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BUSINESS MODELS FOR CIRCULAR ECONOMY IN E-WASTE MANAGEMENT

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Abstract : Electronic waste (e-waste) represents one of the fastest-growing waste streams globally, with a record 62 million metric tons generated in 2022—an 82% increase from 2010—and projections indicating continued growth to 82 million tons by 2030. The linear "take-make-dispose" model that has dominated electronics production and consumption is environmentally unsustainable and economically inefficient. This paper examines innovative business models that apply circular economy principles to e-waste management, exploring how companies can capture value while reducing environmental impact. Through analysis of product-as-a-service models, refurbishment and remanufacturing systems, urban mining initiatives, and extended producer responsibility schemes, this research demonstrates that circular business models can simultaneously address environmental challenges and create economic opportunities. The findings suggest that successful implementation requires collaborative ecosystems, supportive policy frameworks, technological innovation, and fundamental shifts in consumer behavior and corporate strategy.

***Index Terms* - circular economy, e-waste management, business models, sustainability, extended producer responsibility, urban mining**

I. INTRODUCTION

The global proliferation of electronic devices has created an unprecedented waste management challenge. Electronic waste, or e-waste, encompasses discarded electrical and electronic equipment including computers, smartphones, televisions, refrigerators, and countless other devices that have become integral to modern life. The UN's fourth Global E-waste Monitor revealed that the world generated a record 62 million metric tons of e-waste in 2022—an 82% increase from 2010—with only 22.3% formally collected and recycled (Baldé et al., 2024). This represents not only a significant environmental hazard due to toxic materials like lead, mercury, and cadmium, but also a substantial loss of valuable resources including gold, silver, copper, and rare earth elements, valued at $62 billion in unrecovered materials (Baldé et al., 2024).

Traditional linear economic models, characterized by extraction, production, consumption, and disposal, are fundamentally incompatible with planetary boundaries and resource constraints. The circular economy paradigm offers an alternative approach that maintains products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2013). In the context of electronics, this means designing products for longevity, repairability, and recyclability; extending product lifespans through maintenance and refurbishment; and recovering materials for reuse in new production cycles.

Business models serve as the architecture through which companies create, deliver, and capture value (Osterwalder & Pigneur, 2010). Circular business models fundamentally reimagine this architecture to align economic incentives with environmental stewardship. This paper examines how various circular business models can be applied to e-waste management, analyzing their mechanisms, benefits, challenges, and real-world implementations.

II. THE E-WASTE CHALLENGE

E-waste represents the fastest-growing waste stream globally, with generation rates increasing five times faster than documented e-waste recycling (Baldé et al., 2024). The 62 million tonnes generated in 2022 would fill 1.55 million 40-tonne trucks, enough to form a bumper-to-bumper line encircling the equator. Projections indicate this will rise another 32% to 82 million tonnes by 2030 (Baldé et al., 2024). The composition of e-waste is highly diverse, ranging from small equipment like mobile phones and calculators to large appliances like washing machines and photovoltaic panels. This diversity complicates management strategies, as different device categories require specialized collection, processing, and recycling technologies. There are numerous challenges related to e-waste which are mentioned below:

