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# Life cycle assessment of e-waste management system in Australia: Case of waste printed circuit board (PCB)

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ABSTRACT

Electronic waste (e-waste) is one of the fastest-growing waste streams globally. Recycling is one of the environment-friendly waste management strategies that creates a net environmental gain in recovering valuable materials. In some countries, downstream recycling (high-value material recovery) is done overseas, and Australia is one of them. Waste printed circuit board (PCB) is a critical component of various electronic equipment, and it contains metals such as copper, tin, gold, aluminium, iron, silver, and others. Waste PCB, as apart of e-waste is mainly recycled overseas in Australia. However, the overall environmental impacts of recycling the waste stream overseas have yet to be investigated. The benefits of recovering the material in Australia have yet to be extensively understood from a supply chain perspective. This study aims to develop multiple scenarios using lifecycle assessment (LCA) methodology to identify the best possible solution for waste PCB disposal (final sink) derived from e-waste. Using SimaPro and Ecoinvent databases, four scenarios have been developed, along with a baseline scenario where waste PCB is recycled overseas. Receipe 2016 impact assessment methodology was utilized for the analysis, and results of the study showed that Scenario 2 (integrated material and energy recovery) is the best approach for waste PCB recycling in Australia, while landfill and direct incineration were the identified two worst scenarios in terms of final disposal option. When choosing local recycling over overseas recycling of waste PCB (material recovery only), it was found that impact categories such as global warming (human health) and fossil resource scarcity were reduced by 53% and 98%, respectively. In addition, the net positive environmental gain could be achieved for human non-carcinogenic toxicity by 7.16% when the waste stream is recycled in Australia. Uncertainty analysis of the study showed that in almost all major impact categories, material and energy recovery together scored high compared to scenarios when only material recovery was considered. This study is the first systematic attempt to characterize system-level lifecycle environmental impact assessment for waste PCB recycling. Future policies and regulations should focus on data transparency and availability across the value chain, local infrastructure development, and resource circularity. This study will add value to decision-making, policy on investment and future policy planning. It will also help industry and researchers develop optimized recycling-focused low-emission resource recovery supply chains.

## 1. Introduction

Electronic waste (e-waste) is one of the fastest-growing waste streams in the world (Liu et al., 2023). The general composition of e-waste consists of organic materials (30%), ceramics (30%), and metals (40%). Again, the metal fraction is divided into two parts ferrous metals (representing iron and nickel) and nonferrous metals (consisting of copper, aluminum, mercury, lead, zinc, tin, cadmium, and gold). Hg, Zn, Pb, and Be are the hazardous metals, while Au, Ag, Pt, and Pd are the precious metals, and Ta and Ga are the rare earth metals in e-waste material composition (Sahajwalla and Hossain, 2023). Printed circuit board (PCB) is an unavoidable component of e-waste that contains the maximum concentration of precious metals such as Au and Ag and metals such as Al, Cu, and Zn and others (Pokhrel et al., 2020). Finding appropriate management pathways presently is the most critical aspect, both from policy and technological perspectives (Islam and Huda, 2019a). In addition, of course, product design with less harmful materials and substances and consideration of end-of-life (EoL) strategy are some of the critical aspects that have been discussed over the years. According to the Ellen Macarthur Foundation, the circular economy

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(CE) is “an industrial economy that is restorative or regenerative by intention and design” by including three principles, 1) eliminate waste and pollution, 2) circulate products and materials (at their highest value) and 3) regenerate nature (Ellen MacArthur Foundation, 2023b). A paradigm changes in resource management; the CE seeks to decouple economic growth from resource use and environmental damage. Strategies or pathways must be taken to implement the principles depending on the product and material types. Two types of cycles are biological and technical (Ellen MacArthur Foundation, 2023a). The products that are “used” fall under the category of the technical cycle, and materials that are “consumed” are in the biological cycle. The biological cycle is more towards achieving principle number three. For the technical cycle, the pathways are (1) maintained/prolonged use, including sharing and repair; (2) reuse and distribution; (3) remanufacture/refurbishment; and (4) recycling (Ellen MacArthur Foundation, 2023a). Reverse supply chain (RSC), product/service design, business models, EoL recovery, product/service use, and policy are the basic building blocks of the CE concept (Alamerew and Brissaud, 2020). For the recycling strategy, RSC, EoL recovery (both product and materials), and policy are essential components that are directly then integrated with the CE principle. From the closed-loop supply chain perspective, principles one and two will be achieved using recycling. Although recycling is considered the last strategy of the hierarchy (R8 – Recycle) proposed by Potting et al. (2017), it is argued that for material recovery that is encased in products, the strategy should be one of the critical options for obtaining the same (high grade) or lower grade quality materials. Within the framework of a CE, e-waste mines should be regarded as a significant source of secondary raw materials. Due to problems associated with primary mining, market price fluctuations, material scarcity, availability, and access to resources, it has become necessary to enhance the mining of secondary resources and reduce the pressure on virgin materials. By recycling e-waste, nations could at least reduce their material demand sustainably and securely (Forti et al., 2020). Therefore, from the CE perspective, PCB is a specific fraction of e-waste that can provide an impressive diversity of secondary material recovery.

In the CE action plan prepared by the European Commission (EC), electronics and information and communication technology (ICT) are one of the sectors with the most resources and where the potential for circularity is high (European Commission, 2020). Furthermore, at the European policy level, e-waste is considered one of the priority waste streams (Europe of Cities, 2021) implementing extended producer responsibility (EPR) in the Waste electrical and electronic equipment (WEEE) policy (Ecommerce Europe, 2020), making the producers responsible for appropriate take-back. The collection and recycling of e-waste vary substantially across the regions of the world. Despite having long standing policy measures, only 40% of e-waste is recycled in Europe (European Parliament, 2022). In the West Asia region representing countries such as Bahrain, Iraq, Jordan, Kuwait, Lebanon, Oman, State of Palestine, Qatar, Saudi Arabia, the Syrian Arab Republic, the United Arab Emirates, and Yemen, it is reported that 99.9% of e-waste is currently unmanaged or mismanaged with an e-waste generation of 1.5 Mt (million metric tonnes), which is projected to increase more than double, estimating 3.3–3.9 Mt in 2050 (United Nations Institute for Training and Research (UNITAR), 2023). With a CE scenario considering environmentally sound management of e-waste through recycling, it is estimated that for the region, a total of 130 t of gold, 5 t of rare earth metals, 17 Mt of iron and steel, 1.5 Mt of copper, 2.6 Mt of aluminum could be recycled between 2020 and 2050 (United Nations Institute for Training and Research (UNITAR), 2023). According to the Global E-waste Monitor (GEM), 2020 report, Asian countries (including the West Asian countries) generated 24.9 Mt (5.6 kg/capita) of e-waste and only 11.7% (2.9 Mt) of the e-waste was documented to be collected and appropriately recycled (Forti et al., 2020). In the case of Latin America, in 2010, e-waste generation was 0.9 Mt which increased by 49% and reached 1.3 Mt as of 2019. This amount was the representation of the 13 countries analyzed by the UNIDO-GEF 5554 project commissioned by the "Regional E-waste Monitor for Latin-America" team (United Nations Institute for Training and Research (UNITAR), 2022). Over 97% of the region’s e-waste must be collected formally or transported to environmentally sound management (ESM) facilities for appropriate management. Most e-waste is sent to landfills, with the informal sector salvaging valuable components (United Nations Institute for Training and Research (UNITAR), 2022). With the generation in 2019, it was estimated that secondary materials in the waste stream were valued at USD 1.7 billion (United Nations Institute for Training and Research (UNITAR), 2022). By analyzing data from the Commonwealth of Independent States (CIS), which consists of 12 countries, ESM takes place only in a few countries, such as Belarus, Kazakhstan, Russia, and Ukraine, representing only 3.2% of total e-waste generation. Some nations, such as Georgia and Kyrgyzstan, do not collect e-waste due to a lack of organized distinct collection infrastructure (United Nations Institute for Training and Research (UNITAR), 2021). In the Oceania region (mainly Australia, New Zealand, and Pacific Island nations), only 8.8% of the e-waste was documented to be collected and properly recycled, where the generation was recorded at 0.7 Mt (16.1 kg/capita) (Forti et al., 2020). Globally, only 17.4 percent of electronic waste is formally collected and recycled (Forti et al., 2020). From here, accurate and up-to-date documentation around waste handling (including the flow of waste inland and transboundary movement) and ESM are the critical barriers to identifying potential CE opportunities for the regions.

Australia is also part of the Organisation for Economic Co-operation and Development (OECD) countries where the amount of e-waste has increased three times faster than general solid waste (Islam and Huda, 2020). E-waste in Australia is being managed by co-regulatory arrangements such as the National Television and Computer Recycling Scheme (NTCRS). As the name suggests, NTCRS is responsible for recycling computers, television, and IT peripheral products (e.g., printers, internet modems, and others) (DCCEEW, 2021). From a voluntary perspective waste mobile phones have been supported by MobileMuster (Islam et al., 2020), an organisation that collects and recycles old mobile phones.

The recycling process is divided into two segments: 1st stage recycling, in which manual separation of components and mechanical preprocessing results in size reduction. For final material recovery, 2nd stage (downstream recycling) is undertaken overseas (Dias et al., 2018). Components such as waste PCB parts are generally transported overseas for that recovery (ANZRP, 2021). Over the years after the scheme’s inception in 2011, this process is still being continued. As per one of the co-regulatory arrangements, most of the waste PCB being processed (downstream material recycling) is in Japan (ANZRP, 2021). Reverse supply chain transparency has become an issue for many countries, and consumers, product manufacturers, and waste management authorities (including handlers and recyclers) have an integral role to play. The GEM report showed that valuable components such as PCB are being transported from the Southern hemisphere (i.e., Australia is located in the hemisphere) to Northern hemisphere for recycling as the e-waste collection system advances in developing nations (Forti et al., 2020). Supply chain sustainability and the overall efficiency of the chain can only be ensured when materials can be traced and can get back to the manufacturing process. The environmental impact of the (backward) supply chain (starting from EoL disposal) is also a critical aspect that requires scientific investigation and understanding to add value to the waste stream and make it a resource base. It also supports in transparency across the supply chain for making informed decisions. This paper investigates the environmental impact of various waste PCB EoL management scenarios (on a what-if basis) for the Australian context.

