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The Future of E-Waste Management under the Circular Economy: An Analytical and Econometric Study of the Impact of the Internet of Things and Smart Robotics

مستقبل إدارة النفايات الإلكترونية في ظل الاقتصاد الدائري: دراسة تحليلية قياسية لأثر إنترنت الأشياء والروبوتات الذكية

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Abstract :

This study examines the pivotal role of smart technologies in e-waste management within the framework of the Circular Economy. Through the analysis of case studies for both Apple and Sensoneo, the results indicate that the integration of the Internet of Things (IoT) reduces operational expenses by 30%, while advanced robotics facilitate the recovery of precious metals by nearly 100%. Most notably, these advancements contribute to enhancing revenue generation by reclaiming valuable resources. These results confirm the validity of the Corporate Environmental Kuznets Curve (EKC) hypothesis, proving that technological innovation is the primary catalyst for reaching the environmental turning point in the technology sector.

Keywords: Internet of things, Smart robotics, E-waste management, Environmental Kuznets Curve, Circular Economy.

JEL classificationcodes:Q53, Q55, O33, L21, C23

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1. Introduction.

Recent years have witnessed a significant increase in the volume of electronic waste globally, driven by continuous technological advancement. The danger lies in the fact that the vast majority of this waste ends up in landfills, leading to a multi-dimensional threat: environmentally through the leakage of toxic materials, and economically through the massive loss of material value and precious metals.

In light of these challenges, there is an urgent need to adopt integrated management models that enhance both environmental sustainability and economic efficiency. Modern developments in IoT and robotics form the cornerstone of this shift; these technologies significantly improve economic viability by reducing operational collection costs and maximizing the recovery rates of high-value materials.

Using advanced algorithms, these technologies identify and separate precious metals, allowing them to re-enter supply chains as cost-effective production inputs compared to virgin raw materials. Smart recycling is not only an environmental necessity but a powerful economic driver within the circular economy. It aims to transform the burden of waste into sustainable profit margins, achieving a vital balance between financial growth and environmental protection.

Research Problem

To focus our work, we have posed the following problem:

How can the Internet of Things and smart robotics contribute to transforming electronic waste from an environmental burden into a sustainable economic resource within a circular economy model?

Sub-questions

To address the technical and economic dimensions of this research problem, the study seeks to answer the following sub-questions:

1. To what extent can IoT-based smart sensing infrastructures enhance e-waste collection efficiency and mitigate the carbon footprint?
2. Does the integration of advanced robotics support the Corporate Environmental Kuznets Curve (EKC) hypothesis by enabling a technical turning point in the relationship between corporate revenue and environmental impact?

Hypothesis

Based on theoretical trends and preliminary evidence, this study proposes the following hypotheses:

- **Hypothesis 1:** The implementation of IoT technologies transforms traditional waste management into a dynamic, data-driven system, which significantly optimizes collection processes and reduces the carbon footprint.
- **Hypothesis 2:** Smart robotic innovations facilitate a non-linear (inverted U-shaped) relationship between corporate revenue and environmental degradation, allowing firms to reach an "absolute decoupling" point.

The Objective of the Study

The rapid growth of electronic waste is concerning, as millions of tons of discarded devices threaten our environment annually; simultaneously, they represent an untapped treasure of resources. This study aims to highlight the efficiency of IoT in optimizing collection and significantly reducing logistical carbon emissions, followed by intelligent disassembly through advanced robotics for precise material recovery. The impact of this approach is twofold: environmentally, it mitigates the carbon footprint and enables firms to transcend the environmental degradation threshold; economically, it slashes operational costs and maximizes recovered value. This transformation gives every device an opportunity for a new life, fueling the circular economy and achieving an absolute decoupling between economic growth and environmental impact.

The significance of the Study

Globally, the volume of electronic waste is increasing by 7% annually and is expected to double within a decade. It poses a rapidly accelerating global challenge, carrying significant risks due to the leakage of hazardous elements and the massive loss of precious metals. The toxic contents in discarded devices harm environmental health and represent a wasted economic opportunity. Recycling today represents an advanced system that uses smart technologies to transform electronic waste into valuable resources. It relies on intelligent algorithms for tracking and sorting, ensuring the safe treatment of hazardous substances. The economic significance of this system lies in reducing operational costs associated with collection processes and maximizing financial returns by recovering high-value materials that re-enter supply chains. This system aims to achieve a sustainable circular economy by reducing the carbon footprint and utilizing recycled resources, thereby achieving the 2030 Sustainable Development Goals by balancing profitability with environmental protection.

Methodological Approach

This study follows an integrated methodology combining descriptive-analytical and econometric methods. The descriptive-analytical approach is employed to examine official company reports

and financial ratios, providing a deep understanding of how smart technologies optimize e-waste management. Complementing this, the econometric method is used to test the Environmental Kuznets Curve (EKC) hypothesis by modeling the non-linear relationship between corporate revenue and carbon emissions. This dual approach aims to evaluate the effectiveness of technological integration in achieving environmental sustainability alongside economic performance.