- **Scale and Composition:** Modern electronic devices contain complex mixtures of materials. A typical smartphone contains over 60 different elements from the periodic table, including precious metals, rare earth elements, and hazardous substances (Arya & Kumar, 2020). While these materials have significant economic value—the 62 million tonnes of e-waste generated in 2022 contained $62 billion worth of recoverable materials—the complexity of extraction and the current low collection rates mean that most of this value is lost (Baldé et al., 2024). Less than 1% of rare earth element demand is currently met through e-waste recycling, despite these materials being crucial for renewable energy and e-mobility technologies (Baldé et al., 2024).
- **Environmental and Health Impacts:** Improper e-waste management poses severe environmental and health risks. When electronics are landfilled or incinerated, toxic substances including lead, mercury, cadmium, and brominated flame retardants can contaminate soil, water, and air (Heacock et al., 2016). In developing countries, informal e-waste processing—including open burning and acid bathing to recover metals—exposes workers and communities to dangerous toxins and has been linked to various health problems including respiratory issues, neurological damage, and cancer (Grant et al., 2013). The environmental footprint extends beyond disposal. Electronics production is resource-intensive, requiring significant energy, water, and raw materials. Mining operations for materials like cobalt, tantalum, and rare earth elements often involve environmental degradation and human rights concerns (Sovacool, 2019). A circular approach that reduces the need for virgin material extraction can substantially mitigate these impacts.
- **Regulatory Landscape:** Recognition of e-waste challenges has prompted regulatory responses globally. The European Union's Waste Electrical and Electronic Equipment (WEEE) Directive, first implemented in 2003 and revised in 2012, established collection, recycling, and recovery targets for electronics producers (European Parliament and Council, 2012). Similar legislation exists in various forms across Asia, Africa, and the Americas, though implementation effectiveness varies considerably. Extended Producer Responsibility (EPR) has emerged as a key policy instrument, shifting the financial and operational responsibility for end-of-life product management from municipalities to producers (Walls, 2011). While EPR creates incentives for design improvements and establishes collection infrastructure, its effectiveness depends on enforcement mechanisms, target ambition, and coordination among stakeholders.
- **Circular Economy Principles:** The circular economy represents a systemic approach to economic development designed to benefit businesses, society, and the environment. Unlike the linear model of "take-make-dispose," the circular economy is restorative and regenerative by design (Ellen MacArthur Foundation, 2013). Three foundational principles underpin this approach:
- **Design out waste and pollution:** Rather than accepting waste as an inevitable byproduct, circular design eliminates waste and pollution from the outset. For electronics, this means designing products that are durable, repairable, upgradable, and ultimately recyclable. It requires rethinking material selection, component integration, and fastening systems to facilitate disassembly and material recovery.
- **Keep products and materials in use:** The circular economy maximizes the value extracted from resources by keeping products, components, and materials circulating in the economy for as long as possible. This occurs through strategies including maintenance, repair, refurbishment, remanufacturing, and recycling. For electronics, extending product lifespans through repairs and component reuse can significantly reduce environmental impacts compared to premature replacement (Proske et al., 2016).
- **Regenerate natural systems:** The circular economy seeks to enhance natural capital by returning biological nutrients to the biosphere and avoiding contamination of natural cycles with technical materials. While electronics are primarily composed of technical nutrients that should circulate in industrial systems, circular approaches can reduce the extractive pressures on natural systems by decreasing demand for virgin materials.

The application of circular economy principles to electronics requires consideration of multiple value loops: maintaining products through maintenance and repair (inner loops), extending life through refurbishment and remarketing (medium loops), and recovering materials through recycling (outer loops). Research indicates that strategies preserving more of the original product create greater environmental and economic value than those requiring extensive reprocessing (Bakker et al., 2014).

III. CIRCULAR BUSINESS MODELS FOR E-WASTE MANAGEMENT

Business model innovation is essential for transitioning from linear to circular systems. Several circular business model archetypes have particular relevance for electronics and e-waste management.

• Product-as-a-Service Models

Product-as-a-Service (PaaS), also called performance-based or functional economy models, fundamentally shifts the value proposition from selling products to selling the use or performance of products (Tukker, 2004). Customers pay for access to functionality rather than ownership of physical goods. For the provider, this creates incentives to design durable, repairable products since they retain ownership and responsibility throughout the product lifecycle.

In electronics, PaaS models have been implemented across various sectors with increasing adoption. Analysis shows that by 2025, 75% of companies report that product connectivity supports outcome-based pricing and as-a-service models (StartUs Insights, 2025). Philips Lighting's "pay-per-lux" model provides illumination as a service to commercial clients, maintaining ownership of lighting systems while customers pay for light output (Bocken et al., 2016). This approach incentivizes energy efficiency and longevity since Philips bears the operational costs and retains responsibility for maintenance and end-of-life management.

