

## CIRCULAR ECONOMY MODELS FOR ELECTRONIC WASTE MANAGEMENT

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### Abstract

Electrical and electronic equipment is essential to communication, education, health care, commerce, and public services, yet its growing turnover creates a rapidly expanding stream of discarded devices. This paper examines circular economy models for electronic waste management and considers how products, components, and materials can retain value beyond their first use. Rather than treating end-of-life electronics only as a disposal problem, the analysis compares product-life extension, repair, reuse, refurbishment, producer take-back, reverse logistics, certified recycling, and urban-mining approaches. The study applies an evidence-based comparative framework to assess each model through resource retention, environmental protection, technical feasibility, traceability, economic viability, consumer participation, and social inclusion. It draws on peer-reviewed research, international guidance, policy instruments, and documented management practices; it does not claim a new field survey, waste audit, or laboratory experiment. The analysis shows that repair and refurbishment can preserve the highest functional value when devices remain serviceable, whereas dismantling and material recovery are necessary for equipment that cannot be safely reused. Extended producer responsibility can improve financing and collection, but its effectiveness depends on transparent targets, accessible return channels, credible recyclers, and controls against informal dumping or unsafe processing. A genuinely circular system therefore requires more than a recycling target. It needs durable design, access to spare parts and repair information, secure data handling, quality standards for secondary products, worker protection, inclusive collection systems, and reliable markets for recovered materials. The paper concludes that electronic waste management becomes more sustainable when circularity is designed across the entire product life cycle rather than applied only after a device is discarded.

**Keywords:** Circular Economy, Electronic Waste, WEEE, Extended Producer Responsibility, Repair, Refurbishment, Reverse Logistics, Resource Recovery, Urban Mining

### 1. INTRODUCTION

Electronic devices are now embedded in everyday life, from smartphones and computers to refrigerators, medical equipment, educational tools, lighting systems, and industrial controls. Their benefits are substantial, but fast replacement cycles, limited repair opportunities, changing software requirements, and fragmented collection systems lead many devices to be discarded before their technical value has been exhausted. The Global E-waste Monitor reports that 62 billion kilograms of electronic waste were generated worldwide in 2022, while only 22.3 per cent was documented as formally collected and recycled in an environmentally sound manner [1]. This gap highlights the need to move beyond a linear model of purchase, use, and disposal.

Electronic waste is not a uniform material. It may include reusable products, repairable devices, functioning components, critical metals, plastics, glass, batteries, and substances that require controlled treatment. A discarded laptop, for example, may be suitable for direct reuse, refurbishment, parts harvesting, or material recovery depending on its condition, data-security status, and market demand. Treating every item as immediate scrap loses this distinction and can reduce opportunities for value retention. At the same time, uncontrolled dismantling, open burning, unsafe acid treatment, and unregulated export can expose workers and communities to hazardous emissions and contamination [5, 13].

The circular economy offers a framework for organising electronic products around longer

use, repeated circulation, and safer material loops. In this approach, priority is given to preventing waste, extending product life, sharing or leasing products where appropriate, repairing and upgrading equipment, refurbishing suitable devices, and recovering materials only after higher-value options have been considered. This hierarchy is especially relevant for electronics because manufacturing a new device requires energy, specialised inputs, complex supply chains, and in many cases strategically important metals. Circular strategies can reduce pressure on virgin extraction while improving access to affordable equipment and skilled green employment [6, 7].

This study develops a comparative analysis of circular economy models for electronic waste management. It investigates the conditions under which different models can operate effectively, identifies their major implementation barriers, and considers the responsibilities of producers, consumers, repair enterprises, collection networks, recyclers, regulators, public institutions, and informal-sector workers. The central proposition is that circular electronic-waste systems must protect both material value and human well-being; one objective cannot be pursued at the expense of the other.

