].

The system boundary or the life cycle stages of e-waste handling and management start with e-waste generation. The electrical/electronic components that are redundant/unusable at any construction/demolition industry site are considered e-waste. It is challenging to precisely quantify the volume of the e-waste generated from any C&D site; however, it is possible through detailed inventory development and calculation [6]. The total amount of e-waste from Victoria was 109,000 tonnes in 2015, which covers all different types of industries [7]. The second life cycle stage is the transportation of the e-waste from the waste generation site to the waste management/processing facilities. The waste management services use large vehicles such as trays or compactor trucks. Larger businesses or councils usually have commercial arrangements for e-waste transportation. The third stage is waste collection and storage. Generally, e-waste is collected in various ways, including hard-waste curbside pickup, and dropping at designated waste collection facilities. The collected e-waste is then sorted and stored for a period before it is transferred to a landfill or reprocessing facilities. The storage areas can be covered or uncovered with bins/cages/containers/polypropylene bags that can be transported from the site. The common types of collection sites include civic centres, resource recovery centres, retailer outlets, reprocessing sites, etc. The next stage is reprocessing, which can involve manual disassembly into subcomponents that should be intact for either sale, further reprocessing, or mechanical processing. Mechanical processing involves a range of subprocesses, which are crushing, shredding, magnetic, density, optical, or X-ray-based sorting. The reprocessing facilities are private or multinational companies, while in Victoria, most of the companies are working based on manual disassembly [8,9]. Large-scale processing facilities work based on mechanical processing [10]. Mechanical processing is specifically followed by processors who want to recover metals from e-waste. But, at the same time, the number of other wastes they handle to recover metals is significant compared to the e-waste. Some portions of the e-waste reprocessed in Victoria is also transported from inter-states, which incurs higher transportation costs involved in the supply chain [10]. The drivers for the determination of whether the e-wastes would be reprocessed or not are the resale value of the recycled components, commodity prices (prices of the primary materials), reprocessing costs, the costs of landfill/levies in comparison to the reprocessing cost and benefits. The guidelines of the EPA Victoria provided for the management and storage of combustible and waste materials also include e-waste, which can cause fire hazards [11].

Hence, this paper aims to review and qualitatively analyse the circularity pathways of the e-waste from the C&D industries using the life cycle assessment and material flow analysis methodologies. Life cycle assessment (LCA) is a powerful environmental impact assessment methodology underpinned by international standards—ISO14040–ISO14044—and aims to measure the quantitative environmental performance of products and/or services across the entire lifecycle. Material flow analysis is a complementary procedure that analyses the stocks and flows of the materials circulating throughout the supply chain to identify and optimise the sustainability characteristics of the supply chain [6].

A systematic review of the literature is conducted in this article on the e-wastes generated by the construction industries. Policy analysis and recommendations regarding e-waste handling and management are provided as an outcome of this review.

2. Research Methodology

The research methodology facilitates an audit trail of a study and enables the determination of the scope and boundaries of a research process [12]. An integrative review was adopted in this study as it aids in the advancement of knowledge. Furthermore, we followed the approach suggested from the literature by formulating review questions, literature searches, data evaluations, analyses, and policy discussions. The flowchart of the study is provided in Figure 1.

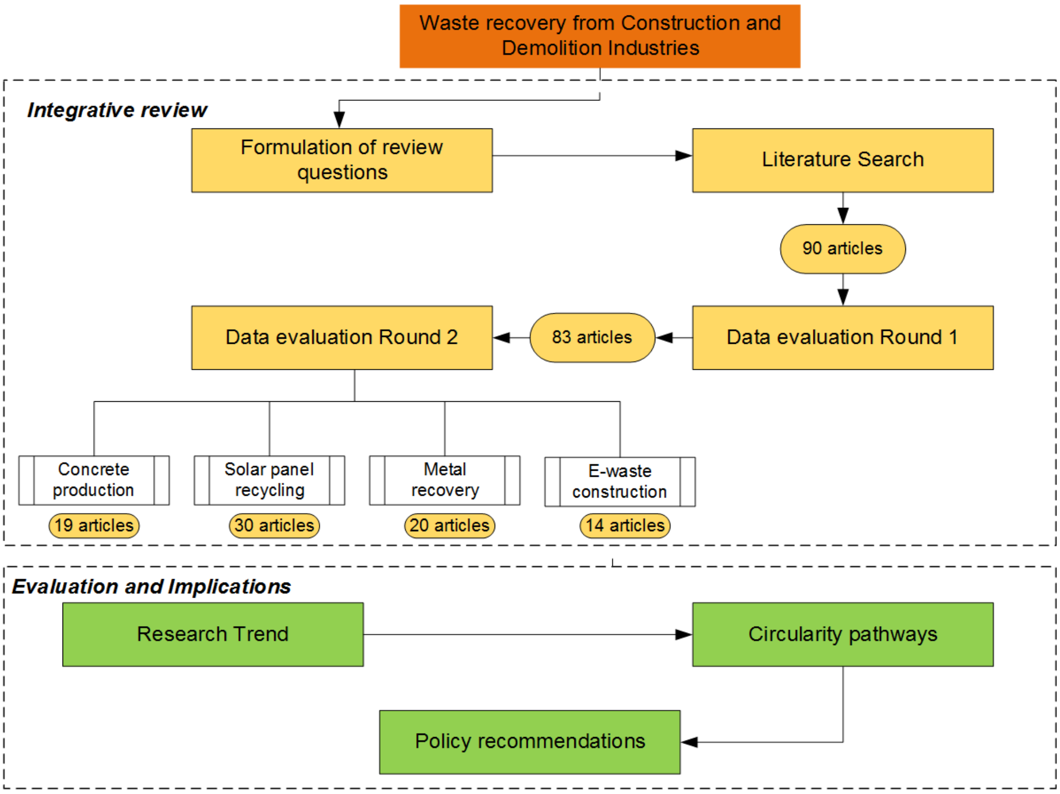

Figure 1. Flowchart of the study.

The research methodology was split into two sections comprising an integrative review and an evaluation phase. Integrative reviews are renowned for their effectiveness in summarising the literature to provide a more comprehensive understanding of a subject matter [13]. Integrative reviews facilitate the inclusion of multiple methodologies and therefore have the potential to generate diverse views and perspectives on a subject. In this study, the integrative review commenced with formulating the review questions followed by a well-defined literature search.

At first, the following review questions were formulated to identify the relevant literature.

(a) What are the existing circularity routes of the e-waste generated from the construction industries?
(b) What are the waste management stages involved in each of these circularity routes to recover and utilize the valuable resources from the e-waste?
(c) What are the key performance indicators to optimise/improve the circularity of the e-waste from the construction industries?
(d) What are the policy recommendations for each of the analysed circularity routes to improve resource recovery?

The next section highlights the research methodology, and the subsequent sections discuss the existing circularity routes of the e-waste from the construction industries, followed by the waste management processes to recover resources from the e-waste of the construction industries. Then, the literature-based articles are critically analysed to identify and present the key performance indicators or drivers of the circular supply chain of e-waste. Finally, the circular economy framework is developed, and policy recommendations are made.