Similar models have expanded significantly in computing equipment. Companies like HPE GreenLake and Dell Technologies APEX offer IT infrastructure as a service, providing computing capacity on a pay-per-use basis while maintaining ownership of hardware. In the consumer electronics space, Grover, a German company partnered with Samsung, offers consumer technology subscriptions including Galaxy smartphones, allowing customers to access the latest devices without ownership (Circuly, 2024). The shift toward PaaS models has accelerated dramatically: companies report moving from questioning "why should we do product-as-a-service?" in 2022 to "how soon can we integrate?" by 2024 (Circuly, 2024).

The benefits of PaaS models include reduced resource consumption through intensive product use, extended product lifespans through professional maintenance, and higher-quality end-of-life management. However, challenges include consumer acceptance of access over ownership, logistics of reverse flows, and capital requirements for maintaining large product pools. Research suggests that PaaS models are most viable in business-to-business contexts where customers value performance over ownership and where use intensity is high (Tukker, 2015).

• Refurbishment and Remanufacturing Models

Refurbishment and remanufacturing extend product lifespans by restoring used products to functional condition. Refurbishment typically involves cleaning, repairing, and testing used products to bring them to satisfactory working condition. Remanufacturing is more extensive, disassembling products to the component level, replacing worn parts, and reassembling to like-new condition with warranties comparable to new products (Thierry et al., 1995).

For electronics, refurbishment and remanufacturing create substantial value. Mobile phones, laptops, tablets, and other consumer electronics retain significant functionality when their original owners upgrade to new models. Companies like Gazelle, Back Market, and Assurant capture and resell millions of refurbished devices annually, creating a multi-billion-dollar market (Parajuly et al., 2020).

Apple's iPhone refurbishment program exemplifies manufacturer-led initiatives. Through Apple Trade In, the company accepts used devices, refurbishes those in good condition for resale, and recycles those beyond repair using specialized disassembly robots like Daisy, which can disassemble 200 iPhones per hour to recover materials (Apple, 2021). This approach creates additional revenue streams, reduces material costs, and addresses sustainability concerns.

The environmental benefits of refurbishment are significant. Life cycle assessments demonstrate that refurbished electronics typically have 70-90% lower environmental impact than new products when considering manufacturing burdens (Benton et al., 2015). Economic benefits accrue through job creation in inspection, repair, and testing operations, often in local markets rather than overseas manufacturing centers.

Challenges include ensuring product quality and reliability, managing consumer perceptions that used products are inferior, navigating complex reverse logistics, and addressing potential conflicts with new product sales. Successful refurbishment models require robust testing protocols, warranties that build consumer confidence, and pricing strategies that differentiate refurbished products while maintaining profitability.

- **Urban Mining and Material Recovery**

Urban mining refers to the recovery of valuable materials from e-waste and other urban waste streams, treating disposed products as valuable resource reservoirs rather than waste (Cossu & Williams, 2015). Electronics contain significant concentrations of precious metals, rare earth elements, and other materials that can be economically recovered and reintegrated into production.

A typical ton of e-waste contains more gold than 17 tons of gold ore, more silver than 800 tons of silver ore, and more copper than 350 tons of copper ore (United Nations University, 2015). Despite these concentrations, current recycling rates remain low globally, with most value lost to landfills, exports to developing countries, or suboptimal processing that fails to recover all valuable materials.

Advanced recycling technologies are improving material recovery rates and economics. Companies like Umicore in Belgium operate integrated precious metals refineries that can recover over 20 different metals from complex e-waste streams, including gold, silver, platinum group metals, and rare earths (Hagelüken, 2006). These industrial-scale facilities use sophisticated pyrometallurgical and hydrometallurgical processes to separate and purify materials to high specifications suitable for reintegration into manufacturing.

Emerging technologies like bioleaching, which uses microorganisms to extract metals from e-waste, offer potentially lower-cost and more environmentally friendly alternatives to conventional approaches (Işıldar et al., 2019). Meanwhile, artificial intelligence and robotics are improving sorting and disassembly processes, addressing a major bottleneck in e-waste processing (Naimaster et al., 2020).