## 2. LITERATURE REVIEW

Research on circular economy has shifted attention from end-of-pipe waste treatment toward system design, product longevity,

material stewardship, and regenerative resource use. Foundational circular-economy literature emphasises that products should remain useful for as long as feasible and that resource loops should be arranged according to the value retained at each stage. For electronics, this means that direct reuse, maintenance, repair, upgrading, and refurbishment usually preserve more embedded value than basic material recycling. Recycling nevertheless remains essential when equipment is damaged, obsolete, unsafe, or unsuitable for further use [6–8].

E-waste scholarship also stresses that collection and recycling outcomes are influenced by product design, consumer behaviour, reverse-logistics capacity, regulation, data-security concerns, commodity prices, and the organisation of formal and informal recovery networks. Extended producer responsibility (EPR) is widely used to create financial and operational obligations for producers, but the design of EPR systems matters greatly. Targets without credible reporting, accessible collection, environmental safeguards, and independent verification may shift paperwork rather than improve real recovery. Studies further show that certified recycling, repair ecosystems, and secondary markets need to be connected through traceable flows so that reusable products are not destroyed prematurely and hazardous fractions are not dispersed [2, 3, 9–12].

### Literature Review Summary Table

| S. No. | Author / Year              | Study Focus                      | Key Contribution                                                                             | Limitations Identified                                        |
|--------|----------------------------|----------------------------------|----------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| 1      | Widmer et al. (2005)       | Global e-waste challenge         | Explained environmental and social concerns associated with growing e-waste flows            | Early overview; market and policy conditions have changed     |
| 2      | Ongondo et al. (2011)      | Worldwide WEEE management        | Compared management approaches and highlighted collection and treatment gaps                 | Pre-dates newer circular-economy instruments                  |
| 3      | Cucchiella et al. (2015)   | Economic value of WEEE recycling | Demonstrated the economic significance of secondary material recovery                        | Focuses strongly on material value rather than reuse pathways |
| 4      | Bovea & Pérez-Belis (2018) | Design for WEEE management       | Identified design factors that enable recovery, disassembly, and safer end-of-life treatment | Implementation varies across product categories               |

|   |                        |                              |                                                                                             |                                                                |
|---|------------------------|------------------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| 5 | Forti et al.<br>(2024) | Global e-waste<br>monitoring | Provided current evidence on<br>generation, formal collection,<br>and recycling performance | High-level global data<br>cannot replace local flow<br>studies |
|---|------------------------|------------------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------|

### 3. OBJECT OF STUDY

The primary focus of this research is to examine how circular economy principles can be translated into practical models for electronic waste management. The study follows the movement of electrical and electronic equipment from active use to collection, assessment, repair, refurbishment, reuse, component recovery, material processing, and residual disposal. It considers the decision points that determine whether value is retained, lost, or transferred into a safer recovery pathway. The objects of study are outlined below:

#### 3.1 ELECTRONIC-WASTE STREAMS UNDER CONSIDERATION

- Information and communication technology equipment, including computers, laptops, tablets, printers, routers, and mobile devices
- Consumer electronics such as televisions, audio equipment, cameras, gaming devices, and display products
- Household appliances, lighting equipment, tools, and small electrical devices with reusable or recoverable components
- Institutional equipment from schools, offices, health facilities, and public organisations where asset tracking can support return and reuse
- Components and fractions such as circuit boards, cables, chargers, batteries, plastics, metals, glass, and storage devices

#### 3.2 CIRCULAR-ECONOMY

##### INTERVENTIONS

- Product-life extension through maintenance, repairability, software support, modular upgrades, and access to spare parts
- Reuse and refurbishment through collection, testing, data erasure, repair, quality assurance, resale, donation, or redeployment
- Producer take-back, retailer return points, and reverse logistics that create convenient and traceable recovery channels

- Component harvesting and remanufacturing where usable parts can be safely recovered for further production or repair
- Certified dismantling and material recovery for equipment that cannot be reused or repaired

