






Chapter 24

Transforming E-Waste into Value: A Circular Economy Approach to PCB Recycling



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Abstract This study delves into the pressing global issue of electronic waste (e-waste), with a specific emphasis on printed circuit boards (PCBs). PCBs, being a crucial component of electronic devices, contribute significantly to e-waste due to their intricate composition of hazardous substances and valuable metals such as gold, silver, and copper. The research explores the concept of the circular economy—an economic system aimed at eliminating waste through the continual use of resources—and its potential application in recycling PCBs. This involves a detailed investigation of the challenges and opportunities associated with various extraction methods and waste management strategies. The study also presents a case study on The Royal Mint’s innovative approach to gold extraction from PCBs. This practical example offers valuable insights into the application of circular economy principles in the context of PCB recycling, demonstrating how these principles can lead to improved resource efficiency, waste reduction, and economic benefits. The findings of this research underscore the need for further development and implementation of sustainable practices in e-waste management to mitigate environmental impact and capitalise on the economic potential of valuable materials in e-waste.

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24.1 Introduction

Swift technological advancement and escalating consumer demand for electronic devices have resulted in a significant surge in e-waste generation [1]. This problem is further magnified by the absence of efficient waste management strategies, thereby leading to environmental and health hazards [2].

The global electronic waste problem has become a significant concern, driven by the rapid growth in electronic devices and their limited lifespans. The rise in modern lifestyles, technological advancements, and global economic progress has led to a significant increase in e-waste, which is causing serious environmental and health problems. Around two billion metric tonnes of waste are generated worldwide each year, with e-waste accounting for 53.6 million tonnes. The amount of global e-waste has been rapidly increasing, reaching 53.6 million tonnes in 2019, a 21% increase since 2015. Unfortunately, most of this e-waste (about 83%) is not properly documented and is likely burned or dumped illegally, posing a threat to both people and the environment. Only 17% of the e-waste produced in 2019 was collected and recycled correctly. In terms of continents, Asia produces the highest amount of e-waste (46.4% globally) in 2019, followed by America, Europe, Africa, and Oceania. However, when we consider the amount of e-waste per person, Asia produces less waste per person compared to Europe, Oceania, and the Americas due to its large population. Africa has the lowest e-waste generation per person [3]. According to the Global-E-waste-Monitor 2020 report by the United Nations University (UNU), United Nations Institute for Training and Research (UNITAR), and International Solid Waste Association (ISWA), 53.6 million metric tonnes (Mt) of e-waste were generated globally in 2019, marking an increase of 9.2 Mt from the previous five years. Disconcertingly, only 17.4% of e-waste was officially collected and recycled [4]. E-waste is highly heterogeneous in nature, composed of various systems housing a diverse range of metals, polymers, and ceramics, thereby being considered as potential secondary resources [4].

PCBs are a key component of electronic waste owing to their universal usage in electronic devices. PCBs have a complex composition, incorporating hazardous substances along with valuable metals such as gold, silver, and copper. The presence of these precious metals has sparked interest in the development of new recycling technologies [5]. However, traditional methods for gold extraction face several challenges, including inefficiency, resource exhaustion, and environmental pollution. Besides, complex and heterogeneous structures of PCBs, including different metals, polymers, and ceramics, pose technical and environmental challenges [6].

E-waste management and recycling are attracting considerable attention due to the presence of precious, critical, or strategic metals combined with the associated environmental burden of metal recovery from natural mines [4]. The direct disposal of e-waste into the environment triggers environmental and human health risks. Improper e-waste recycling practices in developing countries have resulted in the generation of toxic gases such as dioxin and furan (polychlorinated dibenzo-p-dioxins and dibenzofurans), posing environmental and human health risks [7]. The release of acids,