Business models for urban mining require significant capital investment in processing infrastructure, reliable supply chains for waste collection, and markets for recovered materials. Success factors include achieving sufficient scale for economic viability, developing technologies that can handle diverse and complex waste streams, and establishing partnerships with manufacturers who can use recovered materials. Policy support through recycling mandates, virgin material taxes, or recycled content requirements can improve the economics of urban mining operations.

- **Collaborative Consumption and Sharing Platforms**

Collaborative consumption models enable shared access to products among multiple users, increasing utilization rates and reducing the total number of products needed to serve a given population (Botsman & Rogers, 2010). For electronics, sharing platforms allow expensive or infrequently used equipment to serve multiple users, reducing overall resource consumption.

Examples include tool libraries that lend power tools and equipment, peer-to-peer rental platforms for cameras and electronics, and office equipment sharing in coworking spaces. While collaborative consumption is more established for other product categories, applications for electronics are growing, particularly for specialized or expensive equipment like professional cameras, virtual reality systems, and home theater equipment.

The environmental benefits depend on the balance between increased utilization efficiency and any additional impacts from transportation, platform operations, or changes in consumer behavior that might increase overall consumption (Belk, 2014). Life cycle assessments suggest that sharing models provide net environmental benefits when they substitute for product purchases and when transportation impacts are minimized through local sharing networks (Ranjbari et al., 2021).

Challenges for electronics sharing include concerns about data security and privacy, potential device damage through multi-user handling, hygiene considerations, and the rapid technological obsolescence that may make shared devices seem outdated. Successful platforms typically focus on niche markets with specific equipment needs, build strong community trust, and implement clear protocols for device maintenance and data protection.

• Extended Producer Responsibility Systems

Extended Producer Responsibility (EPR) represents a policy approach that creates business model implications for electronics producers. Under EPR systems, manufacturers assume financial and operational responsibility for the collection and recycling of their products at end-of-life (Walls, 2011). This shifts costs from municipalities and taxpayers to producers, creating economic incentives for design improvements that facilitate recycling and reduce end-of-life costs.

EPR implementation varies globally but generally involves producers funding collection and recycling systems, either individually or through collective producer responsibility organizations (PROs). The European WEEE Directive requires producers to finance waste collection and treatment, achieving minimum collection rates of 65% of electronics placed on market or 85% of e-waste generated (European Parliament and Council, 2012). In West Africa, Senegal has set ambitious targets to recycle 90% of the country's electronic and electrical waste by 2025, establishing national e-waste processing centers and partnering with the Global Green Growth Institute (World Economic Forum, 2024). Similarly, Bangladesh's Department of Environment stipulates that within five years, e-waste collection rates should reach 50% of the country's e-waste, with private sector platforms like SWAP facilitating circular economy models by selling 7,000-8,000 second-hand devices monthly (World Economic Forum, 2024).

Well-designed EPR systems can drive circular business model adoption by making producers financially responsible for end-of-life costs, thereby incentivizing design for recyclability, durability, and material recovery. Some EPR systems modulate fees based on product characteristics, rewarding designs that are easier to recycle or contain less hazardous content (Atasu & Subramanian, 2012). This creates direct economic links between design decisions and end-of-life outcomes.

However, EPR effectiveness depends on implementation details. Collective PRO systems may dilute individual producer incentives for design improvement if fees don't adequately differentiate products. Free-riding by non-compliant producers undermines system financing. And inadequate recycling targets or enforcement allow continued low performance (Hickle, 2014). Successful EPR systems typically combine ambitious targets, individual producer responsibility or well-designed fee modulation, strong enforcement, and stakeholder engagement.

IV. DESIGN FOR CIRCULARITY

While not strictly a business model, design for circularity represents a crucial enabler of circular business models in electronics. This approach integrates circular economy principles into product design from the outset, considering end-of-life scenarios during initial development (Bakker et al., 2014). Key design strategies include:

- **Modularity:** Designing products with standardized, interchangeable components facilitates repair, upgrades, and component reuse. Fairphone exemplifies this approach with smartphones designed for user repairability with modular cameras, batteries, and displays (Fairphone, 2020).
- **Material selection:** Choosing materials that are recyclable, avoiding hazardous substances, and minimizing material complexity improve end-of-life processing. Using single-material plastics rather than composites, for example, simplifies mechanical recycling.
- **Fastening and joining:** Using reversible fasteners like screws rather than adhesives or welding enables non-destructive disassembly. This preserves component value and facilitates material separation for recycling.
- **Durability:** Engineering products for extended operational lives reduces replacement frequency. This includes using robust materials, incorporating protective features, and designing for maintenance and repair.
- **Upgradeability:** Enabling component upgrades extends product relevance as technology advances. Modular computers that allow processor, memory, and storage upgrades exemplify this approach.