Literature Review

Within this context. for instance, (Bounab, 2020) addressed the environmental and health risks resulting from the reality of haphazard disposal of electronic waste, presenting alarming figures about the significant growth in the generation of these wastes coinciding with governments' secrecy regarding collection and disposal methods. The researcher concluded that the absence of environmental justice and the imbalance in responsibility-sharing are the main reasons for the persistence of e-waste damages.

(Benaichouba, 2024) focused on sustainable development and e-waste management, revealing crucial findings. E-waste was identified as the fastest-growing segment within solid waste categories, containing hazardous materials capable of contaminating water and soil, thereby posing significant environmental and public health risks. The research emphasizes that strategic investment in e-waste management represents a vital component for achieving sustainable development. This requires adopting sustainable approaches and fostering innovative projects that enhance environmental quality while promoting a sustainable economy.

(Anne P.M. Velenturf , Phil Purnell, 2021) proposed a circular economy framework focused on material extraction from waste through ten key principles. They analyzed this technology-driven approach that generates economic value while reducing environmental pressure, while critically examining potential shortcomings in its implementation to ensure genuine sustainability in material recovery and resource utilization processes.

(Abhishek N. Srivastava et al, 2025) demonstrated that e-waste holds significant economic potential through precious metal recovery. Their study found that an integrated approach combining thermal techniques with bioleaching proved to be a cost-effective alternative for enhanced metal recovery from e-waste. The research highlighted that advancements in treatment technologies have successfully addressed challenges associated with conventional e-waste treatment methods. The study emphasized that there exists ample opportunity for further technological advancement through the integration of discrete techniques, which could lead to more efficient and comprehensive metal recovery from electronic waste materials.

(Abdullah Addas et al, 2024) developed an IoT-based smart waste management system utilizing ultrasonic sensors and dynamic route optimization, which demonstrated significant improvements in pilot deployments in Lahore including a 29% reduction in fuel consumption, 32% improvement in route efficiency, and 33% increase in processing throughput through real-time monitoring and LoRaWAN-enabled cloud analytics.

(Berghout oussama, Boualem maouchi, 2023) concluded that Zen Robotics provides products and solutions that help improve recycling and waste sorting processes. These solutions are distinguished by their ability to handle a wide range of waste types and contribute to enhancing the circular economy by increasing recycling rates and reducing waste sent to landfills, while improving process efficiency which reduces processing costs.

(Boubellouta, A., & Kusch-Brandt, 2020)tested the Environmental Kuznets Curve (EKC) hypothesis across 30 European countries using the STIRPAT model and Panel Quantile Regression. The study focused on measuring the impact of GDP per capita as a primary independent variable to predict e-waste generation. Their findings confirmed an inverted U-shaped relationship, proving that e-waste increases with income growth until reaching a 'turning point' where it begins to decline. This supports the current study's orientation by demonstrating that financial growth, when coupled with technological innovation, is the key driver for achieving environmental 'decoupling' and transitioning toward sustainability.

Previous studies form a fundamental pillar for our research, providing an integrated vision starting from the diagnosis of the e-waste problemBounab, Benaichouba, and the frameworks of circular economyVelenturf&Purnell,.Furthermore ,Boubellouta&Kusch-Brandt, validated the EKC hypothesis, proving that financial growth and innovation drive waste reduction at a specific 'turning point'. This is culminated by proving the feasibility of technical solutions like IoTAddas et al., and roboticsBerghout&Maouchi, in enhancing efficiency and material recoverySrivastava et al,Together, these contributions establish a solid foundation for our research on leveraging smart technologies to transform e-waste into an economic resource.

2. Electronic Waste: A Conceptual Overview

This theoretical framework on electronic waste serves as a fundamental reference for comprehending the core concepts and principles regarding the severity and proliferation of e-waste, as well as the imperative to leverage technology for a more sustainable world.

2.1 Definition and Classification of E-Waste

Establishing a precise definition is the foundational step in understanding its scope, E-waste is commonly defined as "electrical or electronic equipment which is waste, including all components, subassemblies and consumables, which are part of the equipment at the time the equipment becomes waste" (Word Health Organization, 2021, p. 4).

It must be clarified that electrical and electronic equipment comprises a wide variety of products, each with its unique material content, form of disposal and recycling approaches, and each causing unequal harm to the environment and human health if not managed in an environmentally sound manner. EEE is classified by function, material composition, average weight and end-of-life attributes into 54 distinct product-centric categories known as the UNU-KEYs. EEE becomes e-waste (or WEEE) once it has been discarded by its owner as waste without the intent of reuse. The 54 EEE product categories are further grouped into 6 general categories that broadly correspond to their waste management characteristics. (Bladé et al, 2024, p. 21)

This classification aligns with both the EU WEEE Directive and the internationally recognized framework for e-waste statistics set forth in the E-waste Statistics Guidelines: (Bladé et al, 2024, p. 21)

-**Temperature Exchange Equipement:** More commonly referred to as cooling and freezing equipment, this category comprises items such as refrigerators, freezers, air conditioners and heat pumps.

