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Strategic forecasts for circular economy transition: Evaluation of the role of technology in economic development

Abstract. The use of a circular economy, as opposed to linear production, allows for optimal waste utilization, reduces the shortage of resources, reduces the negative impact on the environment, and achieves competitive advantages through innovation. The driving force for this transition is a technological development that enables more efficient and rapid change. The study aims to assess the impact of technology on the transition to a circular economy, which gaining prominence amid challenges posed by population growth, climate change, and environmental degradation. A combination of quantitative and systematic analysis methods was used in the study, namely exploring, categorizing, and analysing case studies, and industry reports and conducting meta-analysis. The research identified key drivers for transitioning to a circular economy, including awareness of resource depletion, environmental concerns, technological advancements, changing consumer values, and government regulations. The study explored various circular economy definitions and categorized the development of its principles into stages from 1966 to 2023. The exploration into the complex role of technology demonstrated its potential to accelerate the adoption of circular economy principles globally. The research extended beyond conventional boundaries, illustrating technology's capacity to amplify the influence of sustainable practices. As industries balanced economic growth with environmental responsibility, the study provided empirical evidence of technology's efficacy in facilitating the transition to circular economies. This study contributed valuable insights into the critical link between technological development and the circular economy transition. Successful case studies and empirical assessments offered a pragmatic foundation for policymaking, corporate strategies, and ongoing research. The study holds theoretical significance in advancing the understanding of circular economy dynamics. At the same time, it practically informs policy formulation and corporate strategies conducive to sustainable economic transformation

Keywords: sustainability; circularity; closed loop economy; regenerative economic system

INTRODUCTION

A primary issue of the modern world is the transition from the economic model of consuming finite natural resources. Substantial growth of the global population and annual expansion significantly increase the usage of Earth's resources, exceeding its regenerative limits. The current trajectory of resource consumption under the prevailing linear economic model has a high risk of causing a disbalance, causing ecological and societal crises, as well as endangering business sustainability. In pursuit of establishing and maintaining equilibrium within the complex

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interplay of the planet's systems, the transition towards a circular economy becomes a promising model. Apart from pressing environmental concerns, this shift is assumed to be a major milestone for the progressive realization of multiple United Nations Sustainable Development Goals (United Nations, 2023). Scientific studies also mention valuable perspectives on the circular economy. These studies echo the evolving narrative on circular economy practices, sustainability goals, technological development, and their integration into various sectors.

N. Trushkina (2021) conducted a comprehensive review of the circular economy, covering its conceptual formation, evolutionary development, challenges, and prospects. The study explores the challenges of its implementation and provides insights into the unique context of the Ukrainian economic landscape. D. Bayura (2021) emphasizes the circular economy as pivotal to the future success of Ukraine, aligning with the broader discussion on the transformative potential of circular practices. N. Horbal *et al*. (2021) addressed the integration of the circular economy in Ukraine based on European experiences, adding a regional perspective to the global discourse. A. Shvets (2022) positions the circular economy as a new model for Ukrainian economic development within the European Integration Process, providing insights into the practical implications of circular principles at the national level. L. Deineko *et al*. (2019) explored the opportunities and barriers for the Ukrainian industry's transition to the circular economy. M. Dubel (2022) described a circular economy for achieving sustainability goals amidst globalization and digitalization, underscoring the importance of technology research for circular economy adoption. V. Loiko *et al*. (2021) addressed financial and credit activities in the context of circular economy principles, highlighting the intersection of economic practices with sustainability goals. S. Lyholat & L. Semeniuk (2021) analysed circular economy as a direction of industrial modernization and emphasised the transformative potential of technology in the implementation of circular practices.

The adoption of innovative technologies, ranging from advanced materials and manufacturing techniques to digital platforms enabling resource tracking and efficient supply chains ensures the transition towards circularity. By describing ways in which technology intertwines with circular economy strategies, humanity can transition from limited linear, wasteful practices. Moreover, technological interventions not only optimize resource use but also support novel business models that prioritize longevity, reuse, and regeneration. The future of circular technology lies in digital transformation, which not only enhances transparency but also expedites the shift toward a circular economy. Digitalization is progressively emerging as a predominant driver across industries. In alignment with the circular economy's resource optimization objectives, a notable relation between the two domains is present. Contemporary digital technologies, such as the Internet of Things (IoT), Big Data, artificial intelligence (AI), 3D printing, and blockchain, are substantial in augmenting the circular economy (Tenyukh *et al*., 2022).