Companies implementing design for circularity often develop service businesses around extended product lifespans, selling repairs, upgrades, and end-of-life management. This creates business model coherence where design decisions and revenue models mutually reinforce circular outcomes.

V. CASE STUDIES

Dell Technologies: Closed-Loop Recycling

Dell Technologies has implemented extensive circular economy initiatives, including closed-loop recycling where materials recovered from end-of-life products are reintegrated into new product manufacturing (Dell Technologies, 2024). Starting in 2014, Dell began using recycled plastics from electronics waste in new computer housings, establishing a circular material flow.

The company's Asset Recovery Services collect used equipment from business customers, refurbishing devices for resale or recycling those beyond use. Dell's recycling partners recover plastics, metals, and other materials, with recycled plastics processed and compounded to meet specifications for new product manufacturing. By 2022, Dell reported that 62 million tonnes of e-waste contained valuable materials, yet only 22.3% was properly recycled, highlighting the importance of their closed-loop initiatives (Dell Technologies, 2024). The company continues to expand its use of post-consumer recycled plastics in products including Latitude laptops, which incorporate up to 50% recycled content in various components including palm-rests, bezels, and battery housings (Dell Technologies, 2024).

This approach delivers multiple benefits. Using recycled materials reduces costs compared to virgin plastics, decreases environmental impact by eliminating upstream production burdens, and supports corporate sustainability goals. The company has also leveraged its circular initiatives in marketing, differentiating products as environmentally responsible.

Dell's experience demonstrates that large manufacturers can implement circular material flows at scale when they invest in reverse logistics infrastructure, develop supplier relationships for recovered materials, and adapt product specifications to accommodate recycled content. The business case strengthens when recycled materials provide cost advantages and when sustainability performance influences purchasing decisions, particularly in business-to-business markets.

HP Instant Ink: Product-as-a-Service for Printing

HP's Instant Ink program demonstrates product-as-a-service principles applied to consumables rather than capital equipment. Customers subscribe to page-based printing plans, with HP automatically shipping ink cartridges when printer sensors detect low ink levels (HP, 2020). The service includes cartridge recycling through prepaid return envelopes.

This model shifts focus from selling ink cartridges—a traditional profit center for printer manufacturers—to selling printing services. HP retains ownership of cartridges and responsibility for end-of-life management, creating incentives to optimize cartridge design for remanufacturing and recycling. The company reports that over 80% of returned cartridges are recycled into new cartridges or other products (HP, 2020).

For customers, benefits include convenience, predictable costs, and elimination of wasteful trips to purchase replacement cartridges. For HP, the subscription model creates predictable recurring revenue, direct customer relationships, and improved loyalty. The closed-loop cartridge system improves resource efficiency and reduces waste.

This case demonstrates how product-as-a-service models can work for consumables, creating circular flows of materials while providing customer value. Success factors include convenient automated service delivery, competitive pricing compared to traditional purchasing, and effective reverse logistics for consumable collection. The model's transferability to other contexts depends on product characteristics and whether service delivery creates sufficient value to overcome consumer preferences for ownership and transaction-based purchasing.

VI. IMPLEMENTATION CHALLENGES AND ENABLERS

Successfully implementing circular business models for e-waste management requires addressing multiple challenges while leveraging key enablers.