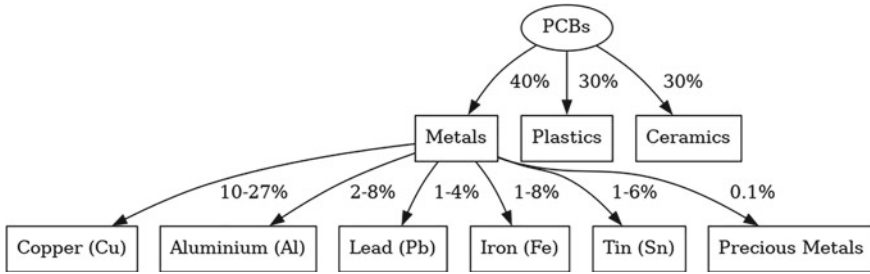


Fig. 24.1 Composition of PCBs. The diagram illustrates the average composition of PCBs, including the breakdown of the metal fraction. Data sourced from [9]

heavy metals, lethal chemicals, and compounds from e-waste can have adverse effects (direct or indirect) on the entire biosphere [7]. Sustainable solutions and the principles of a circular economy present a promising approach for managing PCB waste and extracting gold. The circular economy advocates for the reutilisation of beneficial materials to prevent pollution and manage secondary materials. This strategy can facilitate the achievement of social, economic, and environmental benefits [8].

PCBs represent some of the most valuable elements within waste electrical and electronic equipment (WEEE), making their recovery both economically and strategically advantageous. However, the composition of PCBs can considerably vary based on their place of origin, year of manufacture, and the appliance they were employed in. As illustrated in Fig. 24.1, the composition of PCBs consists of 40% metals, 30% polymers, and 30% ceramics, with the metal fraction further broken down into various elements [9].

The primary aim of this paper is to analyse the prospective application of circular economy practices in recycling PCBs. The circular economy is a model that promotes the efficient use of resources, minimises waste, and encourages the recycling or reuse of materials. In the context of PCBs, this involves investigating strategies for the recovery and reuse of valuable metals such as gold, silver, and copper, as well as the safe disposal or repurposing of hazardous substances.

The paper endeavours to offer a comprehensive overview of the current state of PCB recycling, including the challenges and opportunities tied to various extraction methods and waste management strategies. It further seeks to underscore the economic, environmental, and social implications of these practices, specifically focusing on the role of gold extraction in fostering economic sustainability and lessening environmental impact. In addition to scrutinising existing literature and research on the subject, the paper will incorporate a case study on The Royal Mint’s usage of PCBs for gold extraction. This case study will provide a practical illustration of how circular economy principles can be applied in the context of PCB recycling, offering valuable insights into the benefits, challenges, and potential implications of this approach.

24.2 Methodology

Our methodology began with a comprehensive literature review to understand the composition of PCBs and the challenges associated with their disposal. We examined previous studies and reports to gain insights into the hazardous substances and valuable metals contained in PCBs. We then conducted an in-depth analysis of various gold extraction techniques from PCBs. Each method was evaluated based on its efficiency, environmental impact, and feasibility for large-scale implementation. Subsequently, we explored the concept of a circular economy and its relevance to PCB waste management. We studied how circular economy practices such as recycling, refurbishing, remanufacturing, and material recovery could be applied to mitigate e-waste and foster a circular economy. The implementation of the 3Rs principle (reduce, reuse, recycle) in e-waste management was also discussed.

Finally, our methodology incorporated a case study analysis of The Royal Mint's initiative to recover precious metals from electronic waste. We analysed their partnership with the Canadian clean tech start-up Excir and the patented technology they use to recover over 99% of gold from discarded electronic devices. This case study provided a practical example of applying circular economy principles in the context of PCB recycling. This systematic approach allowed us to gain a comprehensive understanding of the challenges and opportunities associated with PCB recycling and to explore innovative solutions for e-waste management.

24.3 Background

24.3.1 PCBs and Gold Extraction

PCBs are integral to electronic devices, significantly influencing their functionality. Comprising multiple layers of glass fibre and copper, these are safeguarded against oxidation by a solder mask. This mask, however, impedes the exposure of metals to lixivants in waste PCB recycling processes [10].

The extraction of precious metals from PCBs involves a key step known as PCB milling. This process commences with the manual breakdown of PCBs, which are then shredded and undergo hammer milling. The milling time and feed mass ranges are controlled to optimise the release of the desired metals. Post-extraction, the remaining PCB material is handled based on its behaviour during milling and the distribution and liberation of each component. This understanding is crucial for optimising subsequent processing stages [6].