To ensure the quality and analysis of the results, the literature review only focused on peer-reviewed articles from Scopus and Google Scholar. The first search using the relevant keywords identified 90 studies. After a critical evaluation of the literature, 83 research and review articles related to e-waste management from the construction industries were identified. For e-plastic utilization in concrete production, 19 works of literature were selected. For solar panel recycling and material recovery, 30 articles were evaluated after the selection. For metal recovery from e-waste from construction, 20 articles were reviewed. For the policy analysis regarding e-waste handling from the construction industries, 14 articles were reviewed and discussed.

3. Existing Circularity Pathways for E-Waste from the Construction Industries

E-waste is considered one of the fastest-growing challenges in the C&D sector. The chemical composition of e-waste changes with the innovation of new technologies. It is noted that, globally, in 2014, 41.8 million metric tons of electronic components were produced as e-waste, and in 2018, it increased to 50 metric tons [14]. Based on a per-capita basis, it can be expected that C&D e-waste will be at least 20% of the global output of e-waste, leading to at least 10 million tonnes of C&D waste being produced yearly. Managing the construction industry's e-waste is a dynamic process, and the balance will shift and change over time; hence, it is vital to identify and evaluate the circularity pathways for e-waste in the sector.

About 20.4 Mt of C&D waste was generated in Australia in 2016–2017, representing about 30% of the total waste collected [15]. This represents a 20% increase in the total amount of C&D waste generation and a 2% increase per capita, compared with 2006–2007 [16]. In the following financial year of 2018–2019, the states of South Australia and Victoria achieved a C&D waste diversion rate of 91.4% and 87% (Melbourne 2018 and 2018, 2018), respectively [15,17].

3.1. Using E-Plastic for Plastic Aggregated Concrete

One of the promising pathways among e-waste circularity and waste management is the recovery and recycling of the plastics from the e-waste to be used in concrete, which will be reused in the construction industry [18]. Gavhane et al. (2016) analysed the utilisation of e-plastic waste in concrete, and the strength of the concrete with or without e-plastic waste. They suggested that the utilisation of e-plastic waste in concrete will reduce the requirement for conventional fine aggregates, conserving natural resources via cost and environmental pollution reduction [19]. Similarly, Tone et al. (2020) analysed the potential of e-waste for use in the construction industries. They showed that the cement–concrete mix using the e-waste can be used for constructing rigid pavements and structures. They also noted that the cost of construction and landfill will also be reduced if the concrete is manufactured from the e-waste [20]. Ahmad et al. conducted a performance evaluation of the plastic concrete modified with e-waste plastic as a partial replacement of coarse aggregate. They showed that increasing plastic coarse aggregate decreases the absorptivity coefficient, abrasion loss, and ultrasonic pulse velocity (UPV) [21]. Kumar et al. also analysed the recycling potential of e-waste plastics as construction materials. Their findings contradict some other studies as they found that the workability of the mixture was reduced against the increase in the percentage of e-plastic. The compressive strength, split tensile strength, and flexural strength were comparatively less than those of the control concrete mix [2]. In another study, Kaliyavaradhan et al. (2022) reviewed the effective utilisation of e-waste plastics and glasses in construction products and showed that concrete containing PVC fibre has higher compressive, flexural, and split tensile strengths than regular concrete [22]. Goh et al. (2022) analysed the comparative environmental impact of recycled e-waste concrete among conventional concrete, concrete with 20% coarse aggregate replaced by e-plastic, 20% e-plastic with 30% cement replaced by Ground granulated blast furnace slag (GGBS), and 200% e-plastic with 100% cement replaced by GGBS. They reported that scenario 4 showed an overall environmental impact reduction [23]. Lamba et al. (2022) reviewed the recycling and reuse of plastic wastes as construction materials and e-plastics from the construction industries. They mentioned that the addition of waste plastics from low to moderate replacement levels resulted in an increase in compressive strength; however, a higher level of replacement deteriorates the strength [24]. Similar findings have been found and recommended by [3,22]. Shamili et al. (2017) analysed the potential of using e-plastic for concrete production, and they recommended that the recycling of e-waste can build business opportunities. They also showed an increase in the percentage of e-plastic with a decrease in the self-weight of concrete. However, the workability of the concrete decreases when the percentage of e-waste is increased [25]. In summary, recycling the e-plastic waste used in the concrete mixture is a viable, environmentally friendly, and economical circular economy solution for the future.

3.2. PV Panel Recycling

The International Energy Agency (IEA) conducted a life cycle environmental impact assessment of photovoltaic panel/solar panel recycling. They analysed crystalline silicon (c-Si) and cadmium telluride (CdTe) PV modules. Due to the limited number of waste streams, c-Si PBV modules are mainly treated in the recycling plants designated for treating laminated glass, metals, or electronic wastes. But only the bulk materials are covered to recover glass, aluminium, or copper, whereas the cells and other materials like plastics are incinerated. They compiled the life cycle inventories based on the four European recyclers surveyed between 2015 and 2016 and observed a lower environmental burden in the recycling of solar panels compared to the extraction, refinement, and supply of the respective materials [26]. The International Renewable Energy Agency (IRENA) published a report on the end-of-life management of PV panel recycling, which indicates that the 3R approach of the circular economy is applicable to PV panels that are reduced, reused, and recycled. The preferred option is reducing the material contained in the PV panels, which will eventually increase efficiency. Then, the reuse option encompasses different repair and reuse modalities. Recycling is the least preferred option apart from disposal, which only takes place if the first two options are exhausted. In comparison to the growing number of PV panels in use and their waste generation rate, there are insufficient qualities or economic incentives to create dedicated PV panel recycling plants. So, the mechanical separation of the PV panels is the key focus, which even includes recovering a significant number of materials. However, one of the key challenges is the delamination by removing the encapsulant material (ethylene-vinyl-acetate). To establish recycling plants in the future, the considerations should include avoiding further damage to the PV panels during dismantling, collection, and transportation phases; reclaiming as many valuable/scarce/hazardous materials as possible; using durability labelling to identify the material; linking material compositions relevant to the recycling and recovery processes; and creating a recycling-friendly panel design [27].