Alternatives to the present scenario (downstream overseas recycling) can provide alternative options to be pursued so that local scenarios can be designed, and the potential benefit of local recycling understood from a holistic environmental impact assessment perspective. Life cycle assessment (LCA) is one of the critical assessment tools that can be used to identify the best possible solution among various management scenarios. The application of LCA has become an essential part of product development and the product supply chain. For example, European Environment Agency (EEA) recommended that the design and production of new products be based on the LCA concept. To improve current management practices and regulatory frameworks around e-waste, Withanage and Habib (2021), specifically highlighted the importance of cradle-to-grave and cradle-to-cradle LCAs (for a holistic understanding of the e-waste life cycle). It is a basis for eco-labelling (European Environment Agency, 1997). Investigating the EoL disposal scenario has become vital in identifying the impact hotspots of various perceived strategies (i.e., material recovery only vs. material and energy recovery together). The connection between LCA and CE -related strategies has come up in research, which has shown the importance of the assessment methods for (investment in) decision-making and future policy planning. Withanage and Habib (2021) mentioned that as CE is a relatively new field of continuous development, there are significant opportunities for applying CE principles in e-waste management. In addition to LCA, material flow analysis (MFA) is used as a complementary method. Streicher-Porte et al. (2009) mentioned that "an MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time." Islam and Huda (2019b) identified MFA as one of the strategic tools for e-waste management, which creates value and further understanding of the supply chain of the waste stream. Withanage and Habib (2021) identified that MFA and LCA as strategic tools (i.e., although underutilized) can assist in decision-making in e-waste management. The authors claimed that a few studies had combined MFA with LCA to calculate the resulting environmental implications, and there is potential for combining the MFA-LCA method for decision-making regarding the effective use of limited raw resources.

The primary purpose of using LCA is to assess the environmental impact of any process. For example, Streicher-Porte et al. (2009), assessed the impact of refurbishing second-hand computers. In addition to using LCA, the authors utilized MFA to assess the quantities (i.e., the economic evaluation of the material flows that are considered a driving force for material recycling). According to the authors, "an MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time." In that study, the MFA was used for computer systems, for instance, desktop P.C., CRT monitors, keyboards, and mice. The combined approach of MFA and LCA was utilized by Hischier et al. (2005), where MFA was applied to estimate the annual collection of the material flows entering and leaving the SWICO (for computers, consumer electronics, and telecommunication equipment) and SENS (household appliances) systems and LCA was used to understand the environmental impact of reverse logistics activities, subsequent material processing steps and disposal processes of the systems. The tonnage of materials and percentage were the key indicators to assess the resulting fractions (e.g., PCB, cables, plastics, batteries, and others). To calculate the overall environmental impacts of collection, pre-processing, and end-processing of Swiss WEEE collection and recovery systems, as well as of incineration and landfilling scenarios, Wäger, P.A. et al. (2011), applied combined MFA (i.e., to identify the material flows related to the activities) and LCA (i.e., to calculate the environmental impacts related to material flows of the activities).

MFA comprehensively identifies all the critical components an e-waste stream could have and then individually assesses the environmental impacts using an LCA model's impact assessment methodology and inventory data. Fiore et al. (2019) also utilized the combined approach to analyze a full-scale Italian e-waste management system. In this study, using two different scenarios (e.g., partial, and complete recycling), the authors explicitly mentioned MFA as a mass balance approach segmenting the weight fraction of various components such as steel and iron, plastics, glass, rubber, and others (according to treatment lines, e.g., R1-Cooling equipment) into the scenarios and conducted an LCA. A similar approach was utilized by Ismail and Hanafiah (2021) in the case of the Malaysian e-waste management system. However, Biganzoli et al. (2015) explicitly mentioned the MFA application as a mass balance approach rather than mentioning it as an MFA. It is understood from the above examples that MFA applications are primarily in two significant areas in the LCA studies 1) conducting a comprehensive assessment of an e-waste management system (i.e., identifying the flow of materials in various processing routes) and using the MFA results as an input to perform LCA for individual or collective activities, and 2) the inherent requirements of an LCA study where the input (e.g., the assembly of a product, for example, a waste PCB) and output of the materials (after going through a specific process, for example, recycling) must present the equal amounts within a defined system boundary set in the LCA study) to assess the environmental impact of that specific (recycling) process. The output of the process may introduce various types of waste, which are then generally considered to be disposed of on other routes (e.g., incineration or landfills). In this way, the mass balance approach is done. Mass balance and MFA are, to some extent, used interchangeably by researchers in the LCA space. In an LCA model, for example, performed in SimaPro (i.e., One of the LCA softwares), the model must demonstrate a mass balance approach when waste stream needs to be allocated to various process routes (e.g., treatment of scrap) (PRé Sustainability B.V., 2023a). From all these aspects, for this present study, MFA was used as a complementary method to the mass balance and data gathering process that included both reverse flow of waste PCB transferred to overseas downstream processing and recycling process for recovering metals from the e-waste stream.

Ismail and Hanafiah (2019) conducted a comprehensive review of the application of LCA on various e-waste products at the process-level and hazardous waste management perspective. The study shows that although most of the studies are undertaken in OECD countries, only a few studies have been performed around e-waste. More specifically, a limited number of studies have been performed contextualizing Australian e-waste management systems (i.e., both at the product level and process level). For example, Boyden et al. (2016) conducted an LCA focusing on the hydrometallurgy and pyrometallurgy process associated with recycling lithium-ion batteries (LIBs). The authors suggested that environmentally advantageous techniques can recover plastic while operating at low temperatures. Biswas et al. (2013) conducted a comparative LCA focusing on compressors - repaired, remanufactured, and new equipment and the results of their study showed that extended lifetimes dramatically reduced the greenhouse gas emissions and repairing malfunctioned compressors was the best alternative among the three scenarios: both in terms of dollar and carbon savings. Considering two separate scenarios - (1) recycling of precious metal out of waste PCBs through secondary copper smelting (Electronic Waste Processing, EWP); and (2) secondary copper recycling without adding electronic waste to the feed (SCR), Ghodrat et al. (2017) performed a comparative LCA on waste PCB. Transportation distance and type of electricity supply in the smelting operation were two critical variables that determined the potential environmental impacts. Another study by Soo and Doolan (2014) focused on waste PCB from waste mobile as e-waste and compared the toxicity of the waste produced from mobile phone PCB recycling in Malaysia and Australia. In the case of Australia, the authors considered Singapore the destination for waste mobile phones' PCB. Recently, Mairizal et al. (2023) conducted a carbon footprint analysis on waste PCB considering three scenarios: 1) recycling waste PCB in small-scale facilities, 2) in centralized and large recycling facilities, and 3) recycling with other industries.

It can be noted that LCA focusing on e-waste, especially waste PCB is very limited, and there is a lack of understanding on the best solution for Australia recycling waste PCB locally. Furthermore, a study has yet to compare overseas waste PCB recycling with potential options for locally recycling the waste stream. From these aspects, this study provides a novel perspective on assessing potential waste PCB recycling pathways for policymakers and investors for high-value material recovery. Based on the research gap, this study aims to develop various scenarios for waste PCB management options and the current practice of overseas downstream recycling processes. Combing MFA with LCA, a comparative lifecycle environmental impact assessment is conducted in this study to assess the best suitable option for Australia, focusing on waste PCB at the system level.

Following this introduction, Section 2 describes the material and method, Section 3 presents the results and discussion, and Section 4 conclusion.

## 2. Material and methods

### 2.1. *Goal and scope of the study*

The study aims to assess the environmental impact of various waste PCB EoL management scenarios, including overseas downstream recycling process, and propose the best alternative for material recovery locally in Australia. The scenarios are 1) Scenario 0: waste PCB preprocessed in Australia and then transferred overseas (in this case Japan) for downstream material recovery; 2) Scenario 1: material recovery without energy recovery (both 1st stage mechanical preprocessing and downstream material recovery in Australia) with remaining waste going to landfill, 3) Scenario 2: both recycling stages occurs in Australia and energy recovery by passing the process waste from material recovery, and plastic parts (resins and glass fiber) sent to an incinerator, and the remaining waste goes to landfill, 4) Scenario 3: where 100% of the waste PCB goes to an incinerator for energy recovery only and the remaining parts go to landfill and finally 5) Scenario 4: where 100% of the waste goes to the landfill without energy and material recovery. These scenarios were then compared, and the best management scenario for Australia was suggested.

The study was conducted according to the standardized LCA methodology (e.g., ReCipe 2016 (Endpoint)) based on ISO 14040 series as a guiding mechanism. The study used SimaPro version 9.4.0.2, integrated with Ecoinvent database version 3.8. The functional unit for this LCA study is set to analyze 1000 kg of waste PCB from various kinds of e-waste that undergo the scenarios mentioned above. For convenience, details of the scenarios are described in the lifecycle inventory section. To make the assessment comparable to local solutions (scenarios focusing on Australia), transportation has yet to be considered. It is understood that transportation is required to transport the waste to a destination (e.g., to a landfill), which would provide an added layer of transport-related emissions. The only transportation-related activities included in the baseline scenario (Scenario 0) were the waste stream that needed to be transported overseas and, in that case, assumptions made regarding road transport and sea container shipping.

### 2.2. *Life cycle inventory (LCI)*

LCI is the first step in LCA that accumulates all the data required to be put into the model of the LCA. Therefore, from various sources, data were collected. The individual scenario is described below to facilitate the understanding of the required data collection.

#### 2.2.1. *Description of the scenario*

**Scenario 0:** A baseline scenario has been developed, which is considered a transboundary activity. Due to lack of field-level data, this model is considered a two-step process as part of the waste PCB recycling. First, waste PCB is separated and processed in Australia. Data on the actual process is very scarce in this regard; for example, the type of machines are explicitly utilized for the dismantling and size reduction of waste PCB from the Australian context for the purpose of material recovery which is a destructive process. It must be understood that most of the waste PCB portion is transferred overseas after mechanical processing (i.e., size reduction and applying advanced mechanical equipment and machinery such as eddy current separator, magnetic separator, shredding/grinding, and others). Most of the recyclers separate the waste PCB part manually from the equipment and store it (after first stage processing) for further overseas downstream recycling. Dias et al. (2018) mentioned that majority of the processed components after first stage recycling are forwarded to downstream. This study considered that waste PCB is mechanically processed in Australia and transferred to overseas facilities for downstream recycling as baseline scenario. According to Dias et al. (2018), none of the recycling facilities operating directly under the NTCRS employ downstream processes such as smelting, leaching, or electrowinning.