-**Screens and Monitors:** This category typically includes televisions, monitors, laptops, note books and tablets.

-**Lamps:** This category typically includes fluorescent, high-intensity discharge and LED lamps.

-**Large Equipement:** This category typically includes washing machines, clothes dryers, dishwashers, electric stoves, large printers, copying equipment and photovoltaic panels.

-**Small Equipement:** This category typically includes vacuum cleaners, microwave ovens, toasters, electric kettles, electric shavers, electronic scales, calculators, radios, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring and control instruments, and e-cigarettes.

- **Small It and Telecommunt Cation Equipement:** This category typically includes mobile and other phones, personal computers, GPS devices, routers and printers.

2.2 Harmful Compounds in E-Waste: Sources and Health Impacts:

The presence of toxic substances in electronic waste and the absence of necessary safety and precautionary measures during handling pose a significant risk to health. The following table illustrates some of these materials and their associated hazards:

Table1. Harmful compounds in e-waste, their sources, and health impacts

Toxic Constituent	Source of Exposure	Health Impact from High Exposure
Polybrominat eddiphenylether (PBDE)	Fire retardants, plastic housing, keyboards, cable insulation	Hormonal disorders, thyroiddysfunction
Polychlorinat edbiphenyl (PCB)	Capacitors, coolants, motors, dielectric fluids, transformers, lubricants	Thyroid dysfunction, liver damage, carcinogenic in animals
Chromium (Cr)	Corrosion-resistant films, memory tapes, disks, hardeners for housings	Lung dysfunction, reproductive issues, DNA damage
Lead (Pb)	Printed circuit boards (PCBs), monitors, bulbs, CRTs, cabling	Brain damage, nervous system issues, kidney and blood disorders
Nickel (Ni)	Batteries, computer housings, CRTs, PCBs	Allergic reactions, bronchitis, reduced lung function, lung cancer
Copper (Cu)	Wires, PCBs	Headaches, dizziness, eye, nose, and mouth irritation
Cadmium (Cd)	Semiconductor chips, infrared detectors, printer inks, toners, Ni-Cd batteries	Kidney and liver toxicity, neural damage, irreversible health effects
Mercury (Hg)	Batteries, backlight bulbs, flat panel displays, switches, thermostats	Brain damage, kidney failure, fetal harm
Arsenic (As)	Light-emitting diodes (LEDs)	Skin diseases, lung cancer, impaired nerve signaling
Antimony (Sb)	CRT glass, plastic housings, solder alloys	Stomach pain, vomiting, diarrhea, stomach ulcers
Barium (Ba)	Spark plugs, fluorescent lamps, CRT tubes	Brain swelling, muscle weakness, heart, liver, and spleen damage
Beryllium (Be)	Power supply boxes, motherboards, relays, finger clips	Berylliosis, lung cancer, skin disease
Selenium (Se)	Older photocopiers	Silicosisfromprolongedexposure

Source:(Quinto & al, 2025, p. 6)

Without a significant reduction in e-waste generation and improvement in its management strategies, the threat it poses to public health will continue to escalate.

2.3 International agreements on E-Waste

The transboundary movement of hazardous wastes and their disposal is controlled by the Basel Convention. This comprehensive environmental agreement seeks to address issues related to hazardous wastes, including e-waste and its management. In 2019, the Ban Amendment to the Basel Convention came into force, prohibiting the transfer of hazardous wastes - such as e-waste - from OECD countries, European Commission member states, and Liechtenstein to other parties of the Convention. Through various programmes and workshops, the Basel Convention develops and delivers guidance on the environmentally sound management of e-waste. It also offers states guidelines for distinguishing between waste and non-waste, as well as for managing the transboundary movement of e-waste. In addition, regional agreements like the Bamako Convention and the Waigani Convention exist. Both emerged in response to the Basel Convention and aim to impose further restrictions on the movement of hazardous wastes, including e-waste, in Africa and the South Pacific, respectively.(WHO, 2025).