Singh et al. (2021) analysed the LCA of the disposed and recycled end-of-life PV panels in Australia, which evaluated three different end-of-life scenarios for a 1 kWh electricity generation system across a 30-year PV system lifespan: disposal to landfill, recycling by a laminated glass recycling facility (LGRF), and recycling by full recovery of EoL photovoltaics. They showed that recycling by fully recovering EoL photovoltaics has more potential to reduce environmental burdens. However, they presented empirical assessment results as the recycling scenarios do not consider the recycling plant construction. They also suggested to enhance the PV panel's longevity [28]. Ganesan et al. (2022) performed an anticipatory life cycle analysis through stakeholder engagement to identify and prioritise the economic, environmental, and social indicators for PV EoL management. The prioritised indicators were bulk material recycling (centralised and decentralised), high-value material recycling, and landfilling. They showed that high-value material recycling was identified as the most sustainable option followed by the bulk recycling of PV panels, which recovers only the major constituents such as aluminium, glass, and e-waste. Landfilling was the least preferred option, though, currently, this is preferred over recycling [29]. Singh et al. (2021) analysed the life cycle environmental impact of the PV panel recycling system by comparing three scenarios: sending out to the landfill, recycling using a laminated glass recycling facility, and recycling using full recovery of the end-of-life photovoltaics. They showed that recycling technologies reduce the overall impact score of the cradle-to-grave PV systems from 0.00706 to 0.00657 (overall impact reduction based on a single-point scoring system) based on the results of the life cycle assessment (using ReCiPe-endpoint-indicator-based methodology). However, their analysis of the recycling phases does not consider the establishment of the PV panel recycling facilities, due to the lack of sufficient datasets. They suggested that PV recycling steps and strategies should be carefully considered [28].

Lunardi et al. (2020) analysed the life cycle environmental impacts of the two experimental recycling processes for c-Si solar modules: one was organic (toluene—C_7H_8) and the other was inorganic (nitric acid—HNO_3). They showed that electricity consumption from non-renewable energy resources has the largest contribution to the environmental impact of both recycling routes [30]. Rathore et al. (2022) conducted a strategic overview analysis of the management of future solar photovoltaic panel waste generation in the Indian context. They mentioned that outside the European market, very few countries had made any attempt to regulate and recycle PV waste, even though there is an urgent need among the manufacturers for recycling PV panels. China has become the world leader in the installation of PV panels without any policies for recycling and waste treatment [31]. Maani et al. (2020) evaluated the environmental impacts of recycling crystalline silicon (c-Si) and cadmium telluride (CDTE) solar panels, showing that the recycling phase of PV panels has a minor impact on the entire lifecycle impacts of PVs. According to their research, thermal methods are more eco-friendly than chemical and mechanical methods, while the recovery of telluride, copper, and glass should be prioritised for CdTePVs [32]. Adamczyk et al. (2015) analysed the gate-to-grave life cycle assessment of different scenarios for handling used PV cells. The scenarios they analysed were (1) simple scraping with no regard to PV cell recovery potential, (2) simple recovery of aluminium and glass only without treating the Ci-cell, (3) complex recovery and recycling of all possible materials with the use of heat-based processes, and (4) complex recovery and recycling of all possible materials with the use of a hi-tech laser and chemical processes. Their results showed that scenario 3 has lower environmental burdens. However, it is recommended to redesign the PV cell in a way that provides its modular construction and enables recycling without using energy-demanding and highly impacting processes like laser cleaning or chemical separation [33]. Singh et al. (2021) analysed the lifespan of PV systems from 30 years to 50 and 100 years to improve the ReCiPe endpoint single score impact from 0.00706 to 0.00424 (50-year impact) and 0.00212 (100-year impact), respectively. These findings demonstrate that recycling slightly lessens the EoL PV systems' environmental impact [28].

3.3. Recovering Steel from E-Waste

E-waste recycling to recover steel has gained increasing attention in recent years due to its potential to reduce waste, conserve resources, and mitigate environmental impacts. Several studies have been conducted to examine various aspects of steel waste recovery and recycling from e-waste, including its disposal, mobility, supply chain, life cycle assessment, and material flow modelling. Research based on construction and demolition waste recycling and disposal (Wu et al., 2019) identified the importance of policy support, technological innovation, and stakeholder engagement in promoting steel waste recycling [34]. The cross-regional mobility of construction and demolition waste in Australia (Deng et al., 2020) was used to investigate the factors that affect the transportation of steel waste across regions and proposed strategies to improve efficiency and reduce environmental impacts [35]. A reverse supply chain conceptual model for C&D waste (Chen et al., 2016) was used to develop a framework for managing construction and demolition waste through a reverse supply chain approach [36]. A mixed-unit hybrid life cycle assessment applied to the recycling of construction materials (Ryberg et al., 2019) was used to compare the environmental performance of different recycling scenarios and highlighted the importance of considering the entire life cycle of the materials [37]. Integrating G2G, C2C, and resource flow analysis into life cycle assessment framework: A case of construction steel's resource loop (Zhang et al., 2019) proposed a comprehensive framework for assessing the sustainability of construction steel recycling [38].

Rostek et al. (2018) developed a dynamic material flow model for the European steel cycle d to analyse the material flows and resource efficiency of the steel industry in Europe [39]. Park et al. (2018) also investigated the current status of steel waste recycling in Korea and proposed strategies to improve resource efficiency [40]. Gloser et al. (2016) also analysed the material flows, cumulative material demand, and market dynamics of industrial metals within a system dynamics framework: An overview of concepts and exemplary models. They provided a comprehensive overview of material flow modelling and its applications in the steel industry [41]. These studies highlighted the importance of steel waste recycling for sustainable resource management and environmental protection and provided insights into the key challenges and opportunities associated with steel waste recycling. These studies collectively provided valuable insights into the various aspects of steel waste recycling, including waste management, transportation, supply chain models, life cycle assessment, and material flow analysis. The findings contribute to a better understanding of the challenges and opportunities in steel waste recycling and offer guidance for developing sustainable waste management strategies in the construction and demolition industry.

4. Waste Management Processes

4.1. E-Plastic Waste Management Stages

This section describes the supply chain stages of the circularity of e-plastic wastes from the construction industries (Figure 2).

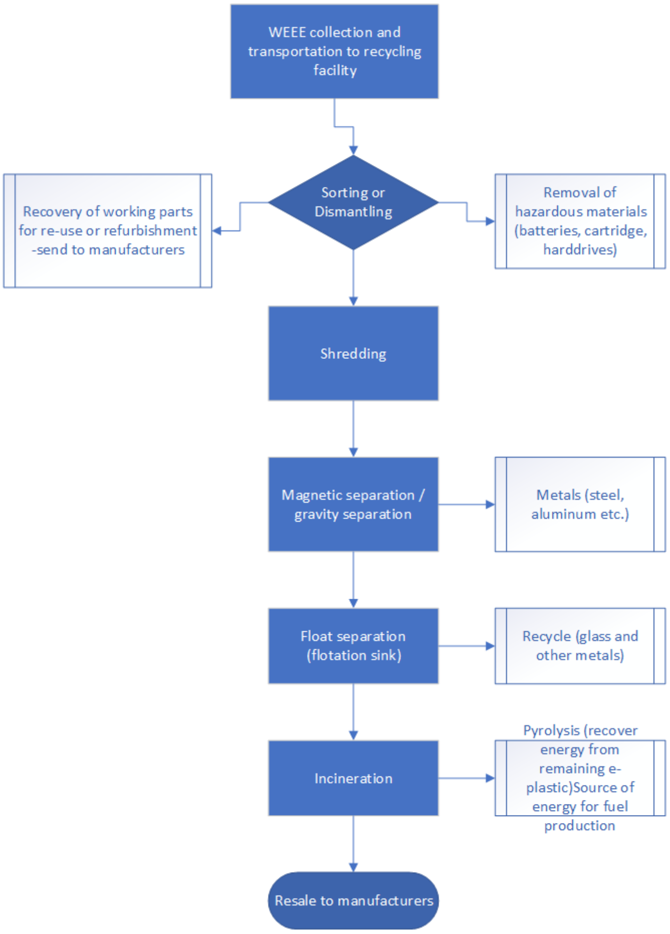

Figure 2. Flowchart for e-plastic waste generation system.