Research by Dias et al. (2019) mentioned that first-stage recycling consumes 39.7 kW per ton of electricity on average; without indicating actual operating hours of the machineries at the processing plant. In such an instance, an average value of the electricity consumption by the types of machinery has been considered from the literature. The data required in this stage is derived from Pokhrel et al. (2020), who noted that pre-treatment and mechanical processing of the waste PCB required an average of 196.27 kWh/ton of waste processing. As mentioned earlier, as there is no clear indication of the types and number of operating hours of the machines for the mechanical pre-treatment process of 1 ton of waste PCB from the Australian context, literature data from Pokhrel et al. (2020) was taken into account. After mechanical processing, it was identified that from 1-ton waste PCB, the various metals and non-metals were removed, which required further downstream recycling (2nd stage material recovery process). In the case of Australia, this is done overseas. Table 1 shows the materials found after the mechanical processing of 1 ton of waste PCB.

After conducting the first processing stage, the waste PCB is shipped overseas. The transport distance with a truck from the processing facility to the seaport was assumed to be around 32 km, in which case a 16–32 metric ton Euro4 lorry was considered. For the distance measurement from 1st stage processing facilities to seaports, existing recyclers located in various states in Australia, along with the adjacent seaports in the states, were identified. ANZRP's recent report (ANZRP, 2021) was used as a reference from which 14 different first stages of processing facilities were identified by their locations, and distances were measured from point A (processing facilities) to point B (seaport). In this way, fourteen different distances were computed, then averaged. In that case, the average distance was roughly 29 km, and by taking a conservative approach (i.e., adding a 10% increase in distance, as alternative routes were found during the calculation), the approximate average value of the distances was rounded to 32 km. On the other hand, as there is no field-level data available on what types of trucks are generally being utilized for such transport distance, data on the truck type was considered as per previous studies conducted in other e-waste LCA studies. For instance, Iannicelli-Zubiani et al. (2017) utilized a 16–32 metric ton Euro3 lorry for their LCA model, assessing the environmental impacts of the hydrometallurgical process in Italy. Similarly, Xiao et al. (2016) used the same truck type in the case of China, identifying the environmental impacts of refrigerator recycling processes. Finally, for a portable prototype plant for metal recovery from e-waste, Rocchetti et al. (2013) used the same transport type for their LCA model. All this evidence justified the use of the truck type (e.g., 16–32 metric ton Euro4 lorry) as

**Table 1**
Metals and non-metals from mechanical processing.

| Input | Output | Mechanically processed material (kg) |
|---|---|---|
| 1 ton waste PCB | Copper (Cu) | 150.32 |
| | Tin (Sn) | 46.1 |
| | Iron (Fe) | 35.07 |
| | Lead (Pb) | 32.07 |
| | Nickel (Ni) | 24.05 |
| | Aluminium (Al) | 4.01 |
| | Zinc (ZN) | 3.01 |
| | Silver (Ag) | 1.59 |
| | Gold (Au) | 0.31 |
| | Resin | 281.388 |
| | Glass fiber | 422.082 |
| | Total | 1000 |

Source: Pokhrel et al. (2020).

part of the LCA model for the present study.

Recently, the co-regulatory arrangements mentioned that most of the downstream recycling process of waste PCB is done in Japan (ANZRP, 2021). It is assumed, therefore, that a container ship is being used to transfer the processed waste PCB for downstream recycling. The Ecoinvent dataset estimates the environmental impact in this instance, along with the emission data of freight ship containers traveling from Australia to Japan. The emission from shipping transferring the waste from Australia to Japan, data presented in Table 2 sourced from Soo and Doolan (2014) is used as part of the input for the scenario. Data was aggregated with the freight distance from Australia to Japan, and reference values were then modified for the per kg emission of the substance for the container shipping distance. The average distance from various seaports to Tokyo port was assumed. Among the ports in Australia, Fremantle Port in Western Australia, Port Adelaide in South Australia, Port Melbourne in Victoria, Port Botany in New South Wales, Port of Brisbane, and Crain's Seaport in Queensland were considered the major ports from where ship freight distances were measured to the port of Tokyo, Japan. Please note that as no data is available from which port the freight shipping container is dispatched from the Australian side, the average value of the distances from the considered ports to the port of Tokyo was considered a conservative approach for the modeling. For that reason, no specific port is chosen from the dispatching side. For the LCA model, transport-related activities are required to have a distance value. In other words, for the six different ports, six different distances are found considering the port of Tokyo, which was then averaged. The average distance from all the considered ports to the port of Tokyo was estimated to be around 9048 km which was included in the LCA model. There are several ports in Japan also available at the receiving end.

The reason for selecting the port of Tokyo in Japan as the receiving port was that there was a nearby recycling facility. It is also assumed that the recycling plant would be near the seaport to reduce costs and unnecessary logistics. Van Yken et al. (2021), stated that DOWA possesses Japan's largest downstream e-waste processing smelters. There are two types of e-scrap recycling and refining facilities by DOWA (DOWA Eco-system, 2023), one is located in Kosaka, Japan, which mainly performs the pyrometallurgical process, and the second facility is located at Honjo, Japan, operates under the hydrometallurgical process (DOWA, 2014). Honja is close to Tokyo, Japan, and the metal purification process presented in this present study is focused on the hydrometallurgical process (i.e., consisting of electrolysis), which justifies considering Tokyo as the main port of entry for the processed e-waste from Australia. As there is a lack of data on which recycling facility is used to process Australian e-waste, such an assumption was made. Co-regulatory arrangements have not disclosed such information in their annual reports. In real-world scenarios, it could vary substantially. However, there must be clear evidence of that and more research on transboundary movement should be conducted on this issue.

The downstream recycling is the material recovery process that recovers precious and valuable materials. The literature data of the metal recovery process mentioned by Pokhrel et al. (2020) is shown in Table 3. It is to be noted that the resin (281.388 kg) and glass fiber fraction (422.082 kg) were disposed of in the municipal waste management system in Japan and have yet to be further processed in the downstream material recycling. With the downstream process, except Tin, the material recovery rate is over 90% for most materials, with an average recycling rate of 93.37%. The latest report of ANZRP (2021) stated that the overall material recovery rate for e-waste is generally around 94%, which closely matches the process that has been taken into account for material recovery in this study.

It is acknowledged that although the actual metal purification process is done in the study by Pokhrel et al. (2020) in Taiwan, due to a lack of site-specific data on waste PCB downstream recycling process, the input and output data were taken into consideration for this study. Notably, it also needs to be mentioned that most of the e-waste in Japan is transferred to neighboring countries for processing, such as China and Singapore. ANZRP (2021) also mentioned that part of the waste PCB is transferred to Singapore after the first stage of recycling (mechanical recycling). Therefore, this study expands the system boundary to the downstream recycling process in Japan. The electricity consumption at the downstream processing is being considered with the low voltage electricity (e.g., 100 V), and follows the Ecoinvent database, including shipping of the waste PCB and inland transportation required in Australia to transfer waste PCB to the 1st stage processing to the seaport from where sea freight transport starts. The schematic diagram of Scenario 0 is presented in Fig. 1(A).

**Scenario 1:** Scenario 1 refers to Australia's waste PCB recycling process, which includes both 1st and downstream recycling processes excluding transportation-related material input. This is one of the first alternative scenarios in which, at a material recovery facility (MRF), both 1st stage, and 2nd stage recycling processes are being conducted in Australia, including the precious metal recovery process. The energy consumption, especially electricity consumption from the Australian context, has been considered, and related elementary flows were derived from the Ecoinvent database (i.e., with Australian medium voltage electricity). Thus, the main difference between this scenario from scenario 0 is the reduced transportation requirement and input energy consumption (e.g., electricity) from the Australian perspective. Fig. 1(B) shows the schematics of the scenario. The remaining portion of the material goes to local landfills. Here, the material recovery rate is the reference value from Pokhrel et al. (2020). The material recovery (metal and non-metal recovery) rate was 27.36%, considering 1000 kg PCB as an input in the mass balance approach. Ismail and Hanafiah (2021) also found a similar material recovery rate.

**Scenario 2:** In this scenario, in addition to the material recovery facilities, the process residue and the plastics-related portion (mainly resin and glass fiber) are sent to the incineration facility for energy recovery. The rest of the part goes to the landfill. At this moment, the incineration process is not currently being practiced in Australia; however, incineration is widely used as part of the waste disposal technique in many parts of the world, such as Sweden (Sahlin et al., 2007) and the Netherlands (Calisto Friant et al., 2022). Therefore, relevant incineration and municipal landfill processes were attributed to the Ecoinvent database. For modelling the incineration process, in SimaPro, the predefined process "Electricity, medium Voltage (Dias et al.) electricity, from municipal waste to generic market for" found in the Ecoinvent database was utilized with substantial modification. From the literature data, the output of incineration was set to 9.97 MJ/kg of e-waste for the incineration process. The input presented in Table 4 was given as input in the waste treatment process (here, incineration) window as part of the process modification. Electricity as input was required for the incineration process model, and in that case, Australian medium voltage electricity was utilized. Bottom ash, fly ash, and flue gas were assigned as process output with the stated values in Table 4. Fig. 1(C) shows the schematics of the scenario. In addition, the input and output of an incineration process described by Li et al. (2015) and cited by Ismail and Hanafiah (2021) have been considered. Table 4 shows the relevant data on the incineration process.