Therefore, the study aimed to evaluate the role of technological advancements in the development of economic practices as well as the transition towards them based on example cases. The research tasks involved exploring, categorizing, and analysing technological factors that influence the circular economy transition, particularly emphasizing successful cases.

MATERIALS AND METHODS

This study employs a methodological framework to formulate the theoretical, methodological, and practical methods to evaluate the role of technology in the circular economy transition. This framework is also used to address the strategic forecasts of such transition based on case studies. The research methodology for this study is characterized by a correlation of quantitative and systematic analysis, providing a comprehensive analysis of the intricate dynamics between technology adoption and circular economy strategies.

This study employs a multifaceted approach to meet the aforementioned goals. The study employed a combination of quantitative analysis to determine relationships and trends between technological advancements and circular transition and case example investigation to analyse real-world contexts to identify further trends. Furthermore, the inclusion of comparative case studies was used to describe contextual factors shaping the correlation between technology and circular economy practices. This approach allows for a nuanced understanding, acknowledging that the adoption of technology in circular transitions is not a one-size-fits-all scenario.

The methodological framework also incorporates systematic data analysis of industry reports to augment insights into the role of the technology in the roadmap to circularity. Industry reports serve as valuable sources of information, providing a broader perspective on the macro-level trends and challenges associated with the integration of technology in circular economy transitions. Additionally, the application of a meta-analysis methodology is chosen for its logical and abstract analysis facilitation. The meta-analysis methodology enables a comprehensive synthesis of existing research, unveiling broader patterns and correlations that transcend individual cases of circular economy transition.

In acknowledging the study's inherent limitations, it is worth noting that while quantitative analysis offers statistical robustness, it may not capture the entirety of contextual nuances regarding circular economy transition, as it is a novel practice that requires further research. Additionally, case examples, despite their usefulness, were not employed in this study. The employment of a meta-analysis methodology, while capable, relies on limited available literature and might be constrained by data availability and quality. These aspects were used in the interpretation of findings, providing a holistic perspective on the study results.

RESULTS AND DISCUSSION

Over the span of the 19th and 20th centuries, the Industrial Revolution has been predominantly governed by a linear production and consumption model. In this model, products are manufactured from raw materials, sold, utilized, and subsequently discarded either through landfilling or incineration. This evolutionary trajectory, enabled by technological development, substantially increased economic productivity and ensured the prosperity of society.

In its pursuit of expansion, this economic structure has incentivized heightened sales and the emulation of economies of scale, thereby engendering a perpetual escalation in the consumption of commodities and services. This economic model exhibits a distinctive "take, make, waste" pattern. It is based on two foundational presumptions: the infinite availability of resources (both energy and raw materials) and the inexhaustible regenerative capaci-ty of the Earth (Wautelet, 2018). As the economy develops, the demand for raw materials increases to meet increased production requirements, consequently resulting in the increased depletion of natural resources and generation of waste. This is illustrated in Figure 1.

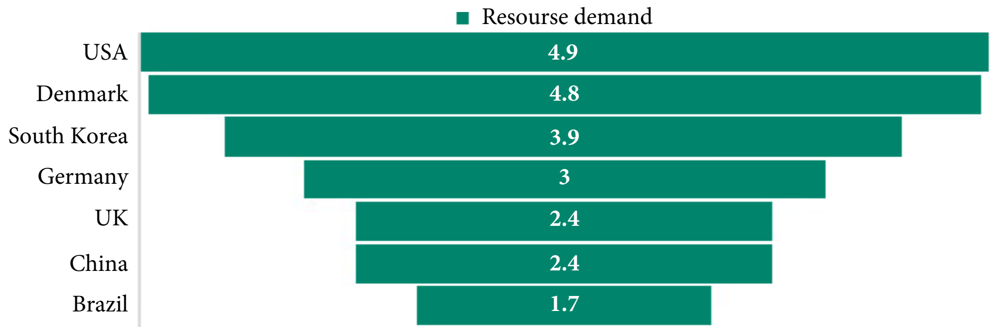

Figure 1. Number of resources needed (in number of Earths) to satisfy 21st-century consumption levels by country
Source: adapted by the authors from A. Fleck (2023)