(a) Collection and transportation: E-waste in all forms is collected at specially designated locations across the country. These include drop-off points across cities and pick-ups organised by the council for larger Waste from electrical and electronic equipment (WEEE). The collection of e-waste is normally organised by a council or recycling facilities. But because there are a few here in Australia, the local council is responsible for collecting filled-up bins and transporting them to recyclers. The disposal of e-waste is governed by policies put in place by relevant government authorities. For example, in Victoria, e-waste storage and disposal are governed by the Waste Management Policy. E-waste is transported from collection points to recycling facilities using trays or compactor trucks.
(b) Sorting: On arrival at recycling facilities, the e-waste is manually sorted, and large components are separated, such as items that can be reused or refurbished and those that would require further processing. The sorting process is a manual process and is very labour-intensive. It is quite a high-skill-level operation, and people at this stage should be qualified and skilled to identify parts for reuse or further processing. At this stage, hazardous substances such as cartridges and batteries are removed to avoid explosions should they be shredded.
(c) Shredding: E-waste for further reprocessing is sent to a shredding machine and broken down into smaller pieces. At this stage, plastic, metals, rubber, etc., are all mixed up and will require further separation. The shredded mix is passed onto a vibrating conveyor and moves on to the next stage.
(d) Magnetic separation: In this stage, the shredded material mix passes through an overhead magnet, which separates the plastic from the metal components. Normally, bins are strategically placed to collect the different material components. The magnetic separation or gravity separation is largely dependent on the specific gravity, density, and particle size.
(e) Flotation sink: Water separation is mainly used for separating glass from the plastic mix. Plastic floats on the floating medium while glass sinks. In this stage, the density of the particles and the floating medium will determine which particles float. For the purposes of this study, water will be used as the floating medium, and therefore, plastic will float while other materials sink.
(f) Incineration: After all the value-adding processes are exhausted for e-plastic recovery, the remaining particles undergo incineration, where they are burnt. Because plastics have a high calorific content, they can be burnt to recover stored energy.
(g) Preparing recycled material for resale: The plastic retrieved at all the different stages is then prepared for sale to manufacturers.

4.2. Solar Panel Waste Management

Like any other electronic device or equipment, solar panels eventually reach the end of their useful life and become waste, known as solar panel waste or photovoltaic (PV) waste. As the use of solar PV panels has grown rapidly in recent years, there is an increasing concern about how to manage and dispose of these panels at the end of their life. Solar panels typically have a lifespan of 25–30 years, after which they need to be replaced or recycled. Solar panels contain a variety of materials that can be recovered and recycled (Figure 3), including:

- Glass: The front layer of most solar panels is made of tempered glass, which can be recycled into new glass products. Approximately 80–85% of a solar panel's glass can be recycled.
- Silicon: The most valuable component of solar panels is the silicon cells, which can be reused to make new solar panels or other electronic devices.
- Aluminium: The frames and mounting hardware of solar panels are often made of aluminium, which can be melted down and reused in new products.
- Copper: Copper wiring is used in solar panels to conduct electricity and can be recovered and recycled for use in new products.

- Plastic: Some components of solar panels, such as the back sheets, are made of plastic materials that can be recycled or reused in other products.

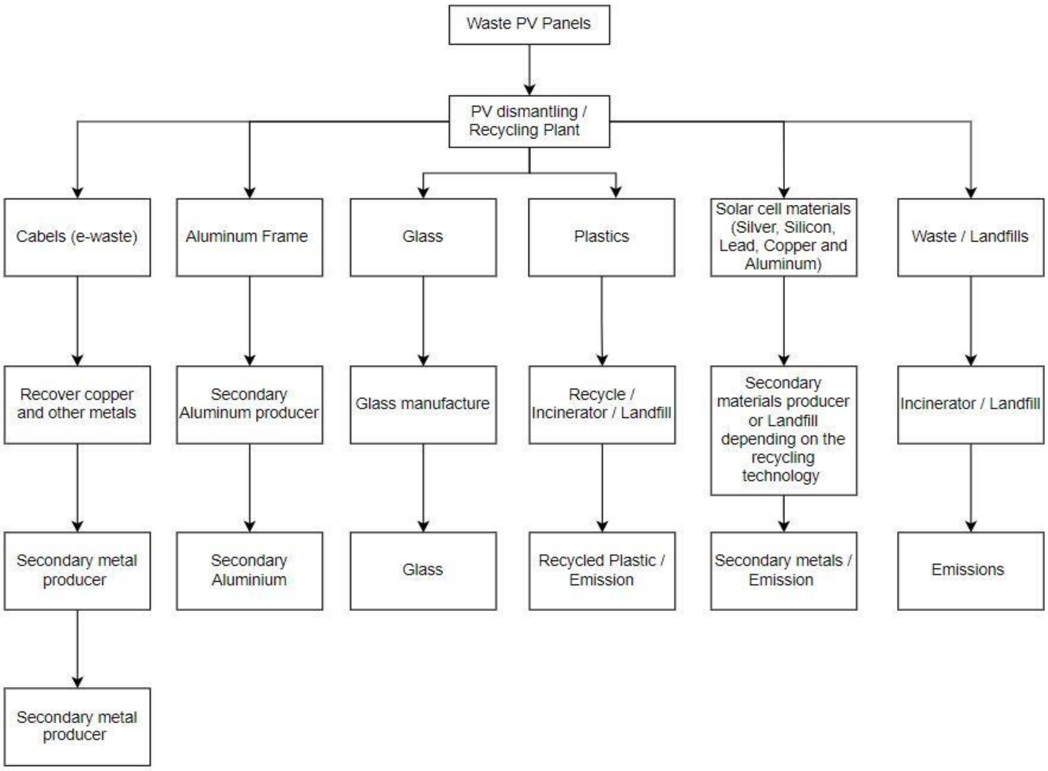

Figure 3. Materials that can be recovered from PV panels.

By recovering and recycling these materials from solar panel waste, the environmental impact of mining for new materials can be reduced and hence conserve valuable resources. Recycling can also help to reduce the amount of waste that ends up in landfills and mitigate the potential environmental and health risks associated with toxic materials in solar panels. Lim et al. (2022) stated that C-Si PV modules are processed in recycling facilities intended for laminated glass, metals, or electrical and electronic waste in first-generation recycling processes. The information used in this study was gathered from recycling facilities for metals and laminated glass. After being mechanically processed, the c-Si PV modules produce bulk materials such as glass culets, aluminium scrap, and copper scrap [42]. According to Ref. [28], when it comes to demanding industry stewardship for photovoltaics (as well as batteries, inverters, and other system components), Europe is setting the global standard, and other countries, including Australia, are following [28]. Unfortunately, it is challenging to disassemble or deconstruct solar modules in a way that is both economical and environmentally responsible. With the goal of maximising the value of separated materials, LCA is used in the current research to provide guidance on module recycling by chemical, thermal, and mechanical methods, as well as their combinations. There are various PV waste management strategies, including landfilling, incineration, recycling, and reuse, and each one has unique qualities and potential environmental advantages and downsides on the total effects of the PV modules. Italy, Japan, South Korea, and other nations are developing recycling techniques for thin-film PV systems. It has been demonstrated that more complicated procedures can reach recovery rates of up to 95% and recover materials with a high commercial value; however, these processes are still being investigated at the laboratory scale [32].