**Scenario 3:** In this scenario 100% of the waste PCB is being incinerated in a typical incineration plant for energy recovery in Australia and the potential energy recovery amount in this case is 20.3% as identified by Ismail and Hanafiah (2021). The remaining portion of the waste goes to landfills. The energy recovery depends on the heating value of waste PCB when incinerated. Similar to the study conducted by

**Table 2**
Approximation of shipping-related emission from Australia to Japan.

| Component | Kg/1 tons of waste PCB |
|---|---|
| Fuel consumption | 266.43 |
| Particulate matters | 0.52 |
| Hydrocarbons | 0.61 |

**Table 3**
Downstream material recycling (inputs and outputs utilized in the LCA modelling in SimaPro).

| Initial input in the mechanical processing (1st stage recycling) | Material (metal and non-metal) | Output from mechanical pre-processing (as an input to the downstream recycling) (in kg) | Required material/ energy | Final output (of the downstream recycling) | Downstream Material recycling rate (considering 1000 kg waste PCB, processed) |
|---|---|---|---|---|---|
| 1000 kg waste PCB | Copper (Cu) | 150.32 | (i) Electricity – 51.15 kWh, (ii) Chlorine – 25.05 l | (i) Copper power - 141.90 kg, (ii) Filtrate – 25.05 L, (iii) Process residue – 8.42 kg | 94.39% |
| | Tin (Sn) | 46.1 | (i) Electricity – 15.69 kWh, (ii) 1:4 = H2: N2 – 50 L | (i) Tin – 36.23 kg, (ii) H2: N2 – 50 L, (iii) Ash – 9.86 kg | 78.59% |
| | Iron (Fe) | 35.07 | (i) Electricity – 11.93 kWh | (i) Iron - 31.70 kg, (ii) Dust ash – 3.37 kg | 90.39% |
| | Lead (Pb) | 32.07 | (i) Electricity – 0.12 kWh, (ii) sodium carbonate – 10.69 L | (i) Lead - 31.75 kg, (ii) Filtrate – 10.69 L, (iii) Residue – 0.32 kg | 99% |
| | Nickel (Ni) | 24.05 | (i) Electricity – 0.09 kWh, (ii) Sodium carbonate – 8.02 L | (i) Nickel – 23.81 kg, (ii) Filtrate – 8.2 L, (iii) Residue – 0.24 kg | 99% |
| | Aluminium (Al) | 4.01 | (i) Electricity – 0.59 kWh | (i) Aluminium ingot – 3.62 kg, (ii) Dust ash – 0.39 kg | 90.27% |
| | Zinc (ZN) | 3.01 | (i) Electricity – 0.011 kWh, (ii) Chlorine ion - 0.50 L | (i) Zinc – 2.72 kg, (ii) Filtrate – 0.50 L, (iii) Residue – 0.29 kg | 90.37% |
| | Silver (Ag) | 1.59 | (i) Electricity – 0.006 kWh, (ii) Sodium carbonate – 0.53 L | (i) Silver ingot – 1.59 kg (ii) Filtrate – 0.53 L, (iii) Residue – 0.02 kg | 100% |
| | Gold (Au) | 0.31 | (i) Aqua regia – 1.55 L | (i) Gold power - 305 g, (ii) Filtrate – 1.55 L, (iii) Residue – 4.6 g | 98.38% |

Source: Pokhrel et al. (2020).

Ismail and Hanafiah (2021), the average value of 9.97 MJ/kg has been considered as recovered energy for the processing the waste percentage. This is shown schematically in Fig. 1(D)

**Scenario 4:** In this scenario, all waste PCB is sent to landfill (Fig. 1 (E)). This scenario is undesirable, however, to make this study a comprehensive one, essential understanding of the potential environmental impacts of waste PCB landfilling is needed. From the study conducted by Islam et al. (2020) (i.e., for the case of waste mobile phone - approximately, 10% of the consumers disposed of their old phones in the household garbage bins) and Islam et al. (2021) (i.e., similar percentage of the consumers mentioned earlier disposed of their e-waste the bins which is not generally recycled or separated search for e-waste for further recovery and that eventually goes to landfills) identified that among consumers, placing e-waste in the garbage bins is one of the typical disposal practices among Australians with the result that the waste ends up in landfill. As the Ecoinvent global landfill process lacks some data, some of the input data were collected from Apisitpuvakul et al. (2008), shown in Table 5. In this process, 100% of the waste PCB went to landfill. For the landfill process, Ecoinvent's "Municipal Solid waste {RoW} treatment of municipal solid waste landfill" unit process was modified using the data presented in Table 5, following the similar approach described for the incineration process. In all the scenarios, input to the processes was 1000 kg of waste PCB. The reason underpinning using the pre-existing processes of Ecoinvent is that there is no available data on the incineration and landfilling process, specifically focusing on e-waste. Therefore, a more quantitative, field-based experimental study is required for developing Australian-specific cases.

### 2.3. Life cycle impact assessment

Various lifecycle impact assessment methodologies were utilized, focusing on e-waste as a main waste stream. For example, Rasheed et al. (2022) used ReCiPe 2016 midpoint (H) method for undertaking an environmental impact assessment for the EOL disposal stages of laptop computers and LCD desktop computers in Pakistan. Boyden et al. (2016) utilized CML 2001 as an impact assessment methodology for LIBs in Australia. Ismail and Hanafiah (2021) utilized the ReCipe 2016 Endpoint (H) methodology for e-waste management alternatives for Malaysia. CML 2001 or the latest version of CML 2002 problem-oriented (or midpoint) approach as part of the impact assessment methodology. Lucio Compagno et al. (2014) performed LCA on the CRT lead recovery process using the IMPACT 2002+ impact assessment method. Yao et al. (2018) used Eco-indicator 99 assessment method for waste mobile phone management and recycling in China. Eco-indicator 99 is a damage-oriented (or endpoint) methodology for impact assessment, while IMPACT 2002+ and ReCiPe 2016 are some of the methodologies that generally combine both midpoint and endpoint approaches (Ismail and Hanafiah, 2021). This present study utilized the ReCipe 2016 Endpoint (H) methodology as it provides the latest and harmonized characterization factors generally representative on a global scale.

### 2.4. Interpretation

To interpret the results of the comparative LCA of various management scenarios, this research set out an interpretation strategy explaining the values obtained from the impact assessment results. Using the ReCipe 2016 impact assessment method, the data on results were converted to a 100% stacked bar chart in Microsoft Excel. The results showed both positive and negative percentages across various impact categories predefined under the ReCipe 2016 (endpoint) method. If any category goes along the positive side of the 100% stacked bar chart, it is called as a burden or negative impact of the process. In contrast, if any of the categories indicates the value in the negative direction (below the 0% line in the 100% stacked bar chart), that reflects the positive gain of a specific process or scenario. Above the 0%-line is a negative impact (creating a burden on the environment), and below is a positive impact (net gain from the process). In the end, the interpretation has been made by comparing scenarios modelled and identifying the best management option for the case of waste PCB in Australia (including the current management scenario of the overseas downstream recycling process). As per guideline of PRé Sustainability B.V. (2023b), the uncertainty analysis results have been described.

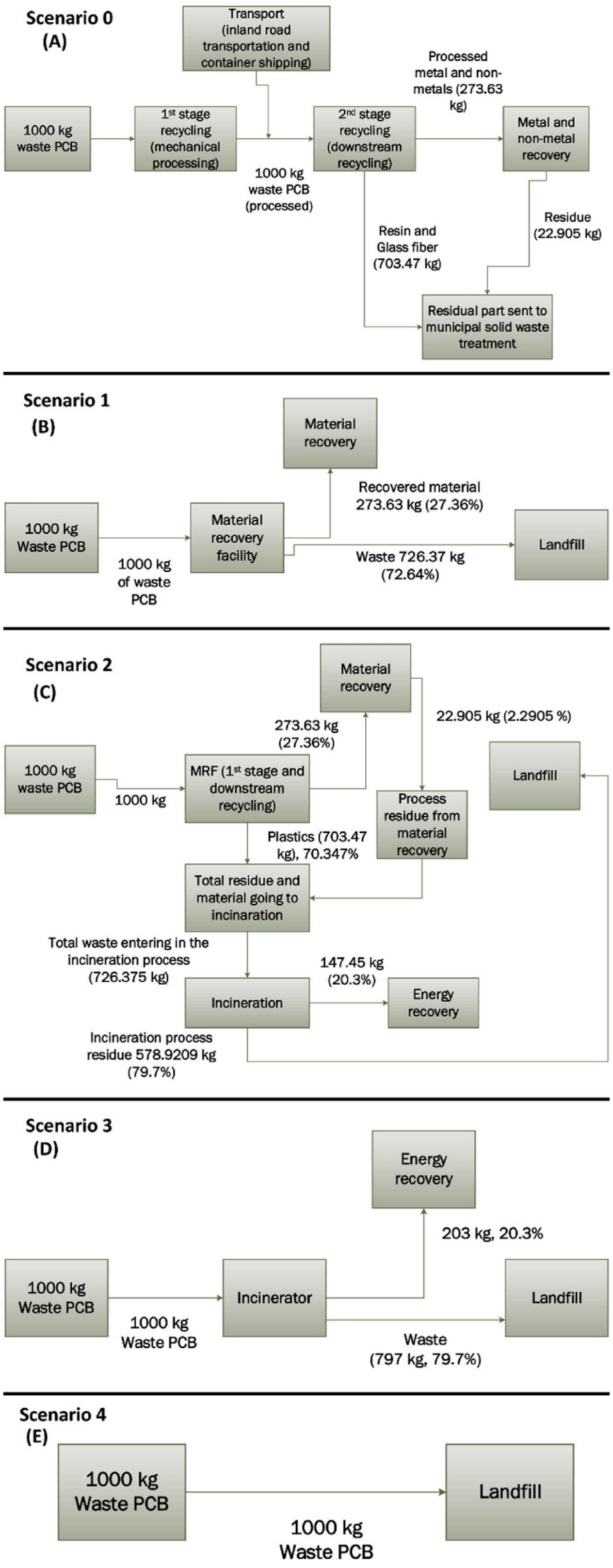

**Fig. 1.** E-waste management alternatives (A) Scenario 0: Overseas waste PCB processing (including first stage and downstream processing), (B) Scenario 1: material recovery without energy recovery, (C) Scenario 2: material recovery with energy recovery, (D) Scenario 3: Energy recovery without material recovery and (E) Scenario 4: Landfill of e-waste.

**Table 4**
Input-output data utilized designing incineration process, adapted from Ismail and Hanafiah (2021) and Li et al. (2015).

| Input | Unit | Value |
|---|---|---|
| Electricity | kWh/ton waste | 232 |
| Assistant fuel (considering diesel fuel) | kg/ton waste | 45 |
| Water | kg/ton waste | 455 |
| Calcium hydroxide (hydrated lime as the commercial name) | kg/ton waste | 50 |
| Activated carbon | kg/ton waste | 2.3 |
| **Output** | | |
| Bottom ash | kg/ton waste | 128 |
| Fly ash | kg/ton waste | 169 |
| Wastewater | kg/ton waste | 200 |
| Flue gas (in the form of dioxins) | kg/ton waste | 23,803 |

**Table 5**
Input required for a landfill process considering PCB waste, adapted from Apisitpuvakul et al. (2008).

| Input - Substance/material/energy | Unit | Value |
|---|---|---|
| Electricity | kWh/ton waste | 25.5 |
| Water | kg/ton waste | 1 |
| Sodium sulphide | kg/ton waste | 70 |
| Cement | kg/ton waste | 1000 |

## 3. Results and discussion

### *3.1. Comparative environmental impact assessment – local vs overseas recycling*

The overseas (Baseline: Scenario 0) showed negative environmental impact under global warming (human health), fine particulate matter formation, and fossil resource scarcity. This may be induced by the long sea container freight transport associated with the downstream material recycling of the waste PCB (from Australia to Japan). Only human non-carcinogen toxicity positively impacts the environment, which might mainly occur due to material recycling. In contrast with overseas recycling, when the materials are recycled in Australia (in the first stage and downstream recycling in Scenario 1), the global warming (human health) impact category was found to be reduced by 70.5%, while fine particulate formation had no negative impact instead had a positive impact. In comparison, fossil resource scarcity was reduced by almost 99%. In the other significant impact category, human non-carcinogenic toxicity, the positive impact increased by 6.9% when waste PCB was recycled in Australia instead of overseas recycling. Fig. 2 shows the comparative impact assessment of PCB waste's overseas and local recycling.