Estimates from the NGO (Non-governmental Organization) Global Footprint Network (2023) reveal that if the entire global population adopted lifestyles akin to those of the United States, the planetary resources would be depleted at a staggering rate, requiring 4.9 more Earths to meet the demand within a year. The driving force behind this advancement is primarily attributed to industrialized nations, with countries like Qatar, Luxembourg, and Bahrain demonstrating even higher resource consumption, equivalent to 5.4 to 8.7 Earths if their lifestyles were universalized. Despite their significant resource demands, their smaller populations temper their global impact when compared to larger nations like the United States.

Across Europe and Asia, major industrialized nations reflect similar patterns, requiring 2.6 to 4.8 Earths to sustain their consumption if universally applied. China's living standards necessitate the use of 2.4 Earths. In contrast, Indonesia aligns closely with the allotted global resource capacity, signifying its responsible consumption practices, while India consumes only 0.7 Earths annually (Fleck, 2023). Consequently, this trajectory will cause increased CO_2 emissions and waste generation. The input from developed nations currently exceeds that of developing countries by over threefold (Hieminga, 2015). This leads to a significant fear for the future of the coming generations if the world does not change the current economic model.

The fusion of industrial and technological progress, coupled with widespread global trade, caused significant economic expansion, catalysing human well-being. Nonetheless, the foundational principles of the linear model are no longer applicable within the contemporary global landscape. Several pivotal trends now imperil its sustainability, thus precipitating demand for an alternative economic paradigm (Wautelet, 2018). Since the 2010s, scientists around the world addressed this problem by investigating a novel economic paradigm known as the "circular economy". Advocates of this concept contend that circular growth holds the potential to address the climate crisis while expediting the emergence of an inclusive green economy. Besides this, the emergence of the concept of a circular economy was driven by several interrelated factors that prompted humanity to reconsider traditional linear economic models. These factors are presented in Figure 2. Collectively, these factors necessitated the analysis and development of the circular economy as a viable alternative to traditional linear economic models. The circular economy's potential to address environmental, economic, and social challenges garnered attention from scientists, policymakers, and businesses alike, prompting the rethinking of established economic paradigms. The essence of this economic model was described in a 2019 study conducted by scholars from the University of Oxford (Haney *et al.*, 2019), describing interviews with participants of the Platform for Accelerating the Circular Economy (PACE). These experts concurred that the circular economy embodies a regenerative design, striving to retain most resources within products, their constituents, and materials. Unlike growth models based on the utilization of finite resources, the circular economy is not contingent upon such resource consumption. It fundamentally emerges as a progressive trajectory steering society toward sustainable development (Trushkina, 2021).

Resource Depletion

The realization that finite natural resources were being rapidly depleted due to linear consumption patterns spurred the need for alternative economic models that could ensure sustainable resource use over the long term.

Environmental Concerns

Escalating pollution, waste generation, and environmental degradation highlighted the detrimental impacts of the linear "take-make-dispose" approach. As the negative consequences became more apparent, there was a growing impetus to explore strategies that minimized environmental harm.

Economic Pressure

The inefficiencies inherent in the linear economy, characterized by the excessive use of resources and waste generation, led to economic inefficiencies. Businesses recognized the potential for cost savings and enhanced profitability by transitioning to models that optimized resource use.

Innovative Technologies

Technological advancements offered new possibilities for resource-efficient production, recycling, and remanufacturing. These innovations provided the tools necessary to reimagine economic systems and their reliance on virgin resources.

Shift in Consumer Values

Evolving consumer preferences towards sustainable and ethically produced products created a market demand for environmentally responsible goods and services. Businesses started recognizing the competitive advantages of catering to these preferences.

Policy and Regulation

Growing awareness of environmental issues prompted governments to introduce regulations aimed at curbing waste and pollution. This regulatory environment nudges businesses to adopt more sustainable practices.

Global Collaborations

International initiatives and agreements, such as the United Nations Sustainable Development Goals (SDGs) (United Nations, 2023), highlighted the urgency of transitioning to more sustainable economic models. This global momentum encouraged research and discussions about circular economy principles.