- **Economic Viability:** Circular business models must compete economically with established linear alternatives. Collection, sorting, disassembly, and processing of e-waste involve costs that may exceed recovered material values, particularly for complex devices or when labor costs are high. Many recycling operations depend on subsidies through EPR systems or voluntary corporate programs rather than standing profitably on their own (Parajuly et al., 2020). Creating favorable economics requires reducing costs through technological innovation, achieving scale efficiencies, and increasing revenues through improved material recovery or premium pricing for refurbished products. Policy interventions like recycled content mandates, landfill restrictions, or virgin material taxes can improve circular business model competitiveness by internalizing environmental externalities in linear model costs.
- **Consumer Behavior and Acceptance:** Consumer preferences for new products, ownership over access, and convenience over sustainability pose barriers to circular models. Research indicates that while consumers express environmental concern, actual purchasing often prioritizes price, performance, and convenience (Kirchherr et al., 2017). Overcoming the stigma associated with used or refurbished products requires quality assurance, warranties, and effective communication of value propositions. Product-as-a-service models face consumer resistance in contexts where ownership conveys status or control. Sharing models encounter barriers related to trust, privacy, and convenience. Changing these preferences requires time, positive experiences, and potentially generational shifts in values. Companies can facilitate adoption through trial periods, compelling pricing, and clear communication of benefits.
- **Technological Innovation:** Processing complex electronics to recover materials efficiently requires continued technological development. Current recycling predominantly recovers common metals like steel, aluminum, and copper but often fails to capture precious metals, rare earths, and other valuable materials. Improving recovery requires innovations in automated disassembly, advanced sorting, and selective material extraction (Naimaster et al., 2020). Design for circularity also needs technological advancement. Creating durable, repairable, upgradeable electronics that maintain aesthetic appeal and performance requires engineering innovation. Standardizing components across manufacturers would facilitate repair and refurbishment but requires industry coordination and may limit design differentiation.
- **Reverse Logistics and Infrastructure:** Circular business models require robust reverse logistics to collect used products from dispersed consumers. Many potential end-of-life electronics remain unused in homes rather than entering collection systems—an estimated 4 billion mobile phones globally (Wilson et al., 2017). Establishing convenient, accessible collection infrastructure is essential but requires investment and coordination. Efficient reverse logistics minimizes transportation impacts and costs while ensuring sufficient material flows to recycling facilities. Strategies include retailer take-back programs, deposit-refund systems, curbside collection, and centralized collection events. Digital platforms can facilitate peer-to-peer transfers and improve matching between product owners and secondary users or recyclers.

- **Regulatory Support:** Government policy strongly influences circular business model viability. EPR regulations create producer obligations that drive investment in circular systems. Recycled content mandates ensure markets for recovered materials. Right-to-repair legislation enables independent repair businesses and consumer self-repair. The right-to-repair movement has gained significant momentum, with 84% of Americans supporting such laws (Repair Association, 2025). By 2024-2025, multiple U.S. states enacted comprehensive right-to-repair legislation. Oregon's law, which took effect January 1, 2025, became the first in the nation to restrict "parts pairing"—a practice requiring replacement parts to be paired to devices using proprietary software (PIRG, 2025). California's Right to Repair Act requires manufacturers to provide tools, parts, and documentation for seven years (for products over $100) or three years (for products $50-$99.99) after last manufacture date, effective July 2024 (Crowell & Moring, 2025). Colorado, Minnesota, and other states have followed with similar legislation, with 30 states introducing or carrying over right-to-repair bills in 2024 alone (PIRG, 2024). These laws are expected to save U.S. households $40 billion annually by enabling repairs instead of replacements (Built In, 2024). Conversely, regulatory barriers can impede circularity. Strict waste classification rules may prohibit beneficial reuse. Trade restrictions can prevent international markets for refurbished products. Inadequate enforcement of existing regulations allows continued illegal dumping and export of e-waste. Effective regulatory frameworks balance environmental protection with flexibility for innovative circular approaches, provide clear requirements that create level playing fields, and include enforcement mechanisms that ensure compliance.
- **Collaboration and Partnerships:** No single organization can implement circular economy transitions alone. Effective e-waste management requires collaboration among manufacturers, retailers, recyclers, policymakers, and consumers. Industry partnerships can establish standards for design, collection systems, and recycling processes. Public-private partnerships can fund infrastructure development. Multi-stakeholder initiatives can address systemic challenges like informal sector integration or cross-border waste flows. Organizations like the World Economic Forum's Platform for Accelerating the Circular Economy (PACE) and the Global Electronics Council facilitate collaboration and knowledge sharing. Industry associations develop voluntary standards and collective initiatives. Such collaboration can overcome competitive barriers to sharing information or technologies that advance circular transitions.