The management of PCB waste is a complex issue due to the diverse and intricate materials involved. Current strategies primarily focus on the recovery of valuable metals, with only a minor portion of the materials being recycled. However, advancements in technology and methodologies are paving the way for improved recycling processes and recovery of valuable metals. From an environmental perspective, these

advancements can contribute to reducing the volume of waste in landfills. Economically, the recovery of precious metals can generate revenue. Socially, sustainable PCB waste management practices can stimulate the creation of green jobs and promote corporate social responsibility [11].

Recycling processes for PCBs can be broadly segregated into thermal and non-thermal procedures. Non-thermal processes, encompassing methods like electro/hydrometallurgical processes, are accompanied by specific operational challenges and environmental concerns. Health risks arise for milling operators due to potential inhalation of fibreglass particles and heavy metals. The milling process also results in a strong, unpleasant odour generated by phenolic resin. These methods necessitate significant investment in wastewater treatment apparatus. Environmental impacts include high water usage, wastewater generation with acidic residues, noise pollution from grinding machinery, and the generation of solid waste. Conversely, thermal processes or pyrometallurgical recovery present different challenges and environmental issues. Non-metallic materials cannot be recovered through these procedures, and there is a considerable upfront cost in equipment and installation, including air pollution control systems. Moreover, the economic efficiency of these processes for low-grade waste is yet to be substantiated. The major environmental impacts of thermal processes include the production of gaseous pollutants, notably dioxins, and lead fumes. Notably, in the metal recovery system, multiple processes might be utilised in tandem, such as milling, which is commonplace in most systems for metal recovery from discarded PCBs [12].

Gold extraction from PCBs presents an economic and environmental concern of considerable magnitude. Conventional gold extraction methods encompass chemical leaching and smelting. Chemical leaching utilises chemicals to dissolve the gold, facilitating its separation from the remaining material. In contrast, smelting involves subjecting the material to high temperatures to extract the gold. Nevertheless, these traditional methods present several restrictions and challenges. For instance, they often yield low recovery rates, resulting in substantial amounts of unextracted gold. Their environmental impact is also high due to the employment of hazardous chemicals and the emission of harmful by-products. Additionally, these methods are energy-demanding, leading to considerable energy consumption [13]. In response to these challenges, alternative gold extraction techniques have been developed. These comprise hydrometallurgical processes, bioleaching, and electrochemical methods. Hydrometallurgical processes entail the use of aqueous solutions for metal extraction, while bioleaching employs bacteria to dissolve metals [10]. This environmentally friendly method has the potential for high recovery rates. Nonetheless, bioleaching is primarily in the experimental phase and has not seen widespread adoption in the industry [14].

24.3.2 *The Circular Economy and PCBs*

The concept of a circular economy (CE) is a sustainable economic development model championing the reuse of valuable materials to limit pollution and manage secondary resources. This method is especially relevant to managing PCB waste because of the valuable materials they contain and the environmental hazards caused by their improper disposal [3]. Within the context of PCBs, circular economy practices encompass recycling, refurbishing, remanufacturing, and material recovery. The recycling and retrieval of materials from PCBs are integral for mitigating e-waste and fostering a circular economy. The 3Rs principle (reduce, reuse, recycle) is a commonly adopted tactic in e-waste management, incorporating reducing e-waste, reusing potential e-products or e-waste, and recycling irreparable e-products [15].

Refurbishing and remanufacturing are also essential aspects of the circular economy's strategy for managing PCBs. For instance, Fairphone, a smartphone manufacturer, has gained recognition for its sustainable design and resource efficiency. This includes assessing the end-of-life phase of their products and strategising how to recover the majority of materials in their phones post their functional lifespan [16].

Adopting circular economy principles in PCB recycling brings several environmental, economic, and social benefits. The circular economy approach encourages the reuse of valuable materials to reduce pollution and manage secondary materials recovered in e-waste streams [17]. This method can facilitate enhanced resource utilisation, pollution prevention, and the realisation of sustainable development goals (SDGs) such as SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production) [18].