#### 3.3 STAKEHOLDERS AND OPERATIONAL CONTEXT

- Manufacturers, brand owners, importers, assemblers, and online marketplaces
- Consumers, households, schools, offices, public agencies, and bulk equipment users
- Repair technicians, refurbishers, collection agents, logistics providers, dismantlers, and authorised recyclers
- Municipal bodies, pollution-control authorities, standards organisations, and customs or trade authorities
- Informal-sector workers and community enterprises whose knowledge, livelihood security, and occupational safety require explicit consideration

#### 3.4 CIRCULAR-ECONOMY

##### EVALUATION PARAMETERS

- Potential to retain product, component, and material value at the highest feasible level
- Environmental and health protection, including control of hazardous substances and emissions
- Technical feasibility, access to tools, repair information, quality testing, and safe processing infrastructure
- Economic viability for consumers, repair businesses, collection systems, and recovery facilities
- Traceability, data-security safeguards, consumer trust, and accountability across reverse supply chains
- Social inclusion, decent work, and practical pathways for informal workers to participate safely in formalised systems

#### 3.5 RESEARCH OBJECTIVE SCOPE

- To map major circular-economy models applicable to electronic waste management

- To compare repair, reuse, refurbishment, take-back, recycling, and digital-traceability approaches
- To identify barriers related to product design, collection, financing, data protection, consumer participation, and regulation
- To explain the role of extended producer responsibility in supporting closed-loop electronic-product systems
- To recommend operational measures that improve resource recovery without weakening environmental safeguards or worker protection

#### 4. RESEARCH METHODOLOGY

The present study uses a qualitative, comparative, and evidence-based methodology. Its purpose is to synthesise published research, international reports, policy frameworks, and documented industry practices in order to evaluate circular models for electronic waste. The study does not report a new household survey, plant-level material audit, experimental recycling trial, or independently measured recovery rate. Instead, it evaluates established approaches by tracing the decisions that occur when an electronic product becomes unwanted or reaches the end of its functional use.

The analytical framework follows a product through six linked stages: acquisition and use, maintenance or repair, collection and return, condition assessment, reuse or component recovery, and certified material processing or final disposal. At every stage, the model asks whether the next action retains the greatest feasible value while protecting privacy, worker safety, and the environment. This sequence helps distinguish a high-value repair pathway from a lower-value recycling pathway and recognises that not all devices should follow the same route.

Evidence was assessed through common dimensions: product condition, remaining functional life, repairability, availability of spare parts, data-security needs, market demand for secondary products, collection convenience, financial incentives, traceability, environmental risk, and regulatory alignment. The discussion also considers how EPR schemes, public procurement, warranty rules, repair-information access, and standards for

refurbished products can influence these dimensions.

#### METHODOLOGY FRAMEWORK

1. The study compares multiple circular models rather than assuming that recycling is the only solution.
2. Published literature, official policy documents, and international reports support the qualitative synthesis.
3. The analysis applies a product-life-cycle perspective from use and return to reuse, recovery, and residual treatment.
4. Higher-value strategies such as maintenance, repair, and refurbishment are assessed before material recycling.
5. Environmental safeguards and worker protection are treated as essential conditions of circularity.
6. Extended producer responsibility is evaluated as a financing and governance mechanism rather than a stand-alone outcome.
7. The study considers the need for convenient collection, transparent reporting, and credible treatment partners.
8. Data-security procedures are included because fear of information loss can prevent consumers and institutions from returning devices.
9. The framework distinguishes formal recycling from unsafe or untraceable handling that may only appear to be recovery.
10. Recommendations are directed toward practical implementation, accountability, and inclusive resource management.

#### 5. DATA ANALYSIS

The data analysis section presents a comparative evaluation of major circular economy models used in electronic waste management. The assessment is qualitative because performance depends on the condition of devices, local repair capacity, consumer behaviour, collection coverage, material prices, legal enforcement, and the availability of certified facilities. The purpose is not to assign a universal numerical score, but to identify where each model retains value, what it requires to operate responsibly, and where policy or market intervention is most needed. Six linked approaches are considered: product-life extension, refurbishment and secondary use, producer take-back, component

harvesting, certified recycling, and digital traceability with reverse logistics. These approaches are complementary. A circular system is strongest when it directs each product to the highest-value safe pathway

rather than forcing every item into the same downstream process.