VII. FUTURE DIRECTIONS AND OPPORTUNITIES

The transition toward circular business models in electronics is still emerging, with substantial opportunities for innovation and improvement.

1 Digital Technologies and Circular Economy

Digital technologies including artificial intelligence, Internet of Things, blockchain, and digital platforms can enable and accelerate circular business models (Jabbour et al., 2019). IoT sensors can monitor product health and usage, enabling predictive maintenance and optimizing product-as-a-service operations. AI can improve waste sorting and material identification, increasing recycling efficiency. Blockchain can track materials through supply chains, verifying recycled content and ensuring ethical sourcing. Digital platforms can match secondary market buyers and sellers, facilitating reuse and refurbishment.

The integration of Industry 4.0 technologies with circular economy principles is accelerating. Research on Indian smart cities identified critical challenges including lack of smart technologies for tracking e-waste, insufficient strategies for integrating Industry 4.0 and circular economy, and inadequate waste management infrastructure (Gupta et al., 2025). The global IoT in product development market was valued at $48.5 billion in 2025 and is projected to reach $187.6 billion by 2035, driven by integration of smart sensors, edge computing, and AI (StartUs Insights, 2025). As of 2024, 99% of companies surveyed have either implemented or are piloting product connectivity, with 48% increasing their annual spend on IoT initiatives (StartUs Insights, 2025).

These technologies remain underutilized in e-waste management, representing significant potential. Companies integrating digital capabilities with circular strategies may achieve competitive advantages through operational efficiency, transparency, and enhanced customer value. Life cycle assessment tools combined with AI can optimize e-waste recycling pathways, particularly for pyrometallurgical and hydrometallurgical processes (Kiehbadroudinezhad et al., 2024).

2 Business Model Innovation

Current circular business models represent early innovations, with room for further development. Hybrid models combining multiple circular strategies may provide stronger value propositions. For example, manufacturers could offer product-as-a-service arrangements where customers lease devices with guaranteed buyback at predetermined values, ensuring return flows while sharing residual value risk. Performance-based contracts could link payments to sustainability outcomes, incentivizing circular behaviors throughout value chains.

Business model experimentation is particularly important for product categories where circular approaches remain limited. While mobile phones and computers have active refurbishment markets, many electronics categories lack developed secondary markets. Small electronics, integrated systems, and rapidly evolving technologies present particular challenges requiring tailored solutions.

3 Policy Evolution

Regulatory frameworks continue evolving, with opportunities to strengthen circular economy incentives. Extended producer responsibility systems could incorporate stronger design requirements, with fees clearly linked to environmental performance. Right-to-repair legislation has expanded significantly: by 2024, 30 U.S. states introduced right-to-repair bills, with several states enacting comprehensive laws (PIRG, 2024). The 2025 legislative template strengthens access to comprehensive repair documentation, now explicitly requiring board-level schematics, full parts lists, and detailed PCB layouts, while broadening prohibitions on parts pairing to cover component-level identification (Repair Association, 2025).

Recycled content mandates could drive demand for recovered materials. Research indicates that if countries could bring e-waste collection and recycling rates to 60% by 2030, the benefits—including through minimizing human health risks—would exceed costs by more than $38 billion (Baldé et al., 2024). Investment in collection and recycling infrastructure could generate $38 billion in annual economic benefits by 2030 (UNEP, 2024). Labeling schemes could inform consumers about product longevity and repairability, enabling informed purchasing decisions.

International policy coordination would address challenges like illegal e-waste exports and harmonize standards across borders. Emerging economies implementing e-waste management systems have opportunities to learn from successes and failures elsewhere, potentially leapfrogging to more effective approaches. The UK is projected to be the most extensive e-waste generator in the European area per capita by 2024, with approximately 2 million tonnes per year discarded (Raghunandan et al., 2024), highlighting the urgent need for coordinated policy responses.