3. Circular Economy Trough E-Waste management

As awareness about the need for electronic waste recycling grows within the circular economy framework, understanding the processes involved becomes essential. E-waste recycling is a comprehensive procedure that entails several stages, from collection to the final recovery of materials, aligning with circular economy principles by maximizing resource efficiency and minimizing waste:

3.1.Circular Economy

As a sustainable alternative to the traditional linear model, the circular economy offers a framework for rethinking how electronic products are managed throughout their lifecycle. It intends to uncouple economic development from resource use via the use of a regenerative model. This approach tries to minimize trash creation and environmental effects associated with e-waste by retaining the value of electronic goods and materials inside the system. It encourages methods like repair, refurbishing, remanufacturing, and recycling to keep goods and materials in use for as long as feasible rather than adhering to the conventional linear "take-make-dispose" paradigm. (Shweta Goyal & Sugam Gupta, 2024, p. 7)

Circular economy substitutes the end-of-life concept with restoration and regeneration., shiftingtowards usage of superior design of materials, products, systems and business models for waste elimination. The Ellen MacArthur Foundation reports that circular economy principles could lead to a 28% reduction in global resource use by 2050 compared to a business-as- usual scenario. (Chinchkhede, 2024, p. 37) It can offer immediate solutions by extending product life cycles, and recovering functional and material

value from e-waste. In a circular economy for electronics, consumer electronic products will be kept in use for as long as possible, then professionally remanufactured for reuse, refurbished, or repaired, and the valuable components within them will be separated and recycled. (Ellen Macarthur Foundation, 2021) .Within this framework, e-waste is considered a crucial resource. By establishing sustainable resource flow loops, circular economy seeks to reduce the consumption of new materials and minimize waste generation. It not only addresses resource scarcity and waste generation but also offers economic opportunities through recycling and recovering valuable materials. It encourages the reuse and recycling of e-waste, making it a promising sector for future development. To achieve this, environmental, health, economic, and technological considerations must be incorporated into the system. (G. Raghunandan et al, 2024, p. 333).

3.2.Eliminating E-Waste

In 2023, UNEP supported countries in reducing waste. According to the Circularity Gap Report, Latin American and Caribbean countries could reduce their material use and carbon footprint by 30 per cent through the implementation of circular economy strategies. The 2050 Electrical and Electronic Waste Outlook in West Asia indicated that recycling electronics in the region could enable the recovery of 130 tonnes of gold, 17 million tonnes of iron and steel, and 5,000 tonnes of rare-earth metals by 2050. This report was released on the inaugural International Day of Zero Waste, which was led by UNEP and UN-Habitat with the support of Türkiye. With backing from the GEF, UNEP led projects worldwide aimed at cleaning up hazardous waste, resulting in the proper disposal of 216 tonnes of electronic waste in Nigeria, 32 tonnes of the pesticide dichlorodiphenyltrichloroethane (DDT) in Ethiopia, and 211 tonnes of polychlorinated biphenyls (PCBs) in Cameroon. (UNEP, 2023, p. 16).

3.3. Innovative Technologies for E-Waste Recycling

Unlike conventional solid waste such as household refuse, electronic waste possesses both hazardous and valuable characteristics. Traditional recycling practices involve manually dismantling devices to separate metals, plastics, and circuit boards—a process that is slow, labor-intensive, and often involves direct handling of hazardous materials. In many cases, electronic devices are simply shredded outright; while this method can recover materials like gold and silver, other critical raw materials, including rare earth elements, are frequently lost. This inefficiency in material recovery remains one of the greatest obstacles to achieving a truly

circular electronics economy, in which products are designed for longevity and recyclability. (Emmino, 2025).

Contrary to conventional solid waste such as domestic garbage, electronic waste possesses both hazardous and valuable characteristics. When considering resource recovery, the metal and non-metal components found in e-waste are amenable to extensive recycling. E-waste encompasses as many as 60 distinct metals, including copper, gold, silver, palladium, aluminium, and iron. (Chaitankar, 2025, p. 104). With ongoing advancements in technology and innovation, new approaches to tackling e-waste continue to emerge. Among these, the integration of artificial intelligence stands out as a promising path, offering a broad spectrum of potential applications for reducing electronic waste. In the context of e-waste reduction, AI can improve product design by facilitating easier disassembly and pinpointing components that are best suited for reuse or recycling. (Quinto & al, 2025, p. 17).

a. Internet of Things (IOT)

In line with the potential of AI to transform e-waste management, the Internet of Things (IoT) offers a broader technological infrastructure that can further support the transition toward smarter and more sustainable systems. It is a concept and a paradigm that considers pervasive presence in the environment of a variety of things/objects that through wireless and wired connections and unique addressing schemes are able to interact with each other and cooperate with other things/objects to create new applications/services and reach common goals. In this context the research and development challenges to create a smart world are enormous. A world where the real, digital and the virtual are converging to create smart environments that make energy, transport, cities and many other areas more intelligent (Ovidiu Vermesan & Peter Friess, 2013, pp. 7-8).

The IoT enables information exchange and communication across device-to-device, device-to-people, and device-to-environment interactions. It is a network system that connects equipped with minuscule identifying devices such as RFID, sensors and smart objects with the Internet according to the information shared by the sensing devices and the agreed protocols to realize quick, reliable and real-time information exchange and communication, achieving intelligent identification, location, tracking, monitoring, and management. The interconnected objects are inexhaustible sources of information, it creates a vast amount of data which need communication infrastructure, computational and processing units to convert this data into useful information to enable real-time decision making. This infrastructure is placed generally in cloud (M. Safa et al, 2016, pp. 2-3).

b. Smart Robotics

The application of automated systems in e-waste recycling represents a fundamental operational shift, moving beyond the limitations of human labor to address the unique complexities of electronic waste. Robots, equipped with advanced sensors and artificial intelligence, can perform the repetitive, precise, and often dangerous tasks of disassembly and sorting with a level of accuracy and endurance that humans cannot match.