Scarcity Concerns

The rising scarcity of certain raw materials and the potential for geopolitical conflicts over resource access underscored the need for strategies that ensure resource security through recycling and reusing materials.

Figure 2. Factors driving reevaluation of traditional economic models
Source: adapted by the authors from S.A. Neves & A.C. Marques (2022)

The concept of the circular economy holds diverse perspectives within the realm of scientific literature. Typically, scholars tend to link this concept to such terms, as "circular economy", "cyclical economy", "renewable economy", "closed-loop economy", and "green economy", among others. Some researchers state that the circular economy signifies a novel phase in the evolution of sustainable development particularly the green economy (Murray *et al*., 2015). The circular economy introduces a novel economic paradigm rooted in cyclical business models. Rather than adhering to the conventional pattern of resource extraction, transformation into products, and eventual waste generation, the circular economy emphasizes the extension of product lifecycles and the reincorporation of raw materials, imbuing them with renewed utility.

However, a less frequent viewpoint regards it as an autonomous trajectory within the economic theory of the 1970s. Notably, the circular economy is not an alternative to the "green economy" but is an intrinsic element of it to attain sustainable development (Trushkina, 2021). As for a more modern view, in the context of the U.S. Save Our Seas 2.0 Act of 2020, the circular economy is defined as a model that employs a systemic approach. This approach is based on renewable or regenerative industrial processes and economic activities. The core idea is to ensure that resources employed in these processes and activities retain their value for as long as possible, thus eliminating wastage (Hope, 2022).

Despite some differences, the diverse schools of thought share a common foundation: the current industrial economic system is unsustainable, necessitating the re-establishment of a harmonious relationship with the environment. Consequently, the ecosystem, encompassing the economy and society, must be viewed as just one of many ecosystems and an integral component of the environment (namely, the biosphere). Faced with these challenges, these schools of thought universally advocate for solutions drawing inspiration from nature, aiming to optimize resource utilization while concurrently mitigating adverse environmental repercussions (Wautelet, 2018).

The idea of the circular economy is to mitigate the life cycle impact of materials, curbing the utilization of deleterious substances, and decreasing material consumption necessity for economic expansion. Moreover, this approach prioritises recycling, encompassing a broader spectrum of strategies to ensure sustainable resource utilization and waste minimization. Therefore, the following two definitions are the most comprehensive and accurate: "The circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design" (Ellen MacArthur Foundation, 2015) and "Circular economy represents a development strategy that entails economic growth without increasing consumption of resources, deeply transform production chains and consumption habits and redesign industrial systems at the system level" (Document of the European…, 2014). The array of defined concepts encompasses a broad spectrum of theoretical foundations from which the circular economy concept draws its origins. These ten concepts have all contributed essential building blocks to the comprehension of the circular economy, and they are arranged in Figure 3 according to their conceptual scope (from broader to more specific).