4 Systemic Transformation

Ultimately, addressing e-waste sustainably requires systemic transformation beyond individual business models or policies. This includes shifting societal values from consumption and ownership to stewardship and sufficiency, redesigning education to build repair and maintenance skills, restructuring tax and financial systems to favor circular over linear activities, and fostering innovation ecosystems that support circular enterprises.

Such transformation unfolds over decades and requires sustained commitment from multiple actors. However, the electronic waste crisis provides compelling motivation. The combination of resource scarcity, environmental imperatives, and economic opportunities creates conditions for significant change. Companies, policymakers, and citizens who recognize these dynamics can position themselves advantageously while contributing to sustainability transitions.

VIII. CONCLUSION

Electronic waste represents both a critical environmental challenge and a significant economic opportunity. The linear production and consumption patterns that have dominated electronics for decades are fundamentally unsustainable, generating enormous waste volumes—62 million tonnes in 2022, rising five times faster than documented recycling efforts—depleting valuable resources worth $62 billion annually, and creating environmental and health hazards (Baldé et al., 2024). Circular economy principles offer an alternative paradigm that can address these challenges while creating economic value.

Business model innovation is essential for circular economy implementation. Product-as-a-service models align producer incentives with longevity and resource efficiency, with 75% of companies now supporting outcome-based pricing models (StartUs Insights, 2025). Refurbishment and remanufacturing operations extend product lives and create employment. Urban mining operations recover valuable materials from waste streams. Collaborative consumption increases utilization efficiency. Extended producer responsibility creates obligations that drive systematic improvements, with countries like Senegal targeting 90% e-waste recycling by 2025 (World Economic Forum, 2024). Design for circularity enables all these approaches by ensuring products can be maintained, upgraded, disassembled, and recycled effectively.

Real-world implementations by companies like Fairphone, Dell, Umicore, and HP demonstrate the practical feasibility of circular business models in electronics. These examples show that companies can build viable businesses around circular principles while generating environmental benefits. However, they also highlight challenges including economic viability, consumer acceptance, technological requirements, reverse logistics complexity, and the need for supportive policy frameworks.

The transition toward circular electronics systems has accelerated significantly. The right-to-repair movement has achieved major legislative victories, with 30 U.S. states considering such legislation in 2024 and multiple states enacting comprehensive laws expected to save households $40 billion annually (PIRG, 2024; Built In, 2024). Digital technologies offer powerful enablers for circular operations, with the IoT market projected to grow from $48.5 billion in 2025 to $187.6 billion by 2035 (StartUs Insights, 2025). Business model experimentation can unlock new sources of value and address product categories where circular approaches remain underdeveloped. Policy evolution can strengthen incentives and remove barriers to circular activities.

Successfully managing e-waste through circular economy approaches requires collaboration among manufacturers, retailers, recyclers, policymakers, and consumers. No single actor can drive the necessary changes alone. However, the confluence of resource constraints, environmental imperatives, and technological capabilities creates unprecedented opportunities for transformation. The dramatic acceleration in right-to-repair legislation, the growth of product-as-a-service models from questioning to mainstream adoption within just two years (Circuly, 2024), and the potential for $38 billion in annual benefits from improved recycling infrastructure (Baldé et al., 2024) demonstrate that circular transitions are not merely aspirational but economically viable and increasingly supported by policy and market forces.

Organizations and societies that embrace circular principles and develop effective implementation strategies will be better positioned for long-term sustainability and prosperity. The electronics industry stands at a crossroads. Continuing linear practices will exacerbate environmental degradation, resource depletion, and social harm. Embracing circular economy principles offers a path toward sustainability that can simultaneously address environmental challenges, enhance resource security, and create economic opportunities. The business models examined in this paper demonstrate that circular electronics systems are not merely aspirational but achievable with commitment, innovation, and systemic support. The challenge and opportunity for coming decades is to scale these approaches from pioneering examples to mainstream practice, fundamentally transforming how electronics are designed, produced, consumed, and managed at end-of-life.

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