The integration of robotics into e-waste recycling facilities is still in its early stages, but the initial applications have demonstrated significant potential. Current systems primarily focus on the critical tasks of sorting and disassembly, which have traditionally been major bottlenecks in the recycling process. These robotic systems leverage a combination of computer vision, machine learning, and sophisticated manipulators to handle the diverse and complex nature of electronic waste.

One of the most developed applications of robotics in this field is in automated sorting. Material recovery facilities (MRFs) are increasingly employing robotic arms guided by AI-powered vision systems. These systems can identify and separate different types of materials with remarkable speed and accuracy.

The technology behind this capability is a fusion of advanced imaging and intelligent algorithms. Hyperspectral cameras, for example, can analyze the unique spectral signature of different materials, allowing the system to identify substances that are visually indistinguishable to the human eye. Machine learning models are trained on vast datasets of e-waste images, enabling them to recognize a wide array of components and materials with increasing accuracy over time. This data-driven approach allows the robotic systems to adapt to the ever-changing composition of e-waste as new electronic products enter the market.

While sorting addresses the separation of bulk materials, the disassembly of complex electronic devices presents a more intricate challenge. Many modern electronics are not designed for easy disassembly, featuring glued components, proprietary screws, and delicate internal structures. Robotic systems are being developed to tackle this complexity with a combination of force-sensing actuators, 3D imaging, and intelligent tool-changing capabilities. These robots can carefully pry open casings, remove screws, and extract specific components like batteries, circuit boards, and valuable chips without damaging them. (Sustainability Directory, 2025)

4. Case Studies

The development and integration of technology and robotics to sustainably manage e-waste is critical to achieving a circular

economy (CE). Economically, these innovations drive cost-efficiency by reducing labor overheads and maximizing the recovery of high-value materials. Environmentally, they facilitate a significant reduction in carbon footprints and toxic leakage by precision-sorting hazardous components. The following technological advancements in robotics have fundamentally influenced e-waste management:

4.1 Internet of Things (IOT) For E-Waste Management"Sensoneo as a Case Study"

Sensoneo has established itself as a global leader in IoT-driven waste management, achieving recycling rates above 90% across five nations. Founded in 2017 in Bratislava, Slovakia, the company transitioned from a niche sensor provider to a comprehensive circular economy integrator. Their core innovation lies in the "Quattro" smart sensors—robust, eco-friendly devices made from recyclable polyamide that offer 97% accuracy in fill-level detection. By providing real-time data updates up to six times daily, Sensoneo enables a transition from "static" collection schedules to "dynamic" data-driven logistics. This shift has proven transformative: in Madrid, the deployment of 11,100 sensors optimized urban waste flow, while in the Czech Republic, a partnership with the Asekol platform facilitated the collection of over 44,500 tons of e-waste in a single year. Ultimately, Sensoneo demonstrates how IoT serves as the technological backbone for meeting stringent legislative recycling mandates and achieving absolute decoupling of growth from environmental degradation (SENSONEO, 2025).

- **Analysis of IoT Impact: Economic, Environmental, and Circular Dimensions**

The following table categorizes the quantitative and qualitative impacts of Sensoneo's IoT integration:

Table2. Analysis of IoT Impact

Dimension	Key Performance Indicator (KPI)	Impact Description
Economic	-30% Operational Costs	Eliminating unnecessary pick-ups of half-empty bins and optimizing fuel consumption and labor hours.
Environmental	-60% Carbon Emissions	Significant reduction in the carbon footprint of collection fleets due to optimized, shorter route planning.
Circular Economy	>90% Recycling Rate	High-purity collection and real-time monitoring ensure that e-waste is directed to specialized recycling streams rather than landfills.
Technical Efficiency	97% Detection Accuracy	High-precision data prevents overflow and improves the reliability of the entire waste management chain.

Source: (SENSONEO, 2025)

- **Strategic Highlights:** These strategic milestones demonstrate how IoT infrastructure and circular design effectively bridge the gap between regulatory mandates and operational sustainability:
- **Infrastructure:** Deployment of 11,100 sensors (e.g., Madrid) demonstrates scalability.
- **Compliance:** Moving beyond the 65% legislative mandate to reach 90%+ recycling rates.
- **Resource Loop**: The hardware itself (Quattro sensors) is part of the circular economy, utilizing recyclable polyamide fibers and replaceable batteries.