### *3.2. Comparative environmental impact assessment – local alternative scenarios*

While analyzing potential alternative scenarios considering the development of the local solutions/scenarios (as described earlier), it is found that material recovery, including energy recovery of the process waste and plastic parts of the waste PCB (scenario 2), is the best solution among the four scenarios (excluding the material recovery scenario in overseas). Under the category of fine particulate matter formation and human non-carcinogenic toxicity were the two dominant categories in which the processes involved in Scenario 2 significantly created a positive impact on the environment. Although, as previously described, the last category (human non-carcinogenic toxicity) also contributed to the positive side, however by adding the energy recovery option integrated into the overall waste PCB processing could create a much better positive impact on the environment. Global warming (human health) could be mitigated by around 76% if Scenario 2 could be considered instead of

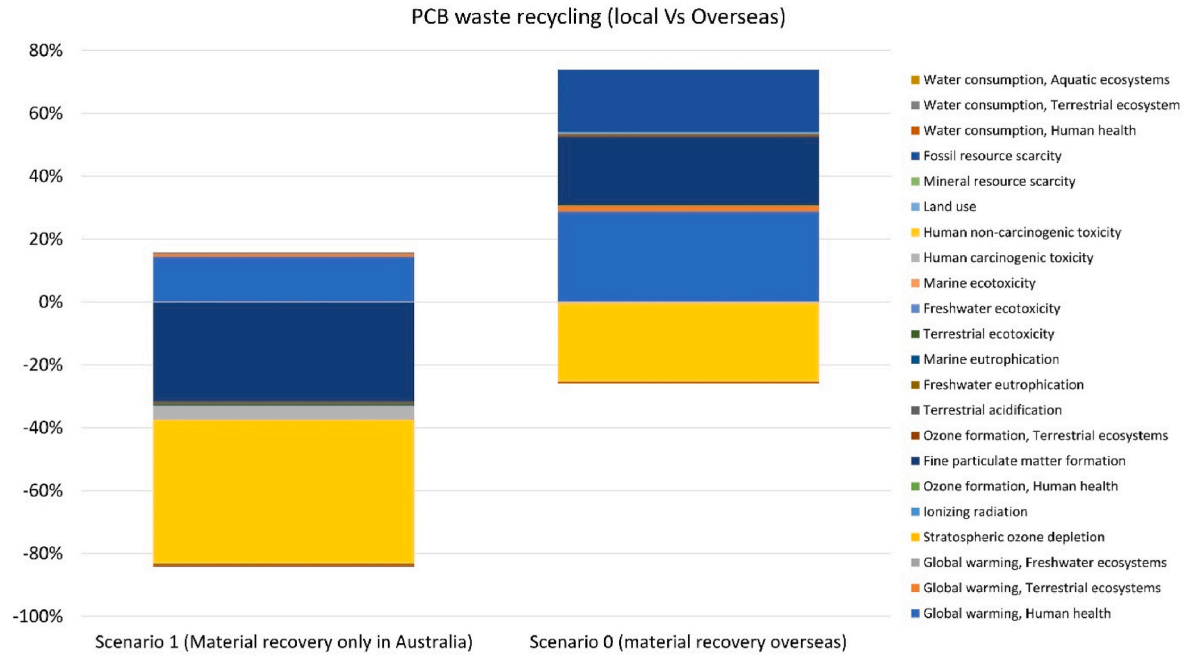

**Fig. 2.** Local vs overseas recycling of waste PCB.

Scenario 1. On the other hand, according to the results, direct incineration (scenario 3 – without material and energy recovery) and the landfill (scenario 4 – all waste goes to landfill) were identified as the two worst scenarios, which both showed potential burden on the environment. For incineration, global warming (human health), fine particulate matter formation, and human non-carcinogenic toxicity ranked first, second, and third impact, contributing to the burden, respectively. For landfill (scenario 4), the global warming (human health) impact category outweighs the occurrence in other scenarios. Human carcinogenic toxicity could be mitigated if material and energy recovery (scenario 2) were considered. Fig. 3 shows impact categories according to the possible scenarios that could be considered local disposal scenarios. To ensure visibility of the categories, different graphs with less categories are shown in the figure. There are in total 22 impact categories identified from the impact assessment.

Scenario 2 also contributes positively to many of the impact categories, which can be seen in Fig. 4. From this analysis, it can be concluded that material recovery with energy recovery is perceived to be the best solution for PCB waste recycling and management in Australia. Furthermore, compared to other scenarios, Scenario 2 showed the lowest proportion under the impact category of global warming (human health), global warming (terrestrial ecosystems), global warming (freshwater ecosystem), and marine eutrophication.

### 3.3. Uncertainty analysis

As it is seen that Scenario 1 and Scenario 2 could be two of the potential candidate solutions for waste PCB management and recycling in Australia (in terms of overall gain or positive impact), it is necessary to conduct an uncertainty analysis of these two scenarios, to ensure the robustness of the analysis. This was done with the uncertainty analysis tool embedded in SimaPro version 9.4.0.2. It is essential to include the uncertainty analysis since the energy recovery process might vary substantially depending on the type and portion of the waste that goes to the incinerator as well as the efficiency of the incinerator (i.e., the current approximation considered 20.3% of the PCB waste goes to the incinerator to recover the 9.97 MJ/kg of energy). Fig. 5 shows the result of the uncertainty analysis. The blue bars represent the number of times Scenario 2 (material recovery plus energy recovery) had a lower load than the life cycle with only material recovery (Scenario 1). For instance, it showed that in 100% of the cases, the global warming-related impact categories score is lower than Scenario 2 (material and energy recovery). Only under the category of fossil resource scarcity, marine eutrophication, and stratospheric ozone depletion impact categories, material recovery only (Scenario 1) represented a higher score than Scenario 2.

With this uncertainty analysis, Scenario 2 (material recovery and energy recovery in an integrated manner in Australia) is the best pathway for managing waste PCB from Australian e-waste. The result of the study matched with the research findings of Hischier et al. (2005) and, who found that material recovery with energy recovery was identified as the best option for managing e-waste in Switzerland.

### 3.4. Impact assessment of recovered materials

Under the material categories, it is found that copper recycling would be the most beneficial aspect of PCB recycling, and it contributed positively to almost all the impact categories (Fig. 6). Tin and gold recovery is also found to be crucial in this regard. The LCA-related research conducted by Ghodrat et al. (2017) showed that in several impact categories, when waste PCBs were processed through secondary copper smelting, that created higher (negative) environmental impact compared to a scenario when no other e-waste would be added in the secondary copper smelting works (as feedstock). This reflects that there should be a dedicated path for copper recycling which might create overall positive benefits in the processing. One potential solution could be considering all the metals and non-metals at once; copper should be separated after the mechanical processing and then fed into the secondary copper smelter. The other metals, such as nickel, zinc, and lead, could be processed in another smelter. This scenario should be focused on future studies from the lab-based experimental work and the LCA study to come up with a concrete decision on the processing route which would create a better environmentally sustainable secondary metal/mineral extraction process.

### 3.5. Policy implications

Local recycling infrastructure development in Australia for e-waste is a well-discussed issue found in the research of Islam and Huda (2019a)