Despite these benefits, implementing circular economy practices in the PCB industry comes with some challenges. Technological constraints, regulatory frameworks, and stakeholder engagement are among the considerable barriers. For instance, many countries with growing economies lack sophisticated technologies to recover materials from PCBs. Additionally, e-waste management faces barriers due to inadequate financial backing, deficient infrastructure, scarce technical skills, and limited community engagement [17].

Regulatory frameworks also pose challenges, as effective e-waste management calls for policy approaches underpinned by sustainability principles and buttressed by science, technology, and innovation. These comprise restrictions on e-waste export or import, regulations on recycling certain e-waste categories, and the implementation of extended producer responsibility [17]. Stakeholder engagement emerges as another pivotal aspect. For instance, implementing extended producer responsibility and the 3Rs strategy in electronics manufacturing regulations globally can promote the production of products intended for reuse rather than obsolescence [17].

24.3.3 *Eco-Friendly Solutions for PCB Waste*

Eco-friendly solutions for managing PCB waste include recycling, reuse, and recovering materials. These strategies aim to lessen the environmental impact of PCB waste and increase recycling rates. Innovative technologies and methodologies are under investigation to enhance PCB recycling and the recovery of valuable metals. For instance, a recent study suggested a method to recycle copper nanoparticles from PCB waste etchants via a microemulsion process. This approach not only recovers valuable materials but also mitigates the environmental footprint of PCB waste [19]. Another work [20] also indicated a strong preference for recycling, particularly due to the economic aspects of e-waste processing, which are acknowledged as another important criterion. Waste recycling, especially e-waste recycling, can lead to advantageous economic impacts, such as the recovery of valuable and precious materials, conservation of natural resources, energy saving, job creation, and landfill saving. The monetary value of e-waste raw materials is estimated to be \$57.0 billion. However, only \$10.0 billion worth of e-waste is recycled and recovered sustainably, counteracting 15.0 million metric tons of carbon dioxide equivalents [3].

However, the informal recycling of metals from waste PCBs, particularly in developing countries, has resulted in severe environmental pollution and human health risks. Implementing the ‘Twelve Principles of Green Chemistry’ is the most effective strategy to address these issues [21]. The authors proposed a green process for metal recycling that co-processes waste PCBs and spent tin stripping solution at room temperature. The green process has substantial advantages over traditional recovery methods of heating waste PCBs, in terms of both material and energy efficiency [21].

Putting these solutions into action is not without challenges. For instance, the wide range and complexity of WEEE, which includes PCBs, poses significant problems for waste management plans. One of the main difficulties noted by many researchers is separating components and materials, due to their diversity, so they can work as needed in the devices. To separate the electronic components and reuse the materials, they need to be detached from the solder, which is a complex process, and it often ruins the components because of the heat used [11].

Our future heavily relies on how we manage our waste. Proper waste management can reduce our global impact and is a crucial part of sustainable development. Ignoring waste issues could lead to serious health, environmental, and financial problems. If we do not handle, monitor, and regulate electronic waste properly, illegal activities could increase, harming our efforts to protect health and the environment and create decent jobs. It is estimated that each year, the European Union exports between 0.5 and 1.3 million tons of used and waste electronic and electrical equipment. This is between 16 and 38% of the collected e-waste. Illegal waste recycling is a problem for the legal waste business. When new European rules on electrical and electronic equipment were introduced, the UK’s recycling industry expected about 1.5 million tons of e-waste for yearly processing. But when these amounts did not appear, UK officials started an investigation and found that up to 1 million tons, or two-thirds of the UK’s e-waste, is not sent to the right recycling facilities but instead

is sent overseas. The estimated result is around a USD 7.5 million profit loss to local treatment of waste electronic and electrical equipment [22].