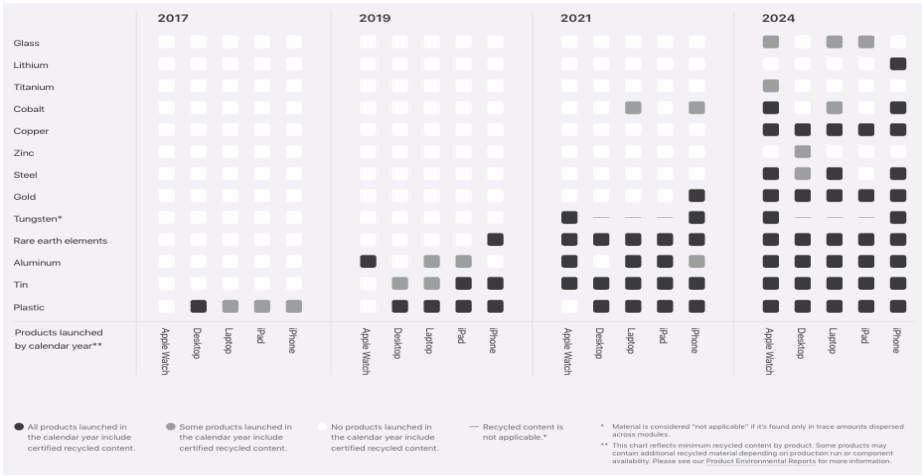
The Sensoneo model proves that IoT is not merely a monitoring tool but a catalyst for Strategic Impact, where economic savings (30%) and environmental restoration (60% emission reduction) occur simultaneously through technological innovation.

5.1 Smart Robotics for Advanced E-Waste Processing: "Apple as a Case Study"

Apple adopts an innovative approach in transitioning towards a circular economy, having developed new intelligent advanced disassembly technologies to maximize material recovery and minimize waste. The company has engineered innovative solutions including the Daisy robot capable of disassembling 36 iPhone models, autonomous mobile robots (AMRs) handling over 80,000 material deliveries in 2024, and specialized machines like Dave for Taptic Engine disassembly and Taz for rare earth element recovery. These technologies are deployed globally through recycling partnerships, supported by augmented reality systems for guided disassembly. Apple's comprehensive approach significantly enhances recycling efficiency while supporting circular economy objectives through scalable, sustainable infrastructure.(Apple, 2025, p. 48).

Apple has made significant, notable, and tangible progress toward its ambitious goal of relying solely on certified recycled or responsibly sourced renewable materials for its products and packaging. The company has always emphasized that the source of materials matters, valuing those that do not deplete the Earth's resources; accordingly, the figure below provides a detailed overview of the performance of recycled materials across Apple's main product lines, based on the latest available reports:

Fig.1.Apple's Transition to Certified Recycled Materials by Product Line



Source:(Apple, 2025, p. 14)

In 2024, Apple reached a pivotal milestone in its circular economy journey, successfully decoupling industrial growth from resource extraction through a sophisticated closed-loop system. By leveraging advanced robotics—specifically Daisy, Dave, and Taz—the company achieved unprecedented recycling rates, including 100% recycled cobalt, gold, tin, and copper in key components, while increasing recycled lithium integration to 53%. This technological evolution has not only slashed aluminum-related emissions by 76% since 2015 but has also transformed e-waste into a high-value economic asset. Ultimately, Apple's transition from virgin material reliance to a certified recycled supply chain serves as a premier global model for applied circular economy, proving that systemic sustainability can drive both environmental restoration and long-term economic resilience (Apple, 2025, pp. 14-17).

- **The Corporate Environmental Kuznets Curve:**

According to (Lin-Sea Lau, 2023), the Environmental Kuznets Curve (EKC) hypothesis describes the dynamic, non-linear relationship between economic growth and environmental degradation, traditionally represented as an inverted U-shaped curve. It studies how environmental quality initially declines during the early stages of economic development but eventually improves after reaching a specific income threshold. This improvement is driven by the 'technological effect,' where innovation leads to cleaner production methods.

Recent empirical studies have demonstrated that leading corporations in the technology sector successfully reach an "environmental turning point" through strategic technical innovation.

The current research aims to validate this hypothesis specifically forApple.

In this study, net revenue, total headcount, and energy consumption were utilized as proxy variables for Gross Domestic Product (GDP) and population growth, respectively, to measure their impact on total carbon emissions. This adaptation aims to test the EKC hypothesis for Apple by analyzing time-series data (2015–2024) extracted from its annual reports (Apple, 2015-2019), (Apple, 2020-2024) . For econometric estimation, variables were transformed into logarithmic forms, and a squared term for the logarithm of revenue was integrated to test for non-linearity using the following multiple regression model:

$$CO2 = f(PIB, PIB^2, EC, LP)$$

$$LCO2 = \beta_0 + \beta_1 LPIB + \beta_1 LPIB^2 + \beta_3 LEC + \beta_4 LP + \varepsilon$$

The model was estimated using the Ordinary Least Squares (OLS) method, enhanced with the Newey-West (HAC) estimator to address potential issues of autocorrelation and heteroscedasticity arising from the small sample size.