## 5.1 COMPARATIVE CIRCULAR-MODEL ANALYSIS

| S. No. | Circular Model                             | Core Activities                                                                  | Value Retained                               | Key Requirement                                       | Relative Priority |
|--------|--------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------|-------------------|
| 1      | Product-life extension                     | Maintenance, repair, upgrades, spare-part replacement, software support          | Use value of the whole product               | Repairable design and affordable parts                | Very High         |
| 2      | Refurbishment and secondary use            | Collection, testing, data wiping, repair, grading, warranty, resale or donation  | Functional devices and selected components   | Quality standards and trusted secondary markets       | High              |
| 3      | Producer take-back and EPR                 | Return points, financing, transport, reporting, verified treatment               | Controlled product and material flow         | Convenient collection and transparent compliance      | Very High         |
| 4      | Component harvesting and remanufacture     | Safe disassembly, testing, parts recovery, integration into repair or production | Reusable parts and modules                   | Technical testing and compatibility controls          | High              |
| 5      | Certified recycling and urban mining       | Depollution, dismantling, separation, refining, residual management              | Metals, plastics, glass, and other materials | Environmental controls and viable recovery technology | High              |
| 6      | Digital traceability and reverse logistics | Asset records, product passports, return scheduling, chain-of-custody evidence   | Information that enables recovery decisions  | Interoperable data and privacy safeguards             | High              |

## 5.2 EXTENDED CIRCULAR-ECONOMY EVALUATION

Product-life extension is the most resource-efficient option when a device can remain in safe and functional use. Repair, maintenance, replacement of worn components, battery renewal, and software support can delay the need for a new product and conserve the embodied energy and materials already invested in manufacturing. However, this pathway requires products that can be opened without damage, accessible diagnostics, available spare parts, fair repair prices, and consumer confidence that repaired devices will perform reliably. Design choices that rely on permanent adhesives, proprietary connectors, restricted parts access, or premature software

obsolescence can weaken this model before a product reaches the consumer.

Refurbishment provides a structured route for devices that are no longer wanted by their first users but still have significant functional life. This model is particularly relevant for institutional computers, mobile phones, office equipment, and selected household electronics. Effective refurbishment includes collection, asset identification, secure data erasure, cleaning, testing, repair, grading, and an appropriate warranty. Its social value can be substantial because functional equipment may be made available to students, community organisations, and low-income households at lower cost. Nevertheless, refurbished-product markets require transparent quality standards

so that secondary users do not receive unsafe, unreliable, or non-compliant equipment.

Producer take-back and extended producer responsibility can connect financing with end-of-use management. Under an effective EPR system, producers are expected to support the collection and environmentally sound treatment of products placed on the market. This can create incentives for longer-lasting design, easier disassembly, and investment in recovery infrastructure [2, 3]. Yet EPR requires more than a regulatory obligation. Collection points need to be accessible, public awareness must be sustained, records need to reflect real material flows, and recycling partners must meet environmental and labour standards. Where verification is weak, untraceable transfers can obscure whether e-waste has actually been repaired, recycled, stored, or illegally dumped.

Component harvesting and certified recycling address equipment that cannot be reused as complete products. Functional memory modules, displays, chargers, casings, motors, and other parts may still be valuable in repair and remanufacturing chains. For the residual fraction, certified treatment can remove hazardous components, separate material streams, and recover metals such as copper, aluminium, iron, gold, palladium, and other elements. The recovery of these materials has economic and strategic value, but processes must be selected according to their environmental performance. Informal burning, uncontrolled manual dismantling, and acid leaching may recover some materials while creating much greater health and environmental damage [5, 13].