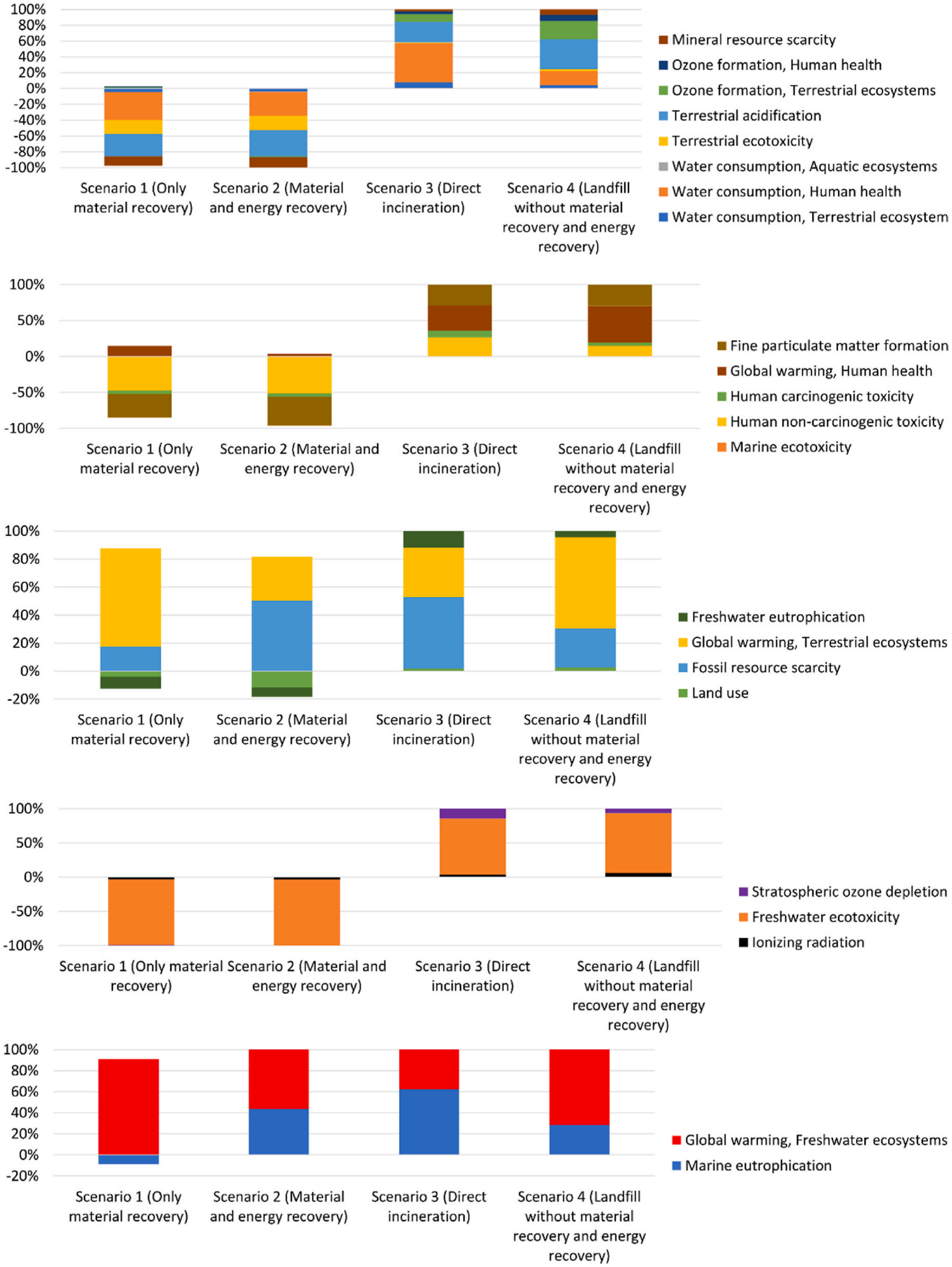

**Fig. 3.** Potential local solutions and their environmental impacts around PCB waste management.

and Golev et al. (2016). Minister's waste priority list by the Department of Climate Change, Energy and the Environment and Water showed that e-waste is one of the priority waste streams in Australia, which has been recognized only recently (DCCEEW, 2022b) and further processing steps are required for full material recovery facilities in Australia. From those aspects, this study contributed to the future decision-making process on selecting the path of material recovery with potential energy recovery for less environmental burden. This is the first systematic LCA of waste PCB developing a baseline scenario (i.e., considering the destination of most of the waste PCB) along with potential alternative scenarios focusing on waste PCB recycling in an overseas country and Australia. The landfill scenario conclusively indicates that a landfill ban should be

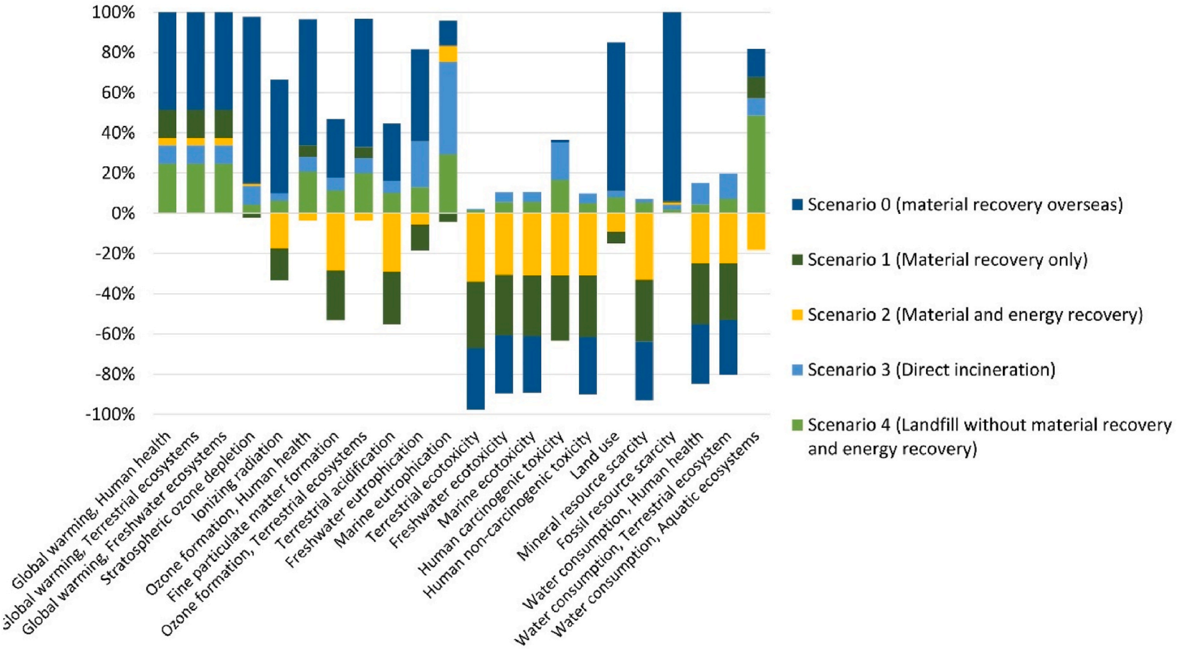

**Fig. 4.** Individual impact categories for all scenarios.

introduced across the jurisdiction in Australia. Currently, landfill of e-waste is banned only in Victoria, Australia (EPA Victoria, 2020).

To bring the CE principle and sustainability into practice, LCA has already been identified as a critical tool (Dahiya et al., 2020). MFA is also a strategic tool used by many organizations in their operational activities, such as SWICO and SENS in Switzerland (Islam and Huda, 2019b; Wäger, P.A. et al., 2011), which also brings the focus of the accurate collection of data and information on waste handling. In this study, in several aspects, for example, the port of departure for transboundary movement of waste for recycling and the type of technology used in material recovery, is assumed and/or estimated due to lack of data. Nevertheless, this study provides a quantitative assessment of the environmental impact of the waste PCB recycling process from a reverse supply chain perspective, which could be understood if field-level data could be found. In this way, a holistic perspective of the closed-loop recycling process could be achieved within the context of CE underpinning the principles and recycling strategy. Australia is a resource-rich nation with a large metal stock of critical minerals and base metals (Islam and Huda, 2019a). However, research has shown that urban mining (i.e., recovering valuable metals from the e-waste streams, such as copper and gold) has a competitive advantage over virgin mining (Zeng et al., 2018), which is one of the significant economic activities in the country. With the implementation of principle number one of CE (i.e., eliminate waste and pollution), the waste materials can be converted to secondary raw material stock that could substantially divert waste from landfills and reduce the volume of waste. It could also substantially reduce the environmental impacts that occur during virgin mining. Due to the current technological advancement and manufacturing process of PCB design, mature technology such as hydrometallurgy and pyrometallurgical process and, to some extent, the microbiological process should be implemented, which would align the principle number two (i.e., use product and material for longer at their highest value). From the "closing resource loop" (Bocken and Ritala, 2021) and "material ownership" (Velis and Vrancken, 2015) and "decarbonization" (Murthy and Ramakrishna, 2022) perspectives, the secondary materials encased in waste PCB should be processed within Australia combining material and energy recovery, and this LCA study provided that scientific evidence.

Future policies and regulations should focus on data transparency and availability across the value chain, local infrastructure development, and resource circularity. Australia has taken an ambitious target on advanced manufacturing (i.e., international investment reached AUD 117 billion) (Australian Government, 2023) which should include a mandate of using secondary material resources available from local e-waste streams, specifically, waste PCB. Japanese example of creating medals from metal extracted from recycled consumer electronics (International Olympic Committee, 2021) could be an excellent inspiration for Australian policymakers following a similar path for the 2032 Summer Olympics, which will be held in Brisbane, Australia (International Olympic Committee, 2023). This could be a practical example of closing the resource loop within Australia and a practical implementation of CE principles. Technology transfer from Singapore and Japan could be advantageous as these countries currently process Australian waste PCBs (ANZRP, 2021). The recycling modernization fund proposed by the Australian Federal Government (DCCEEW, 2022a) could target waste PCB processing and the e-waste sector to achieve CE. Currently, only glass, plastic, tires, paper, and cardboard are the waste streams targeted for the fund (DCCEEW, 2022a).

### 3.6. Limitations and future research

The study has limitations in terms of data as much of the data is collected from literature, especially in the material purification process. Furthermore, the reverse supply chain (PCB waste transport to overseas) was modelled for Scenario 0 is based on the understanding of the various reports and academic publication which could be far more complicated in real-world scenario. Future researchers are suggested to conduct field-level data collection for the modelling and future analysis. Direct waste analysis at the first stage recycling process identifying the material content of various waste PCB and downstream recycling would be essential to make final planning decisions. On the other hand, as energy recovery is found as an essential part of the overall process, and among the metals, copper is found to be the critical metal in the material recovery process, an integrated material recovery with energy recovery at a copper smelting facility should be designed to further identify the full potential both in terms of investment decisions as well as an environmental hotspot of material processing stages.