Table3. Estimation Results of the Corporate EKC Model for Apple

Variable	Coefficient	Prob
C	0.0256	-80.54
$LPIB$	0.0053	35.24
$LPIB^2$	0.0055	-3.05
LEC	0.0379	-0.33
LP	0.0046	-1.49

Source: by the author using Eviews .13

The results (Appendice 1) provide empirical confirmation of the EKC hypothesis for Apple. The coefficient for revenue is positive, while its squared term is negative, with both being statistically significant at the 5% level. This sequence of signs confirms the existence of a non-linear, inverted U-shaped relationship. Economically, this indicates that Apple underwent an initial phase where financial growth increased pollution; however, upon reaching a structural turning point, the company successfully reduced emissions despite rising profits a phenomenon known as Absolute Decoupling.

The negative coefficient for the energy variable (LEC) reflects a breakthrough in resource efficiency. While traditional models correlate increased energy consumption with higher emissions, Apple's model shows that a 1% increase in renewable energy inputs and efficient technologies results in a 0.33% reduction in emissions. This confirms that energy consumption at Apple has transitioned from a source of pollution to a tool for environmental improvement, driven by the shift toward 100% renewable sources.

Furthermore, the labor variable (LP) exhibits a strong negative elasticity. This suggests that Apple's workforce growth is strategically oriented toward high-value-added roles (R&D and eco-design) rather than carbon-intensive manufacturing, thereby contributing to the overall reduction of the company's carbon footprint.

Based on an R-squared value of 0.88, the model demonstrates high reliability in explaining Apple's environmental behavior, providing robust econometric evidence that tech giants can achieve sustainable economic growth aligned with Circular Economy objectives.

Normality Test: The Jarque-Bera test yielded a probability of 0.8934 > 0.05, indicating that the residuals are normally distributed and the model is free from unexplained disruptive shocks(Appendice 2).

Breusch-Godfrey Serial Correlation Test: With a Prob. Chi-Square of 0.7460 > 0.05, the test confirms the absence of serial correlation, ensuring the independence and reliability of the model (Appendice 3).

Wald Test: To ensure the robustness of the results, the Wald test was conducted to verify the significance of the EKC turning point. The high F-statistic and a p-value of (0.000) indicate that Apple's transition from increasing to decreasing emissions is statistically significant and stems from the company's technical policies (Appendice 4).

Ramsey RESET Test: To ensure the mathematical specification of the model, the Ramsey RESET test was performed. The F-statistic probability of 0.7853 > 0.05 confirms the correct structural specification and the absence of omitted variable bias (Appendice 5).

These results reinforce the reliability of the extracted EKC findings, confirming that the selected independent variables (Revenue, Energy, and Labor) accurately explain changes in Apple's carbon emissions. Consequently, it can be concluded that Apple has successfully adopted a Circular Economy model, leading to a structural reduction in emissions.

This comprehensive integration of robotics, automation, and material innovation underscores Apple's commitment to leading the transition toward a circular and sustainable industrial model.

Conclusion

The world today is advancing at a very fast pace; with evolving technologies and continuous innovations, the future of e-waste management has become inextricably linked to the digitalization and automation of the value chain. This study confirms

that integrating modern technological devices, such as the Internet of Things (IoT) and advanced robotics, into existing processes forms the cornerstone of achieving an effective circular economy. IoT systems enable precise monitoring and smart tracking that ensures the strategic distribution of resources, while advanced robots equipped with artificial intelligence enhance the efficiency of extracting precious materials such as gold and platinum.

The evidence derived from Apple and Sensoneo underscores that these technologies effectively bridge the gap between stringent regulatory compliance and economic profitability, transforming electronic waste from an environmental burden into a sustainable economic resource. Through the lens of the Corporate Environmental Kuznets Curve (Corporate EKC), it is evident that the 'environmental turning point' is no longer a distant goal, but a reality that is technically and economically achievable through focused technological innovation, ensuring supply chain resilience and achieving global sustainability.

In light of the findings, this study addresses its primary **research problem** by asserting that the integration of IoT and smart robotics contributes to transforming the burden into a resource, thereby creating a closed-loop system that achieves profitability and sustainability**.**

Confirmation of **Hypothesis1**: IoT technologies transform waste management into a dynamic data-driven system, fundamentally enhancing collection efficiency and reducing logistical emissions

Confirmation of**Hypothesis2**: The results demonstrated the existence of a non-linear relationship in the form of an (inverted U-shape) between revenue and emissions, where the company succeeded in reaching the 'environmental turning point.