As per this research, in terms of commercial PV recycling, mechanical delamination with junction box removal and aluminium frame removal has been the most popular technology. Glass, aluminium, and e-waste are materials that can be recovered using only mechanical methods. As the polymer sheets completely pyrolyze or burn off, thermal delamination techniques enable the pure material stream recovery of glass and the PV core comprising silicon and metals. The dissolution of EVA in organic or inorganic solvents is a component of chemical delamination techniques. Although the first treatment duration is measured in days, breakdown under ultrasonic irradiation allows quicker dissolution times. As per the literature on PV recycling methods, glass and aluminium are commonly recycled through the recycling process worldwide. However, it is important to note that the effectiveness and feasibility of silicon recycling and reuse strategies may depend on a range of factors, such as the purity of the silicon, the efficiency of the recycling process, and the demand for recycled silicon on the market. Therefore, the further study of silicon as a material in the context of waste PV panels and circular economy can provide valuable insights into the feasibility and effectiveness of different circular economy strategies for managing waste PV panels, as well as identifying opportunities for promoting the reuse and recycling of silicon and other materials from these panels.

4.3. Steel Recovery and Recycling from E-Waste

Electrical components used in construction typically contain a significant amount of steel, and hence steel waste recovery and management would play a crucial role in e-waste circularity. The steps involved in steel waste management are shown below and also in Figure 4:

(a) Waste collection: Once the waste is generated, it must be collected and transported to a waste storage facility.
(b) Waste transportation: Steel waste must be transported to a dump site or a recycling facility, depending on whether it is recyclable or non-recyclable.
(c) Regulatory compliance management: Steel waste management needs to comply with local, state, and federal regulations to ensure that the environment and public health are protected.
(d) Waste storage: Non-recyclable waste is usually disposed of in landfills or dumpsites, designated areas where waste is dumped and covered with soil to prevent it from causing environmental pollution.
(e) Waste segregation: Before recycling, steel waste needs to be sorted and separated according to its type and quality. This is performed using various methods such as hand sorting, crushing, magnetic separation, and separation cyclones.
    i. Hand sorting: This method involves manually separating waste by trained personnel. Workers identify and separate different types of waste, such as steel, wood, and plastics, based on their appearance and characteristics.
    ii. Crushing: This method breaks down large pieces of waste into smaller pieces, making it easier to handle and transport. For example, steel waste can be crushed into smaller pieces for more efficient recycling.
    iii. Magnetic separation: This method uses magnets to separate ferrous metals, such as steel, from non-ferrous and other waste materials. The waste stream is passed through a magnetic field, which attracts the ferrous metals and separates them from the rest of the waste.
    iv. Separation cyclones: This method uses a cyclonic air flow to separate materials based on their size and weight. The waste stream is passed through a series of cyclones, which create a vortex that separates materials by their density. This allows for efficient separation of different types of waste.
    v. Eddy current separation: This method uses a magnetic field to create an electric current in non-ferrous metals, such as aluminium and copper. This current then repels the non-ferrous metals from the waste stream, allowing them to be separated and recycled.
    vi. Density separation: This method uses the difference in density between materials to separate them. Heavy materials, such as steel and glass, will sink, while

lighter materials, such as plastics and paper, will float. This allows for efficient separation of different types of waste.

(f) Reused waste and recyclable waste: Steel waste that can be recycled is melted in a furnace, cast into molten steel, and then given back to the site for reuse.

   i. Melt the steel waste in the furnace: Steel waste that is recyclable can be melted down in a furnace to create new steel products. The steel waste is heated to a high temperature until it melts, which allows impurities to be removed.
   ii. Cast the molten steel: Once the steel waste is melted down, it can be cast into new steel products, such as bars, plates, and beams. The molten steel is poured into moulds of the desired shape and allowed to cool and solidify.
   iii. After that, give back to the site: The new steel products that are created through recycling can be used in construction and other industries. By using recycled steel, resources are conserved, and waste is minimised. Additionally, reusing and recycling steel waste can reduce the demand for raw materials and energy, which helps to reduce the environmental impact of industrial processes.

(g) Non-recyclable waste: Non-recyclable waste is typically disposed of in a landfill. This type of waste cannot be reused or recycled and is instead buried in the ground. However, proper landfill management practices are important to ensure that the waste does not threaten human health or the environment. This includes measures such as lining the landfill with impermeable barriers to prevent contamination of soil and water and covering the waste with soil or other materials to prevent the release of odours and gases.

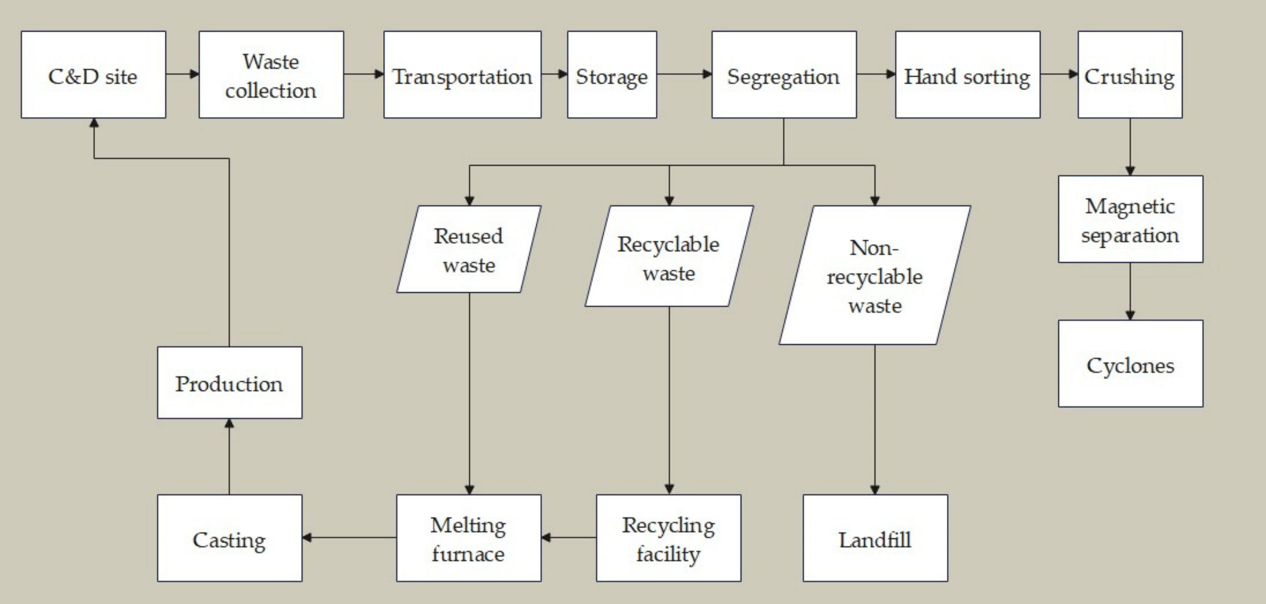

Figure 4. Waste management flowchart of steel.