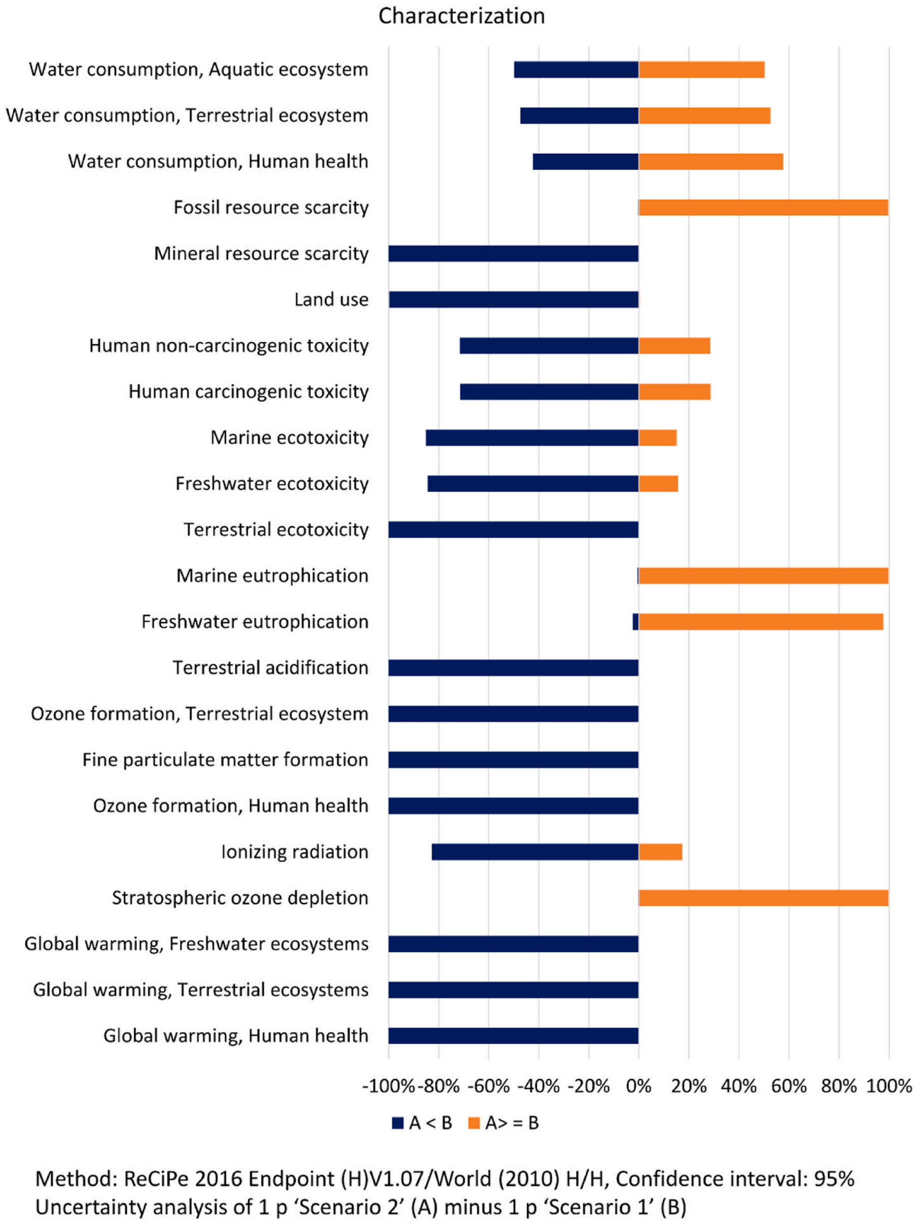

**Fig. 5.** Uncertainty analysis of Scenario 1 and scenario 2.

## 4. Conclusion

E-waste contains high values and environmentally harmful metals, creating opportunities for material recovery with an appropriate path. By conducting a comparative lifecycle assessment, this study concluded that instead of overseas recycling of waste PCB for downstream metal recovery, local material recycling integrated with energy recovery in an incineration plant would be the best option for Australia for this emerging waste stream.

Global warming (human health), particulate formation, and fossil resource scarcity were identified as the three main impact categories responsible for the overseas downstream recycling process (i.e., baseline scenario, scenario 0 – overseas recycling). The result of the study also showed that when waste PCB is recycled in Australia, the global warming (human health) impact category would be reduced by 70.5%. In comparison, fossil resource scarcity is reduced by 99%, which should be considered a significant and critical improvement opportunity in decarbonizing the reverse supply chain and overall material recovery process. The preliminary assessment made by this study, conducting LCA, supports local recycling over the overseas recycling process. For scenario 2 (integrated material and energy recovery), the less environmental burden was observed for global warming and marine eutrophication impact categories. When this scenario is considered, it was found that global warming (human health) could be reduced by around 76% when compared to only the material recovery process. Cu, Tin, and gold were identified as the three primary valuable materials in the waste PCB with tremendous potential, which should be considered for future local recycling infrastructure (i.e., particularly secondary smelter development).

In contrast, incineration and landfilling were found to be the worst two scenarios that could contribute to adverse environmental impact in some categories, such as human non-carcinogenic toxicity and global warming (human health), respectively, which can be mitigated by integrating material and energy recovery that indicated better environmental performance then material recovery only. One of the significant constraints of the study was to model the energy recovery process (via incineration). Unfortunately, no real-world data is available, considering Australia's context and the incineration process's technical

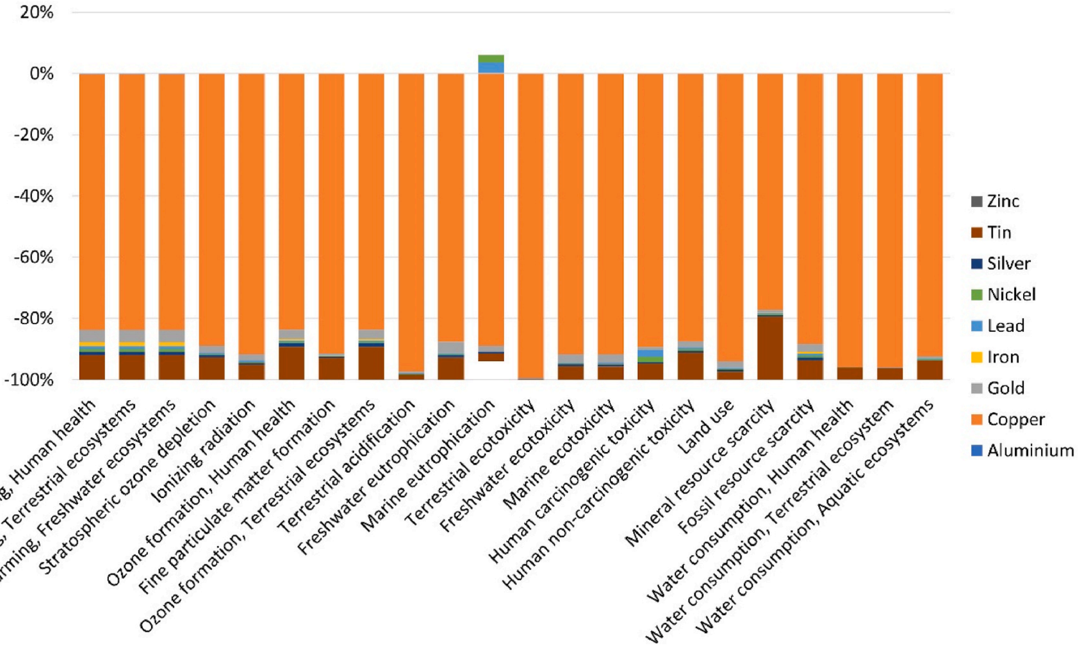

**Fig. 6.** Environmental impacts of recovered metals from waste PCB.

specifics. Similar aspects were evident in the landfilling process. To understand the environmental impact and economic gain, the process modeling should be based on field-level and laboratory experimental-based data which require further investigation. Future researchers should capitalize on such opportunities.

From a methodological standpoint, to conduct an LCA, a mass balance approach must be followed to define the allocation of process routes and/or flow of materials, which was done in this study. However, when it comes to MFA, other than a complementary data gathering and allocation exercise, future researchers should focus on developing a standalone MFA model identifying product flow and, subsequently, substance flow at the material level of a material recovery process by direct waste data analysis at collection points and/or at recycling facilities. It would provide greater clarity and a holistic understanding of the overall system-level material recovery process's positive environmental and economic impact.

Circular economy emphasizes the elimination of waste and pollution, material, and resource use at their highest value for an extended period, following various strategies, and recycling is one of them. LCA has become a critical assessment tool to assess the environmental impacts of any given process. Reverse supply chain and closed-loop material recycling are the key components of the circular economy that bring recovered materials into a production process that signifies implementing the circular economy principles. Thus, LCA application in CE-related aspects has long-term implications, which to some extent investigated by this present study to focus on waste PCB recycling, as it contains valuable secondary raw materials. This study quantitatively assessed impacts and proposed management alternatives from the Australian context using LCA. To realize CE potential even stronger, data availability and transparency for accurate modeling using LCA could provide better decision-making opportunities using secondary raw material from the waste PCB recycling within the Australian context.

This study would be very critical in planning future recycling infrastructure development around e-waste especially waste PCB recycling which is currently being processed overseas. It would also benefit from undertaking associated costings to ensure the policy platform provides realistic options for the community in Australia.

## CRediT authorship contribution statement

**Md Tasbirul Islam:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. **Usha Iyer-Raniga:** Validation, Writing – review & editing, Supervision, Visualization, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## References

Alamerew, Y.A., Brissaud, D., 2020. Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: a case study on electric vehicle batteries. J. Clean. Prod. 254, 120025.

ANZRP, 2021. Annual report 2020/2021. https://www.anzrp.com.au/wp/wp-content/uploads/ANZRP_Annual-Report-2020-2021_DOUBLE-SPREAD.pdf. (Accessed 28 February 2022). Available at:

Apisitpuvakul, W., Piumsomboon, P., Watts, D.J., Koetsinchai, W., 2008. LCA of spent fluorescent lamps in Thailand at various rates of recycling. J. Clean. Prod. 16 (10), 1046–1061.

Australian Government, 2023. Advanced manufacturing. https://www.globalaustralia.gov.au/industries/advanced-manufacturing. (Accessed 20 June 2023). Available at:

Biganzoli, L., Falbo, A., Forte, F., Grosso, M., Rigamonti, L., 2015. Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy). Sci. Total Environ. 524–525, 361–375.

Biswas, W.K., Duong, V., Frey, P., Islam, M.N., 2013. A comparison of repaired, remanufactured and new compressors used in Western Australian small- and medium-sized enterprises in terms of global warming. J. Remanuf. 3 (1), 4.

Bocken, N., Ritala, P., 2021. Six ways to build circular business models. J. Bus. Strat. 43 (3), 184–192.

Boyden, A., Soo, V.K., Doolan, M., 2016. The environmental impacts of recycling portable lithium-ion batteries. Proc. Cirp 48, 188–193.

Calisto Friant, M., Lakerveld, D., Vermeulen, W.J., Salomone, R., 2022. Transition to a sustainable circular plastics economy in The Netherlands: discourse and policy analysis. Sustainability 14 (1), 190.

Compagno, Lucio, Ingrao, Carlo, Antonio Giuseppe Latora, N.T., 2014. Life cycle assessment of CRT lead recovery process. Int. J. Prod. Lifecycle Manag. 7 (2–3), 201–214.

Dahiya, S., Katakojwala, R., Ramakrishna, S., Mohan, S.V., 2020. Biobased products and life cycle assessment in the context of circular economy and sustainability. Mater. Circ. Econ. 2, 1–28.

DCCEEW, 2021. National television and computer recycling scheme. https://www.dcceew.gov.au/environment/protection/waste/product-stewardship/products-schemes/television-computer-recycling-scheme. (Accessed 7 March 2023). Available at:

DCCEEW, 2022a. Investing in Australia's waste and recycling infrastructure. https://www.dcceew.gov.au/environment/protection/waste/how-we-manage-waste/recycling-modernisation-fund. (Accessed 20 June 2023). Available at:

DCCEEW, 2022b. Minister's priority list 2021-22. https://www.dcceew.gov.au/environment/protection/waste/product-stewardship/ministers-priority-list/2021-22#:~:text=New%20to%20the%20Minister's%20Priority,well%20as%20plastic%20oil%20containers. (Accessed 7 March 2023). Available at:

Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian e-waste recycling scheme. J. Clean. Prod. 197, 750–764.