Key Finding

This study identifies three critical achievements in smart e-waste management:

- The Sensoneo model proves that IoT transitions waste management from 'static' to 'dynamic' data-driven logistics, resulting in a 60% reduction in carbon footprints.
- Apple’s robotic innovations (Daisy, Dave, and Taz) have enabled the use of 100% recycled cobalt and gold in key components, effectively transforming e-waste into a strategic economic asset.
- The study confirms that technology-driven circularity allows corporations to increase revenue while simultaneously

decreasing their total environmental footprint, supporting the non-linear EKC trajectory.

Recommendations

The following recommendations are proposed:

- Governments and municipalities should incentivize the deployment of smart sensor networks (e.g., LoRaWAN) to create transparent and traceable urban waste flows.
- Manufacturers should prioritize "Design for Disassembly" to harmonize product architecture with robotic sorting capabilities.
- Update regulatory frameworks to move beyond simple collection targets toward 'high-purity recovery' mandates that reward the use of advanced sorting technologies.

Future Research Prospects

This study outlines several promising directions for advancing e-waste management technologies. Building on current achievements in IoT and robotic systems, future research should focus on:

- Exploring the application of generative AI for optimizing entire reverse supply chains and developing new methods for recovering high-purity, critical raw materials from complex e-waste.
- Investigating the scalability and economic viability of these advanced models in developing economies.
- Developing frameworks for seamlessly integrating IoT data from collection points with robotic disassembly processes to create a fully automated, data-driven circular economy system.
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5. Appendices

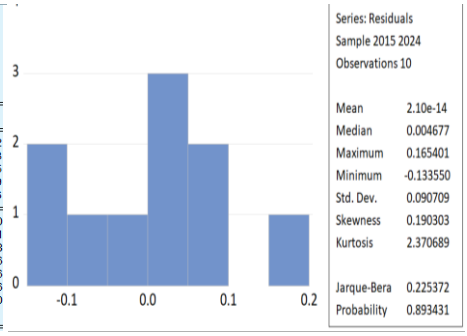
Appendix 1. Estimation Results of the Corporate EKC Model

Method: Least Squares
Date: 05/17/26 Time: 18:00
Sample: 2015 2024
Included observations: 10
HAC standard errors & covariance (Prewhitening with lags = 1, Bartlett kernel, Integer Newey-West fixed bandwidth = 3.0000)
No d.f. adjustment for standard errors & covariance

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-80.54326	24.62236	-3.271143	0.0222
M_LPIB	35.24727	7.478728	4.713004	0.0053
M_LPIB2	-3.050397	0.654086	-4.663606	0.0055
LEC	-0.335315	0.119670	-2.801988	0.0379
LP	-1.491542	0.306247	-4.870389	0.0046

R-squared	0.888122	Mean dependent var	3.160340
Adjusted R-squared	0.798619	S.D. dependent var	0.271191
S.E. of regression	0.121698	Akaike info criterion	-1.067688
Sum squared resid	0.074053	Schwarz criterion	-0.916396
Log likelihood	10.33844	Hannan-Quinn criter.	-1.233656
F-statistic	9.922865	Durbin-Watson stat	1.662386
Prob(F-statistic)	0.013482	Wald F-statistic	1612.080
Prob(Wald F-statistic)	0.000000		

Appendix 2. Normality Test for Residuals



Appendix 3. Breusch-Godfrey test

Breusch-Godfrey Serial Correlation LM Test:
Null hypothesis: No serial correlation at up to 1 lag

F-statistic	0.042419	Prob. F(1,4)	0.8469
Obs*R-squared	0.104934	Prob. Chi-Square(1)	0.7460

Test Equation:
Dependent Variable: RESID
Method: Least Squares
Date: 05/17/26 Time: 18:42
Sample: 2015 2024
Included observations: 10
No d.f. adjustment for standard errors & covariance
Presample missing value lagged residuals set to zero.

Appendix 4. Wald Test

Wald Test:
Equation: Untitled

Test Statistic	Value	df	Probability
t-statistic	-281.3514	5	0.0000
F-statistic	79158.61	(1, 5)	0.0000
Chi-square	79158.61	1	0.0000

Null Hypothesis: C(2) / (2 * C(3)) = 0
Null Hypothesis Summary:

Normalized Restriction (= 0)	Value	Std. Err.
C(2) / 2 / C(3)	-5.777489	0.020535

Delta method computed using analytic derivatives.

Appendix 5. Ramsey RESET

Ramsey RESET Test
Equation: UNTITLED
Omitted Variables: Squares of fitted values
Specification: LCO2 C M_LPIB M_LPIB2 LEC LP

	Value	df	Probability
t-statistic	0.291305	4	0.7853
F-statistic	0.084859	(1, 4)	0.7853
Likelihood ratio	0.209928	1	0.6468

F-test summary:

	Sum of Sq.	df	Mean Squares
Test SSR	0.001538	1	0.001538
Restricted SSR	0.074053	5	0.014811
Unrestricted SSR	0.072514	4	0.018129

LR test summary:

	Value
Restricted LogL	10.33844
Unrestricted LogL	10.44340

Source: by the author using Eviews .13