5. Identification of the Key Drivers of Circulating E-Waste Materials

5.1. E-Plastic Waste

Althaf et al. (2021) analysed and found that the waste flow data were determined through the material flow analysis model, which uses mass balance principles to estimate the yearly waste flows of products. In their paper using the US as a case study, the total waste flow was estimated at around 0.5 million tonnes/year. The data collected to parameterise the MFA model were product lifespan and sales, product mass and material content, as well as sensitivity analysis. All the data were sourced from the National Centre for Electronics Recycling. The data collected ranged from annual sales data of different electronic equipment to the average mass of sample products. They analysed the recycling efficiency where all forms of WEEE were included ranging from phones to PCBs, household appliances, etc. The collection included the use of trucks, containers, and e-waste transported to different facilities in Belgium. They have worked on recycling efficiency, where 50% of total waste is recycled [43]. In a review paper by Buekens and Yang et al. (2014), the waste collection data were obtained by reviewing the waste collection tendencies of countries in the EU. This was a much broader spectrum as compared to focusing on one country; hence, the study provided a more realistic indication of the global waste flow. They reviewed the EU e-waste management. Some of the waste was recycled in facilities located in the same country, while some had to be transported to other neighbouring countries in the EU. The key indicator was the total waste collected from households or other sources [44]. Marconi et al. (2019) reported that the effective disassembly time is one key factor in e-waste recycling that depends on factors such as component shape, size, weight, and type of disassembly tools or equipment [45]. Zeng et al. (2017) identified that the recycling rate can be determined early in the sorting stage. The total weight of all the recovered valuable materials (plastic) was divided by the total weight of the input e-waste to determine the recycling efficiency at the sorting stage [46]. Vanegas et al. (2018) [47] showed that the ease of disassembly metric is an essential indicator. Given a product and the sequence of actions to disassemble it, the ease of Disassembly Metric (eDiM) can be calculated by associating a value from the reference table to each of the actions. Evram et al. (2020) showed that different types of shredders can be used to achieve a select particle size. Particles can be shredded more than once to achieve the mentioned range of particle sizes [48]. Semiyaga et al. (2023) analysed and showed that the particles from the shredder were grouped into different particle sizes using a sieve. Particles can go through multiple shredders to achieve the desired size, which will enable the next process steps to occur [49]. Ardente and Mathieux et al. (2014) analysed e-waste management and showed that the recoverability rate is important at the incineration stage. Through pyrolysis, energy is recovered by burning the residual waste. The energy recovered can be used in other industries, such as steam [50]. Favi et al. (2017) showed that the incineration index establishes whether the combination of materials can be incinerated for energy recovery purposes [51].

Zeng et al. (2017) went a step further into determining the recycling rate after the sorting process. Knowing this information may help in coming up with new methods of sorting that could potentially increase the recycling rate [46]. Marconi et al. (2019) identified disassembly as a key parameter in determining the efficiency of the dismantling or sorting process. The factors that determine the total disassembly time of a component are the size, weight, shape, and type of tools or equipment used for disassembly [45]. Comparing the sorting data provided by Marconi et al. (2019) and Zeng et al. (2015), the data provided in the latter are more comprehensive and detailed as it gives an actual value of the recycling rate of the process, whereas the former source, the recyclability, is determined by how good the technology being used to identify the plastics is [45,46,52].

For the shredding process, three sources were used, and in Evram et al. (2020) and Semiyaga et al. (2023), both articles reveal particle size as a key parameter [47–49]. The shredding process resulted in materials with particle sizes ranging between 0 and 20 mm, meaning some materials were shredded to powder form. This large range enables further processing of the materials to determine their type, i.e., plastics and metals. The same sources also look at other parameters, such as the fineness modulus of plastic that has been shredded to powder form [49].

Another key parameter, as noted by Mathieux et al. (2014), is the recoverability rate after the incineration stage. The remaining waste is incinerated, and energy is recovered through pyrolysis. The recoverability rate can be linked to how much energy is recovered. The heat generated can be supplied to paper mills [50]. In research conducted by Park et al. (2014), steam generated via waste heat is supplied to paper mills. About 23.5 tons/hr of steam is generated by incinerating 80 tons/hr of waste [53].

Plastic particles can be further separated from metallic particles through flotation. According to [54], the density of the materials and the floating medium used are factors to consider for the successful separation of plastic from other e-waste materials. Plastic is less dense than the other metallic particles present in e-waste and hence will float in the flotation sink. Literature review on the e-plastic waste management and the KPIs identified from the literature are described here in Table 1.

Table 1. Literature review on e-plastic waste management—KPI identification for key life cycle stages.

References	Life Cycle Stages Considered	Key Parameters	Datasets
[43,48]	Recycling	Recycling efficiency	50% of the total waste collected is recycled.
[44]	Waste collection	Total waste collected from households	3,106,472 tonnes (analysis)
	Waste collection	Total waste collected from other sources	192,691 tonnes (analysis)
[45]	Sorting	Effective Disassembly Time	N/A
[52]	Recycling	Recycling rate (r)	r = 33.4%
	Sorting, magnetic, and float separation	Eco-efficiency	NA
[48]	Sorting	Ease of Disassembly metric (eDiM)	For LCD monitor—eDiM = 644.11 s
[52]	Shredding	Particle size	5–14 mm
[49]	Shredding	Particle size	0–2 mm 2–4 mm 4–8 mm 8–20 mm
[50]	Waste separation	Recoverability rate	N/A
[51]	incineration	Incineration index	Incineration index ≤ 1