Dias, P., Bernardes, A.M., Huda, N., 2019. Ensuring best E-waste recycling practices in developed countries: an Australian example. J. Clean. Prod. 209, 846–854.

DOWA, 2014. Environmental management & recycling. https://www.dowa.co.jp/en/about_dowa/group/ecosystem.html. (Accessed 19 June 2023). Available at:

DOWA Eco-system, 2023. Group company. https://www.dowa-eco.co.jp/en/group/. (Accessed 19 June 2023). Available at:

Ellen MacArthur Foundation, 2023a. The butterfly diagram: visualising the circular economy. https://ellenmacarthurfoundation.org/circular-economy-diagram. (Accessed 18 June 2023). Available at:

Ellen MacArthur Foundation, 2023b. What is a circular economy? https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview. (Accessed 18 June 2023). Available at:

EPA Victoria, 2020. Managing electronic waste. https://www.epa.vic.gov.au/for-business/find-a-topic/manage-e-waste#:~:text=It's%20illegal%20for%20e%2Dwaste,human%20health%20and%20the%20environment. (Accessed 7 March 2023). Available at:

Europe, Ecommerce, 2020. Extended producer responsibility policies that work for SMEs in Europe. https://ecommerce-europe.eu/press-item/extended-producer-responsibility-policies-that-work-for-smes-in-europe/. (Accessed 7 March 2023). Available at:

Europe of Cities, 2021. The must-know facts about E-waste recycling in Europe. Available at: https://www.europeofcities.com/blog/need-to-know-facts-about-e-waste-recycling-europe#:~:text=E%2Dwaste%2C%20according%20to%20a,move%20towards%20a%20circular%20economy, 07 March 2023.

European Commission, 2020. Circular economy action plan. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en. (Accessed 18 June 2023). Available at:

European Environment Agency, 1997. Life Cycle Assessment: a guide to approaches, experiences and information sources. https://www.eea.europa.eu/publications/GH-07-97-595-EN-C/Issue-report-No-6.pdf. (Accessed 7 March 2023). Available at:

European Parliament, 2022. E-waste in the EU: facts and figures (infographic). https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93325/e-waste-in-the-eu-facts-and-figures-infographic. (Accessed 7 March 2023). Available at:

Fiore, S., Ibanescu, D., Teodosiu, C., Ronco, A., 2019. Improving waste electric and electronic equipment management at full-scale by using material flow analysis and life cycle assessment. Sci. Total Environ. 659, 928–939.

Forti, V., Balde, C.P., Kuehr, R., Bel, G., 2020. The Global E-Waste Monitor 2020: Quantities, Flows and the Circular Economy Potential.

Ghodrat, M., Rhamdhani, M.A., Brooks, G., Rashidi, M., Samali, B., 2017. A thermodynamic-based life cycle assessment of precious metal recycling out of waste printed circuit board through secondary copper smelting. Environ. Dev. 24, 36–49.

Golev, A., Schmeda-Lopez, D.R., Smart, S.K., Corder, G.D., McFarland, E.W., 2016. Where next on e-waste in Australia? Waste Manag. 58, 348–358.

Hischier, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective?: the environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25 (5), 525–539.

Iannicelli-Zubiani, E.M., Giani, M.I., Recanati, F., Dotelli, G., Puricelli, S., Cristiani, C., 2017. Environmental impacts of a hydrometallurgical process for electronic waste treatment: a life cycle assessment case study. J. Clean. Prod. 140, 1204–1216.

International Olympic Committee, 2021. Designs of Tokyo 2020's recycled medals unveiled. https://olympics.com/en/news/designs-of-tokyo-2020-s-recycled-medals-unveiled. Available at:

International Olympic Committee, 2023. Brisbane 2032 Olympic and paralympic games host - Queensland. https://olympics.com/en/olympic-games/brisbane-2032. Available at:

Islam, M.T., Huda, N., 2019a. E-waste in Australia: generation estimation and untapped material recovery and revenue potential. J. Clean. Prod. 237, 117787.

Islam, M.T., Huda, N., 2019b. Material flow analysis (MFA) as a strategic tool in E-waste management: applications, trends and future directions. J. Environ. Manag. 244, 344–361.

Islam, M.T., Huda, N., 2020. Assessing the recycling potential of "unregulated" e-waste in Australia. Resour. Conserv. Recycl. 152, 104526.

Islam, M.T., Dias, P., Huda, N., 2020. Waste mobile phones: a survey and analysis of the awareness, consumption and disposal behavior of consumers in Australia. J. Environ. Manag. 275, 111111.

Islam, M.T., Dias, P., Huda, N., 2021. Young consumers' e-waste awareness, consumption, disposal, and recycling behavior: a case study of university students in Sydney, Australia. J. Clean. Prod. 282, 124490.

Ismail, H., Hanafiah, M.M., 2019. An overview of LCA application in WEEE management: current practices, progress and challenges. J. Clean. Prod. 232, 79–93.

Ismail, H., Hanafiah, M.M., 2021. Evaluation of e-waste management systems in Malaysia using life cycle assessment and material flow analysis. J. Clean. Prod. 308, 127358.

Li, W., Huang, Q., Lu, S., Wu, H., Li, X., Yan, J., 2015. Life cycle assessment of the environmental impacts of typical industrial hazardous waste incineration in Eastern China. Aerosol Air Qual. Res. 15 (1), 242–251.

Liu, K., Tan, Q., Yu, J., Wang, M., 2023. A global perspective on e-waste recycling. Circ. Econ., 100028

Mairizal, A.Q., Sembada, A.Y., Tse, K.M., Haque, N., Rhamdhani, M.A., 2023. Carbon footprint assessment of waste PCB recycling through black copper smelting in Australia. In: Alam, S., Guillen, D.P., Tesfaye, F., Zhang, L., Hockaday, S.A.C., Neelameggham, N.R., Peng, H., Haque, N., Liu, Y. (Eds.), Energy Technology 2023. Springer Nature Switzerland, Cham, pp. 107–118.

Murthy, V., Ramakrishna, S., 2022. A review on global e-waste management: urban mining towards a sustainable future and circular economy. Sustainability 14 (2), 647.

Pokhrel, P., Lin, S.-L., Tsai, C.-T., 2020. Environmental and economic performance analysis of recycling waste printed circuit boards using life cycle assessment. J. Environ. Manag. 276, 111276.

Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain, vol. 2544. Planbureau voor de Leefomgeving.

PRé Sustainability, B.V., 2023a. SimaPro tutorial. https://simapro.com/wp-content/uploads/2023/05/SimaPro-Tutorial.pdf. (Accessed 19 June 2023). Available at:

PRé Sustainability, B.V., 2023b. SimaPro tutorial. https://support.simapro.com/s/article/SimaPro-Tutorial. (Accessed 7 March 2023). Available at:

Rasheed, R., Rizwan, A., Javed, H., Sharif, F., Yasar, A., Tabinda, A.B., Mahfooz, Y., Ahmed, S.R., Su, Y., 2022. Analysis of environmental sustainability of e-waste in developing countries—a case study from Pakistan. Environ. Sci. Pollut. Control Ser. 29 (24), 36721–36739.

Rocchetti, L., Vegliò, F., Kopacek, B., Beolchini, F., 2013. Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. Environ. Sci. Technol. 47 (3), 1581–1588.

Sahajwalla, V., Hossain, R., 2023. Rethinking circular economy for electronics, energy storage, and solar photovoltaics with long product life cycles. MRS Bull. 1–11.

Sahlin, J., Ekvall, T., Bisaillon, M., Sundberg, J., 2007. Introduction of a waste incineration tax: effects on the Swedish waste flows. Resour. Conserv. Recycl. 51 (4), 827–846.

Soo, V.K., Doolan, M., 2014. Recycling mobile phone impact on life cycle assessment. Proc. cirp 15, 263–271.

Streicher-Porte, M., Marthaler, C., Böni, H., Schluep, M., Camacho, Á., Hilty, L.M., 2009. One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia. J. Environ. Manag. 90 (11), 3498–3511.

United Nations Institute for Training and Research (UNITAR), 2021. Regional ewaste monitor CIS + Georgia. https://ewastemonitor.info/wp-content/uploads/2021/11/REM_2021_CISGEORGIA_WEB_final_nov_11_spreads.pdf. (Accessed 18 June 2023). Available at:

United Nations Institute for Training and Research (UNITAR), 2022. REGIONAL E-WASTE MONITOR for Latin-America. https://ewastemonitor.info/wp-content/uploads/2022/01/REM_LATAM_2022_ENG_Final.pdf. (Accessed 18 June 2023) results for the 13 countries participating in project UNIDO-GEF 5554. Available at:

United Nations Institute for Training and Research (UNITAR), 2023. UNEP-UNITAR 2050 electronic and electrical waste outlook in West Asia. https://ewastemonitor.info/wp-content/uploads/2023/03/UNEP-UNITAR-2050-Electronic-and-Electrical-Waste-Outlook-in-West-Asia.pdf. (Accessed 18 June 2023). Available at:

Van Yken, J., Boxall, N.J., Cheng, K.Y., Nikoloski, A.N., Moheimani, N.R., Kaksonen, A.H., 2021. E-waste recycling and resource recovery: a review on technologies, barriers and enablers with a focus on oceania. Metals 11 (8), 1313.

Velis, C.A., Vrancken, K.C., 2015. Which Material Ownership and Responsibility in a Circular Economy? SAGE Publications Sage UK, London, England, pp. 773–774.

Wäger, P., Hischier, R., Eugster, M., 2011. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): a follow-up. Sci. Total Environ. 409 (10), 1746–1756.

Wäger, P.A., Hischier, R., Eugster, M., 2011. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): a follow-up. Sci. Total Environ. 409 (10), 1746–1756.

Withanage, S.V., Habib, K., 2021. Life cycle assessment and material flow analysis: two under-utilized tools for informing E-waste management. Sustainability 13 (14), 7939.

Xiao, R., Zhang, Y., Yuan, Z., 2016. Environmental impacts of reclamation and recycling processes of refrigerators using life cycle assessment (LCA) methods. J. Clean. Prod. 131, 52–59.

Yao, L., Liu, T., Chen, X., Mahdi, M., Ni, J., 2018. An integrated method of life-cycle assessment and system dynamics for waste mobile phone management and recycling in China. J. Clean. Prod. 187, 852–862.

Zeng, X., Mathews, J.A., Li, J., 2018. Urban mining of e-waste is becoming more cost-effective than virgin mining. Environ. Sci. Technol. 52 (8), 4835–4841.