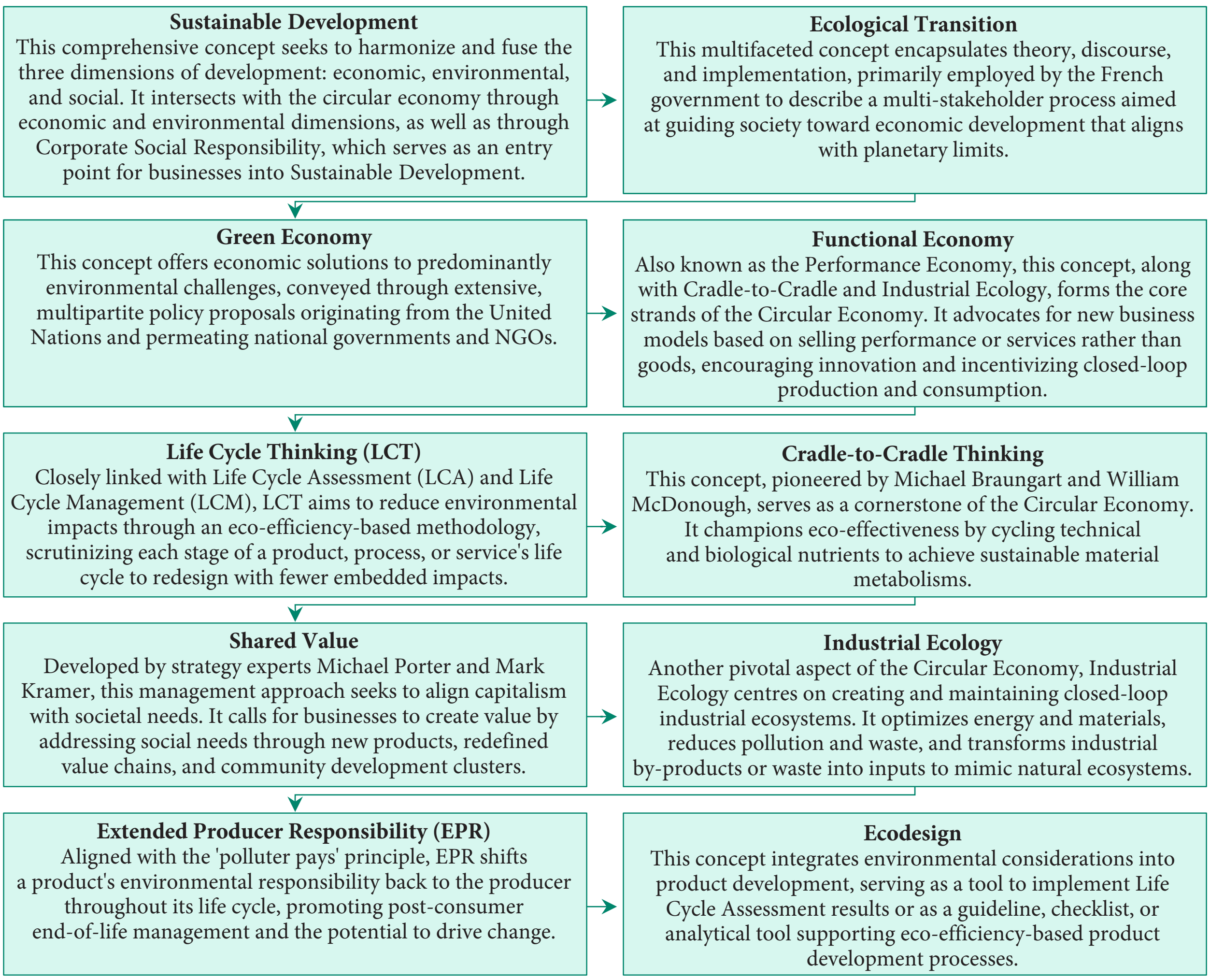

Figure 3. Underlying circular economy concepts
Source: adapted by the authors from Ciraig (2015)

Tracing the development of the circular economy is crucial as it provides invaluable insights into the development, adaptation, and impact of this transformative economic model. The evolutionary progression of the circular economy can be traced through three principal stages (Reike *et al.*, 2018).

Stage 0 (1966) – Origin With Ecological Focus:

The trajectory from an industrial to a post-industrial society during the 1960s, propelled by technological progress and innovative developmental models, laid the foundation for the circular economy concept. Originating with the ecological orientation, the concept transitioned to embrace economic dimensions (Boulding, 1966).

Stage I (1970-1990) – Waste Management:

During this phase, European nations and the United States enacted environmental legislation, spearheading the concept of the "3R" (Trushkina, 2021). These principles, such as reuse, remanufacture, and recycle, are considered fundamental for circular economy concepts. Despite their significance, the circular economy literature has not extensively focused on providing definitions and a specific order for these R-principles. This lack of consensus is evident in the presence of various R frameworks and definitions, ranging from 3Rs to 10Rs. For instance, the term 3R includes the well-known "reduce, reuse, recycle" approach, which is accepted by Chinese scholars. However, the 3R concept can also encompass other triple combinations, such as "reuse, remanufacture, recycle" and "reduce, recovery, reuse" (Kirchherr *et al.*, 2017). To clarify the definitions of R-principles, Table 1 illustrates the classification of different Rs based on various layers and objectives. Each R-principle is illustrated within the context of a product system containing multiple components and recyclable materials.