5.2. PV Panel Waste Management

Singh et al. (2021) analysed the life cycle environmental impact of PV panel recycling in Australia. They showed that compared to the mounting method, inverter, and electrical installation, the PV panel has the largest environmental impact [28]. Ganesan et al. (2022) showed that high-value material recycling or 100% material recovery appears to be the most sustainable approach for EoL management based on the stakeholder interaction carried out in their research [29]. Lunardi et al. (2019) conducted LCA-based analysis of two experimental recycling processes in Australia. It has been demonstrated that the costs of some valuable raw materials are crucial in lowering the overall production cost of silicon-based photovoltaic (PV) modules. It is anticipated that 70–75% of the metal value from PV wastes could be recovered with the technologies that are currently available, which promotes the recovery of clean and reusable materials from solar cells and modules [30]. In another study by Monteiro et al. (2020), they showed that among the landfill, reuse, and incineration scenarios, their LCA analysis demonstrated that recycling strategies can achieve low environmental impacts. Compared to the other EoL scenarios examined, the incineration process has more negative effects, presuming that the heat energy and electricity generated by the incineration process are ignored during the study. However, it is feasible that the effects on transportation might be substantial [55]. Rathore and Panwar et al. (2022) analysed the end-of-life impacts of solar panel waste generation in the Indian context, where the constant reduction in energy payback time and CO_2 emissions has caused the solar PV industry to develop quickly. Harmful and poisonous compounds such as Cd and Pb are employed in very small amounts during the production of PV modules. To prevent their negative effects on people and the environment, it is crucial to monitor and manage these compounds in solar waste, which will be present at the end of their useful lives (after 25 years) [31]. Blömeke et al. (2023) analysed the environmental impact of recycling solar panels. The LCA results showed that the recycling of c-Si and CdTe PVs contribute 13–25% and 3–4%, respectively, to the entire PV lifecycle impacts. Also, for both c-Si and CdTe PVs, the thermal-based recycling methods resulted in lower environmental impacts than chemical and mechanical methods, except for pyrolysis [56]. Fthenakis (2000) analysed the end-of-life management processes, including recycling, and recommended that recycling is technologically and economically feasible, but not without careful forethought [57]. A recycling program was outlined based on the current collection and recycling infrastructure [57,58]. Literature review on the PV panel waste management and the KPIs identified from the literature are described here in Table 2.

Table 2. Literature review on PV panel waste management.

References	Life Cycle Stages Considered	Key Parameters/Drivers	Datasets
[34]	Manufacturing	Treatment Cost	0.275 EUR/kg
	Waste Transportation	Transport Cost and Distance	0.025–0.105 EUR/kg
[28]	Manufacturing, transportation, use, disposal	Manufacturing process	
[29]	End-of-life stages	Economic	0.35 (Weightage)
		Environmental	0.4 (Weightage)
		Social	0.25 (Weightage)
[57]	Ends of Life	Cost of collection and recycling	USD 0.08–0.11/W

5.3. Steel Waste Recovery from E-Waste and Management

Wu et al. (2020) analysed the end-of-life C&D waste management, which uncovered the cross-regional mobility of C&D waste in Australia, and found three major types of waste mobility, which were driven by factors such as facility availability, tax, and market [34]. Brandao et al. (2016) analysed the reverse-supply-chain-based conceptual model of C&D waste management. The study proposes a conceptual model for a CDW-specific reverse supply chain (RSC), which incorporates stakeholders and government policies. Through effective waste management strategies, the model aims to reduce the negative environmental impact of CDW [59]. Teh et al. (2018) conducted a mixed-unit hybrid LCA study in which in comparison with other methods, the mixed-unit hybrid LCA approach produced a more accurate and Australian-specific result for LCA. The electric arc furnace route employing iron and steel scrap is expected to reduce glasshouse gas emissions by 43% compared to the basic oxygen furnace method [60]. Lanfang et al. (2015) conducted cradle-to-grave and cradle-to-cradle LCA analysis of steel, which showed that the construction steel RL shows that for every 1 kg of construction steel product manufactured and disposed of, 0.74 kg remains in the loop through reuse or recycling, while the remaining 0.26 kg ends up in landfills as unrecoverable "leaks." [61]. Vitale et al. (2017) conducted LCA of end-of-life residential buildings, which showed that effective selected demolition procedures might enhance the quality and quantity of wastes delivered to resource recovery and safe disposal. Recycling reinforced steel was found to be critical in minimizing environmental impacts, accounting for 65% of total averted impacts related to respiratory inorganics, 89% of those related to global warming, and 73% of those connected to mineral exploitation [62]. Rostek et al. (2022) reviewed the dynamic MFA studies for steel waste, which provides a retrospective and dynamic model of European steel flows from 2002 to 2019. According to the report, European steel and iron utilisation hit saturation in 2007, with 5600 Mt in use. A total of 140 Mt of steel reached the usage phase in 2019, with 6 Mt being dispersed or abandoned and 110 Mt being collected for recycling. Steel recycling peaked in 2007 at 140 Mt, but has since dropped in accordance with overall output, with a recycling input rate of 57% maintained [39]. Park et al. (2011) analysed the dynamic material flow analysis of steel resources in Korea and showed that some of the key indicators are product group, scrap self-sufficiency ratio, and recycling rate. The scrap self-sufficiency ratio, which indicates the ratio of scrap recycling to scrap demand, was considered a key indicator for resource management. The analysis revealed that the current scrap self-sufficiency ratio in 2008 was

97%, but it is expected to decrease to approximately 93% by 2020. Maintaining the current recycling rates would lead to a decrease in the self-sufficiency ratio and necessitate importing more scrap to meet the demand [40]. Literature review on the steel waste management and the KPIs identified from the literature are described here in Table 3.

Table 3. Literature review on steel waste management.

References	Life Cycle Stages Considered	Key Parameters	Datasets
[34]	Waste generation, transportation, treatment, and disposal	C&D waste composition and creation, waste management techniques, waste flows and mobility, waste materials, causes and consequences of cross-regional mobility.	Site surveys, expert interviews, expert seminars, and desktop surveys are examples of datasets.
[61]	Waste distribution, generation, collection, processing, recycling	recycling rate, revenue margins, recovery process costs, stakeholders, and government rules	Various statistics on CDW generation and recycling rates in various countries, including the United States, Brazil, Australia, and China, are cited in the article.
[39]	from mining to recycling, including the use phase, end-of-life scrap processing, and recycling.	Scrap generation rate, scrap collection process/rate, separation process, and recycling process parameters	separation efficiency 0.95 (%) collection rate 1.37
[40]	Production, use, disposal	scrap self-sufficiency ratio	Product Group and Recycling rate Construction Products—90% Transportation Equipment—100% Other product groups—40%
[57]	Extraction, processing, manufacturing, use, waste management, recycling	resource efficiency	

6. Discussion and Policy Recommendations

In this review, the e-waste generated from the C&D industries is analysed based on their circularity routes, their waste management stages, and their key performance indicators to maximise the recovery of valuable waste materials. The three key types of e-waste considered here are plastic wastes from the e-plastic wastes, which are dominantly used for producing concrete materials for construction works once they are recovered from the wastes. Waste collection efficiency, recycling efficiency/rate, and particle size are the key factors to maximise the recovery of the e-plastic wastes from the C&D wastes. For solar panel waste management, multiple types of materials can be recovered from the solar panels, but these are subject to the types of recycling process/capacity. High-value material recycling is preferred over bulk material recycling. However, the key indicators are efficient dismantling and waste collection processes so that the materials do not break down/deform to maximise the value of the recovered waste [63,64]. The other important indicators are the costs of waste collection and treatment. The last type is steel waste recovery and recycling, which is dominantly used in the construction industries. The steel waste scrap generation rate, scrap collection rate, and costs of revenue and collection are the dominant KPIs. In summary, for these different types of e-waste, the KPIs common for all types of e-waste are the waste collection cost and collection efficiency, and recycling cost and efficiency. There are some other KPIs that are particularly for the e-waste types and their recycling methodology. Figure 5 describes the e-waste management policy recommendation process from this review paper.