Digital traceability strengthens every circular model by recording product identity, ownership history, repair status, hazardous content, parts replacement, return arrangements, and treatment outcomes. For institutions, asset registers can make planned collection and redeployment easier. For consumers, secure data-erasure certificates and clearly visible return options can reduce concerns about privacy. Product passports and chain-of-custody systems may also improve compliance reporting, but they should be designed with interoperability, affordability, and data protection in mind. Technology alone cannot solve poor collection or unsafe

processing; it must be paired with accessible services, accountable operators, and public oversight.

### 5.3 OBSERVATIONS FROM DATA ANALYSIS

- Circularity is most effective when management decisions follow a value-retention hierarchy rather than treating all discarded electronics as scrap.
- Repair and refurbishment depend heavily on durable design, repair information, spare-part access, diagnostics, and fair warranty practices.
- Collection systems must be convenient and trusted; otherwise valuable devices may remain stored in homes or enter unregulated channels.
- EPR can support financing and accountability, but it should be assessed through verified outcomes rather than only reported targets.
- Data-security concerns are a major practical barrier for the return of computers, phones, and institutional equipment.
- Formalisation should protect livelihoods and improve safety for informal workers rather than simply exclude them from the recovery chain.
- Recycling is essential for non-reusable equipment, but it is a lower-value loop than extending the life of a functioning product.
- Public procurement, repair-friendly standards, and secondary-material markets can create demand-side support for circular electronic systems.

### 6. DISCUSSION

The comparative analysis shows that circular electronic-waste management is a system-design challenge rather than only a waste-treatment challenge. A collection target alone cannot establish a circular economy if products are hard to repair, consumers have no trusted place to return devices, data cannot be erased securely, refurbishers lack access to parts, or recyclers operate without environmental controls. Each element affects the next. Product design influences repair; repair influences the volume available for reuse; reuse affects the quantity and quality of material entering recycling; and traceability

determines whether regulators and producers can verify what happened after collection.

The distinction between reuse and recycling is particularly important. Reuse preserves the whole device and the energy, labour, and components embedded in it. Refurbishment may retain much of the same value while addressing condition, software, storage, or battery issues. Recycling becomes essential when the device cannot be safely reused or when components are beyond recovery, but it cannot recover all of the value created during manufacturing. Policies that promote only weight-based recycling may therefore unintentionally encourage the processing of devices that could have remained functional. A balanced framework should recognise repair, reuse, refurbishment, component recovery, and material recycling as different but connected outcomes.

Extended producer responsibility offers an important governance route because producers influence design, product information, distribution, and end-of-use pathways. Under India's E-Waste (Management) Rules, 2022, EPR is a central mechanism for managing e-waste and supporting registered collection and recycling systems [3]. Its circular value will depend on implementation quality: robust registration, realistic targets, independent verification, clear treatment standards, public disclosure, and mechanisms that ensure generated e-waste is directed to responsible operators. EPR should also encourage product improvements such as longer support periods, easier disassembly, parts availability, and design for recovery.

A socially responsible circular economy must address informal-sector realities. In many locations, informal collectors and repair workers possess extensive knowledge of device markets, repair practices, and material flows. Policies that ignore these actors can reduce collection reach or push activities further underground. The practical aim should be safer integration through training, protective equipment, fair purchasing arrangements, access to formal facilities, and pathways to enterprise development. This approach can combine the collection strengths of local networks with the environmental safeguards of authorised treatment systems.

Public institutions have a distinct role because they purchase, use, and retire large quantities of electronic equipment. Repairable procurement specifications, asset-management systems, scheduled refresh policies, data-erasure procedures, and transparent resale or donation programmes can demonstrate circular practice at scale. Similar measures can be adopted by universities, hospitals, companies, and local governments. By creating reliable supply for refurbishment and transparent demand for secondary equipment and recovered materials, institutional action can make circular models more commercially viable.

## 7. CONCLUSION

This study examined circular economy models for electronic waste management through a comparative framework covering product-life extension, refurbishment, producer take-back, component harvesting, certified recycling, and digital traceability. The analysis shows that electronic waste should not be approached as a single residual stream. Depending on product condition, safety, data-security requirements, and market demand, a device may be repaired, reused, refurbished, dismantled for components, or processed for material recovery. The most sustainable outcome is generally the one that retains the greatest safe value for the longest appropriate period.