Table 1. Classification of R-principles

	Original function	Better original function	Another function
Raw materials	Recycle	Recycle	Recover
Components	Repair, Remanufacture, Reuse	Remanufacture	Repurpose
Product	Repair, Resell, Reuse, Remanufacture	Refurbish, Remanufacture	Repurpose, Remanufacture

Source: adapted by the authors from J. Potting *et al.* (2017) and E. Uçar *et al.* (2020)

For instance, the implementation of remanufacture at the product-system level can retain the original product function, enhance this function, or even create an entirely new function. This visualization helps clarify the relationships and distinctions among the different R-principles in a structured manner. In the same period, the "polluter pays" principle was created, while waste management remained central. However, the absence of robust environmental consciousness led to a disposition where less affluent nations became destinations for waste disposal and recycling.

Stage II (1990-2010) – Environmental Efficiency Strategies:

This stage witnessed the influence of environmental payments and pollution charges, which were used as a basis for circular economy principles. Environmental concerns were increasingly perceived as economic advancement opportunities. While waste-free production strategies emerged primarily in the industrial sector, global environmental challenges gained prominence, culminating in the recognition of global problems like ozone depletion and global warming.

Stage III (approximately 2010-present) – Maximum Conservation in the Era of Resource Depletion:

In this phase, the circular economy crystallized into its definitive form, merging theoretical research concepts with practical applications. The survival of humanity amidst dwindling natural resources, escalating global populations, and escalating waste generation became a priority. Businesses were encouraged to adopt three cardinal principles: green innovations, alternative sourcing, and a transformation of the industrial paradigm. Presently, approximately 500 global companies have embraced the circular economy strategy (Trushkina, 2021).

To assess the extent to which the concept of circularity is integrated into the daily operations of corporations, an analysis was conducted on the first 100 companies listed in the Fortune Global 500. It is visually illustrated in Figure 4. Among these corporations, a significant 89% have chosen to either publish a sustainability report or an equivalent Corporate Social Responsibility (CSR) report. Notably, the content and scope of these reports exhibit a wide range of variation in terms of their depth and length. Furthermore, the study revealed that approximately 44% of these corporations had already implemented a circular economy concept or strategy. In contrast to the diverse nature of the sustainability reports, the landscape appears more consistent when focusing on initiatives related to the circular economy. As such, the corporations consistently elaborated on the application of circular economy tools, the advantages derived from their utilization, and the alignment of these tools within their overall business models (PriceWaterhouseCoopers, 2018).

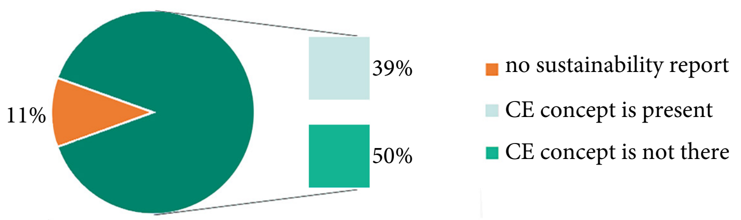

Figure 4. Integration of circularity in top 100 companies from Fortune Global 500

Source: built by the authors based on PriceWaterhouseCoopers (2018)

Upon closer examination of individual sectors, a heterogeneous pattern is notable. Among sectors displaying advanced initiatives linked to the circular economy, the fast-moving consumer goods (FMCG) manufacturers and vehicle industry companies took the lead. Conversely, the oil industry, financial services, and health sectors exhibited a lower degree of circularity adoption. However, it is noteworthy that even within these sectors, there exist exemplary corporations that have successfully woven the principles of the circular economy into their operational practices (Rizos *et al*., 2020).

Expanding the analysis beyond the preliminary findings, it is evident that the adoption of circular economy strategies is an increasingly pertinent consideration for corporations across diverse sectors. While the degree of integration may vary, the presence of circular economy initiatives highlights a growing recognition of the need for sustainable and resource-efficient business practices. The circular economy is developed using key factors such as resource scarcity, population growth, and shifts in consumer behaviour. However, a vital prerequisite for its realization is the advancement of technology and the latest technological breakthroughs. The convergence of the physical, digital, and natural realms is giving rise to a new interconnected reality. The rapid expansion of technologies across these domains is providing the remarkable potential to reimagine how products and services are provided, reshape their supply ecosystems, and revolutionize how people monitor waste and value creation.