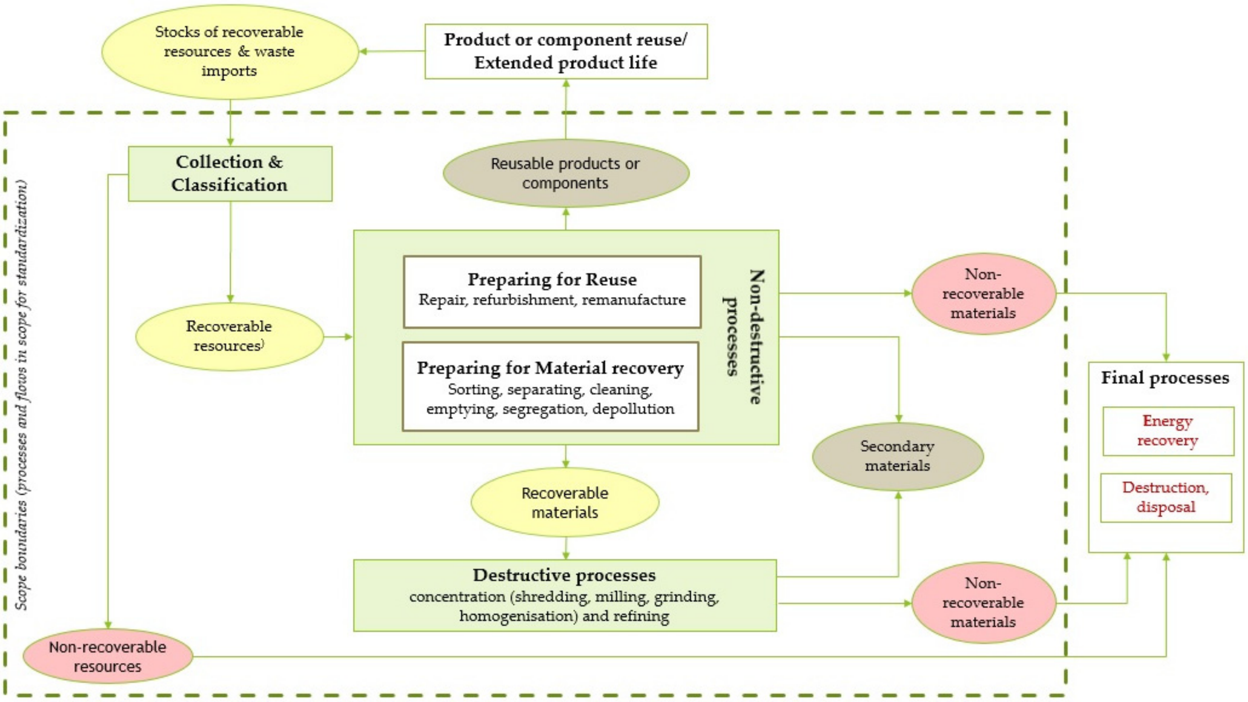

Figure 5. Integrative framework on the circularity of e-wastes in C&D industries.

Based on the review of the implementation of circularity principles for C&D wastes, there are four potential outputs: (i) recovered materials that wholly substitute all the original materials; (ii) recovered materials that have the potential to partially substitute components of the same material; (iii) recovered materials with partially recycled content to substitute components of different material; and (iv) energy [59]. The main issues that stifle the effectiveness of Australia's policy relate to economic issues such as the lack of standards that guarantee the quality of secondary materials, as well as the higher prices of secondary materials over primary raw materials. In addition, stakeholder issues still undermine the effectiveness of waste management, as many parties involved in the process are, for the most part, poorly coordinated. It is, therefore, expedient for the further analysis of stakeholders and a better understanding of the economic, technical, and social barriers to be addressed in a holistic manner. Lastly, more policies could be included to account for the waste materials during the whole life cycle of a material. This design method for disassembly is an alternative to materials' once-through life cycle use that dominates the construction industry. This is where a material is used once in a construction project and then disposed of when the building is eventually taken apart. This alternative would ensure that materials are dismantled and taken apart from buildings at the end of the building life to then be re-used on the next project [65,66]. Re-focusing on the life cycle of materials could be carried out through Government action, whereby a government would set up a financial incentive program to encourage waste recovery and to maintain and develop the recycled material market to drive more waste recovery in the industry.

In order to facilitate the circularity of e-waste in the C&D sector, we adopt a study to allow for an integration of life cycle assessment and circularity for e-waste. The proposed framework is valuable for managing secondary materials and is useful at an organisational level. The framework is adapted from initial work from the joint working group of the International Standards Organisation (ISO59014), which has been working on providing a standard for secondary materials across all industries and sectors.

The integrative circularity framework will facilitate sustainable actions and strategies for the reduction, reuse, recovery, recycling, designing, upcycling, and energy recovery of e-waste in C&D industries. Although Australia does not have a circularity framework like those in Europe [60], there is increasing emphasis on waste management policies, especially regarding the diversion of wastes from landfills. A circularity framework will, however, be required to advance policy directives with robust scientific backing to avoid problem-shifting and poor financial viability and eliminate the potential for unplanned obsolescence in material recovery and circularity frameworks. Therefore, integrating standardised LCA approaches and the circular economy can support environmental- and financial-performance-based policymaking for material circularity in e-wastes from C&D industries.

7. Conclusions and Recommendations

This paper reviews the circularity potential for recoverable materials from e-waste from the construction and demolition industries. The study identifies circularity routes of the e-waste from the construction industries, accompanied by the waste management processes to recover resources from the e-waste. Key performance indicators of each of the circularity routes are evaluated and the policy framework for the circularity of e-waste in Australia is then evaluated. Finally, an integrative framework on the circularity of e-waste in C&D industries is provided to optimize the performance of the sector in Australia. Key findings from the study include the following:

- Waste collection efficiency, recycling efficiency/rate, and particle size are the key factors to optimise the recovery of the e-plastic wastes from the C&D wastes.
- Efficient dismantling and waste collection processes are the key indicators that optimise the value of the recovered waste from solar PV panels.
- Waste scrap generation rate, scrap collection rate, and costs of revenue and collection are the key considerations to optimise recovered waste from steel-based wastes.

Finally, a proposal is made for an integrative circularity framework that will facilitate sustainable actions and strategies for the reduction, reuse, recovery, recycling, designing, upcycling, and energy recovery of e-waste in C&D industries. There is, however, a need for better government policies and directives to support the effectiveness of achieving circularity in the C&D e-wastes sector to minimise the environmental impact and achieve the better utilisation of secondary resources from the construction and demolition sector. Future work should seek to enshrine the holistic principles of life cycle sustainability assessment in the circularity of e-waste in the C&D sector. Furthermore, there is a need for more stakeholder involvement to ensure that circularity becomes a societal norm that can be applied irrespective of financial incentives from the government and policymakers.

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