A successful circular system needs durable and repairable product design, accessible return channels, secure data handling, quality-assured refurbishment, transparent EPR, certified recycling, and social safeguards for workers throughout the recovery chain. Recycling remains necessary, but it must be placed within a wider hierarchy that prioritises prevention, continued use, repair, and reuse. Policies and business models should therefore measure circular performance not only by tonnes processed, but also by product life extended, components reused, hazardous materials safely managed, and livelihoods improved.

Future research should develop local material-flow data, evaluate the environmental performance of repair and refurbishment pathways, examine consumer willingness to use secondary electronics, and study how design, warranties, software support, and right-to-repair measures affect device longevity.

Evidence on safe integration of informal workers, product-passport systems, and reuse-oriented EPR targets would further strengthen

the transition from linear electronic consumption to accountable circular resource management.

## 8. REFERENCES

1. Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2024). *The Global E-waste Monitor 2024*. International Telecommunication Union and United Nations Institute for Training and Research.
2. Organisation for Economic Co-operation and Development. (2016). *Extended Producer Responsibility: Updated Guidance for Efficient Waste Management*. OECD Publishing.
3. Ministry of Environment, Forest and Climate Change, Government of India. (2022). *E-Waste (Management) Rules, 2022*. Gazette of India.
4. European Parliament and Council. (2012). Directive 2012/19/EU on waste electrical and electronic equipment (WEEE). *Official Journal of the European Union*, L 197, 38-71.
5. Basel Convention Secretariat. (1989). *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal*. United Nations Environment Programme.
6. Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11-32.
7. Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232.
8. Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy - A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757-768.
9. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., & Böni, H. (2005). Global perspectives on e-waste. *Environmental Impact Assessment Review*, 25(5), 436-458.
10. Ongondo, F. O., Williams, I. D., & Cherrett, T. J. (2011). How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Management*, 31(4), 714-730.
11. Cucchiella, F., D'Adamo, I., Lenny Koh, S. C., & Rosa, P. (2015). Recycling of WEEEs: An economic assessment of present and future e-waste streams. *Renewable and Sustainable Energy Reviews*, 51, 263-272.
12. Bovea, M. D., & Pérez-Belis, V. (2018). Identifying design requirements for the management of WEEE: A systematic review. *Renewable and Sustainable Energy Reviews*, 82, 2206-2217.
13. Zeng, X., Mathews, J. A., & Li, J. (2018). Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environmental Science & Technology*, 52(8), 4835-4841.
14. Nnorom, I. C., & Osibanjo, O. (2008). Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. *Resources, Conservation and Recycling*, 52(6), 843-858.
15. Kumar, A., Holuszko, M., & Espinosa, D. C. R. (2017). E-waste: An overview on generation, collection, legislation and recycling practices. *Resources, Conservation and Recycling*, 122, 32-42.
16. Tanskanen, P. (2013). Management and recycling of electronic waste. *Acta Materialia*, 61(3), 1001-1011.
17. Baldé, C. P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2017). *The Global E-waste Monitor 2017*. United Nations University, International Telecommunication Union, and International Solid Waste Association.
18. European Commission. (2020). *A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe*. COM(2020) 98 final.
19. Ellen MacArthur Foundation. (2013). *Towards the Circular Economy, Volume 1: Economic and Business Rationale for an Accelerated Transition*.
20. United Nations Environment Programme. (2019). *Basel Convention Technical Guidelines on Transboundary Movements of Electrical and Electronic Waste and Used Electrical and Electronic Equipment*. UNEP.
21. International Telecommunication Union. (2024). *The Global E-waste Monitor 2024: Key Findings and Statistics*. ITU.



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22. Central Pollution Control Board. (2022). *E-Waste Management Rules, 2022: Producer, Manufacturer, Refurbisher and Recycler Responsibilities*. Government of India.