The Interplay between the fourth industrial revolution (Industry 4.0) and the development of the circular economy is synergistic. Tools that facilitate the rise of Industry 4.0 can expedite and facilitate the transition toward circular practices. Concurrently, these tools are subject to continuous evolution, propelling the Fourth Industrial Revolution to new heights by engendering solutions that effectively curtail the wastage of valuable resources. These innovations thereby pave the pathway toward a waste-free economy. As the Circular Economy is inherently linked to the development of new business models that focus on reducing resource consumption, implementing reuse or closed-loop production, restoration, redesign, recycling, and secondary processing to ensure a sustainable lifecycle, it is undividedly dependent on technological advancements like big data, cloud computing and AI (artificial intelligence) (PriceWaterhouseCoopers, 2018).

Data plays a pivotal role in the competitive advantage offered by the circular economy. When combined with other digital technologies like IoT sensors, data enables real-time sensing of the surrounding environment, leading to valuable insights. Understanding the location, source, genuineness, state, and valuable materials contained within material assets is facilitated by the flow of information packets. This has far-reaching importance. Not only does understanding the location and potential reuse of assets provide multiple business benefits, but it also offers key sustainability advantages. Data analytics, for instance, can forecast the health of products and assets, minimize production downtime, facilitate predictive maintenance, proactively order spare parts, and optimize energy consumption (Lawson, 2022). Data serves as the foundation for measuring an organization's sustainability level and progress towards transitioning to a circular economy, as well as reporting on these efforts. Figure 5 shows a few examples of how data and IoT technologies drive the circular economy forward.9

Cars	One of the prominently recognized sharing-oriented platforms is notably car sharing, which has witnessed numerous initiatives. These initiatives encompass the sharing of both conventional automobiles and electric vehicles. The convenience of a smartphone application allows users to locate available cars within their vicinity while also affording insights into their charging status and projected range. Moreover, this application serves as a means to unlock and access vehicles. Naturally, such seamless interactions are contingent upon a network of intelligent devices that are capable of intercommunication.
Tools	The majority of households harbour valuable technical equipment that owners frequently utilize only on rare occasions (e.g., drills, chainsaws, etc.). Capitalizing on this realization, a multitude of companies have sprung up, specializing in the rental of such tools – an avenue aligned with the principles of the circular economy. In addition, certain facets of Industry 4.0, marked by technological advancements, can further amplify the efficiency of these enterprises. For instance, the integration of sensors into these tools can vastly streamline the management of the equipment pool for rental firms.

Figure 5. Data and IoT examples in the circular economy
Source: compiled by the authors based on J. Lawson (2022)

Utilizing IoT technology enables operational enhancements and post-activity oversight, effectively reducing waste stemming from maintenance oversights and quality assurance gaps. Sensors enable targeted maintenance interventions based on real-time operational data, minimizing scheduled maintenance inefficiencies. Furthermore, IoT aids in detecting and addressing early-stage manufacturing errors, mitigating downstream waste. In the "Product as a Service" model, manufacturers retain ownership while offering hassle-free functionality to consumers, achieved through continuous product monitoring. This concept allows devices to self-report issues and suggest repairs or replacements, when necessary, with end-of-life insights for recycling possibilities. Smart waste collection solutions, driven by IoT and data analysis, address inefficiencies in urban waste collection due to unpredictable consumer behaviour.

The transformative influence of Industry 4.0 on the shift from a linear to a circular economic model is notably manifested in the proliferation of automation, encompassing machine learning and robotics, alongside intelligent logistics driven by data analysis, the Internet of Things (IoT), and sensor networks. These advancements offer the potential to significantly curtail waste generation and facilitate the efficient reintegration of produced waste back into the manufacturing cycle. The conventional boundaries of robotics have been expanded, and a new paradigm is being shaped by control systems rooted in artificial intelligence and learning algorithms.

This dynamic landscape provides many novel opportunities for developers and programmers to explore. This elevated level of robotics progress empowers manufacturers to apply mechanized operations across a broader spectrum of activities, resulting in heightened output yields, waste reduction, and elongated product lifespans. Illustrative case studies and instances that underscore the economic influence arising from the synergy between robotics, artificial intelligence, and waste reduction and recycling are noteworthy. The following Figure 6 depicts cases that illustrate these ideas.