24.4 Royal Mint Case Study

The Royal Mint, renowned for its expertise in coin minting and precious metal production, has embarked on a pioneering venture to recover precious metals from electronic waste. This initiative, in partnership with the Canadian clean tech start-up Excir, utilises a patented technology capable of recovering over 99% of gold from discarded electronic devices, such as laptops and mobile phones. This innovative approach not only offers a solution to the escalating e-waste problem but also aligns with the principles of a circular economy by turning waste into a valuable resource [23].

By specifically targeting components such as PCBs, The Royal Mint has devised a process to extract valuable precious metals, including gold. These metals, once deemed waste, are now being reclaimed and repurposed, contributing to a more sustainable and circular economy. The e-waste recycling process at The Royal Mint involves several stages, each presenting its unique challenges. Figure 24.2 provides a simplified representation of the process, which begins with the collection of electronic waste and concludes with responsible waste management, ensuring minimal environmental impact. The Mint is continually exploring ways to optimise its operations, maximise resource recovery, and minimise environmental impact.

Cardiff University, as part of the TransFIRE program [24], is working with The Royal Mint to make this process even more sustainable and minimise the current waste streams or find more sustainable solution for the current by-products streams. By focusing on these areas of improvement and collaborating with partner organisations, researchers, and technology providers, The Royal Mint can continue to lead the way in sustainable e-waste recycling practices. This collaboration underscores The Royal Mint's commitment to sustainable e-waste management and its role in promoting a circular economy.

The Royal Mint's endeavours to recover precious metals from electronic waste represent a significant stride towards reducing reliance on primary mining and promoting responsible use of finite resources. Embracing the principles of the circular economy, they demonstrate the potential to transform electronic waste into valuable secondary resources. This innovative approach not only provides environmental benefits but also presents economic opportunities. The recovered precious metals can



Fig. 24.2 Simplified representation of The Royal Mint's process for gold recovery from PCBs

be reintroduced into the supply chain, supporting sustainable manufacturing practices and reducing the demand for new materials. Through extensive research and development, The Royal Mint has refined their methods for efficiently and effectively recovering precious metals from electronic waste. This involves employing advanced technologies, such as selective leaching and precipitation, to separate and purify the metals from the PCBs. By doing so, they achieve high material yield percentages and minimise environmental impact.

The precious metals recovered from this process are later used in the production of a new jewellery line, 886, launched by 28-piece gender-neutral sustainable collection of which 70% currently being produced in Llantrisant, South Wales by The Royal Mint. The jewellery is made sustainably, using e-waste precious metals. Solid gold and silver pieces are ‘struck’ like coins rather than being ‘cast’ a process superior to casting as it makes the product 30% stronger with more lustre [25]. As the global demand for electronic devices continues to surge, The Royal Mint’s work serves as a valuable case study, showcasing the potential for collaboration between the metal industry and the recycling sector. Their efforts inspire further exploration and partnerships to develop scalable and sustainable solutions for electronic waste management, ultimately contributing to a more circular and resource-efficient future.

24.5 Conclusion

The study concludes that the management of electronic waste, particularly PCBs, presents significant challenges but also unique opportunities. The extraction of valuable metals from PCBs, whilst currently facing constraints and challenges, holds immense potential for economic and environmental benefits. Alternative methods of gold extraction, although promising, require further research and development to enhance their efficiency and feasibility for large-scale implementation. The concept of a circular economy, which champions the reuse of valuable materials to curb pollution and manage secondary resources, bears particular relevance to PCB waste management. However, the implementation of these practices is not without its challenges, including technological limitations, regulatory frameworks, and stakeholder engagement.

The case study of The Royal Mint serves as a practical example of how circular economy principles can be applied in the context of PCB recycling. Their innovative approach to gold extraction from PCBs showcases the potential for collaboration between different sectors to develop scalable and sustainable solutions for e-waste management.

As the global demand for electronic devices continues to surge, the need for effective and sustainable e-waste management strategies becomes increasingly critical. The Royal Mint’s work inspires further exploration and partnerships to develop scalable and sustainable solutions for electronic waste management, ultimately contributing to a more circular and resource-efficient future. In conclusion, the

study underscores the importance of continued research, innovation, and cross-sector collaboration in advancing sustainable practices in e-waste management and contributing to a more sustainable and resource-efficient future.

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