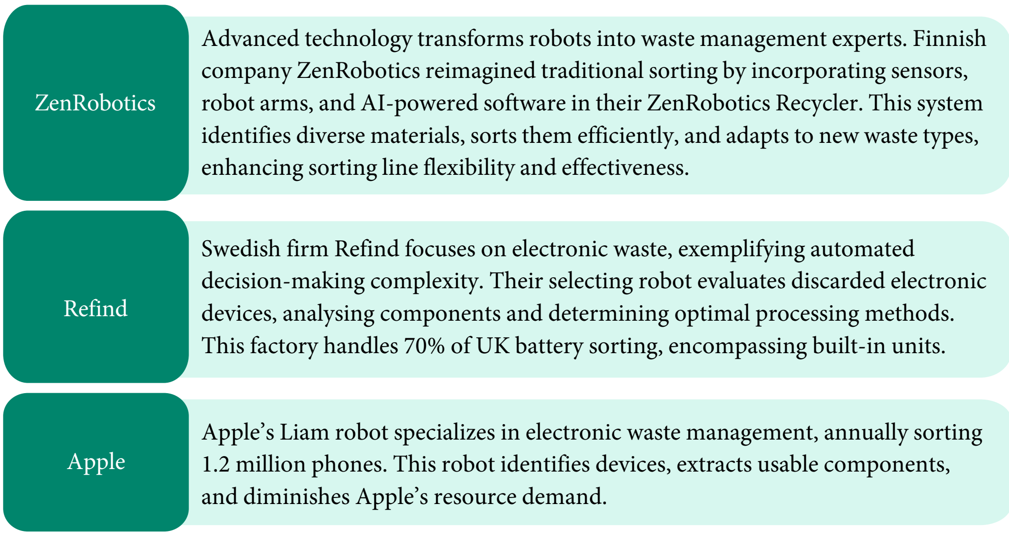

Figure 6. Cases of synergy between robotics and waste reduction and/or recycling
Source: compiled by the authors based on J. Lawson (2022)

These robots demonstrate the symbiosis between technological innovation and waste management, revolutionizing industrial practices. Incorporating these technologies, the circular economy gains momentum, demonstrating its potential to minimize waste, enhance product design, and create sustainable alternatives. In this, 3D printing is a catalyst for the shift from linear to circular economy models. This technology enables on-demand production of replacement parts, enhancing device maintainability, product longevity, and manufacturing efficiency. By adopting sustainable and durable products, 3D printing aligns with circular economy principles. Furthermore, it significantly curbs manufacturing time and costs for intricate, low-volume items. Materials technology plays a vital role in waste reduction. Designing materials for either biological or technical cycles enhances circularity. Compostable materials align with the biological cycle, while recyclable polymers and alloys support the technical cycle. Additionally, material advancements can lead to efficient use of resources, such as creating lighter products with reduced crude oil dependence.

Maximizing the operational efficiency of the technology infrastructure is critical for achieving Net Zero and circular economic goals. Transitioning to the cloud is a significant step towards a more environmentally sustainable technological framework. Cloud computing helps dematerialize value chains by optimizing the resource use of individual servers. Nevertheless, informational centres still have a significant environmental footprint. Google, for instance, has implemented measures in its data centres to combat this issue. They've utilized intelligent design and machine learning to optimize energy usage, generating substantial energy savings. The proprietary design of their infrastructure has enabled the refurbishment of server components to extend their lifespan. Google has also established secondary markets for the resale of excess components, creating additional revenue streams (Lawson, 2022).

Artificial intelligence (AI) contributes to designing products for modularity and tracking trends in big data, which is crucial for understanding material flows in a circular world. Integrating AI, twin technologies, and big data not only lessens design impact but also amplifies reusability potential. Simply put, technology plays a pivotal role in designing a sustainable future. Numerous companies are actively experimenting with the integration of blockchain technology to enhance the traceability of chemicals, particularly plastics, throughout their entire lifecycle. A collaborative effort between Mitsui Chemicals and IBM Japan aims to establish a resource circulation platform utilizing blockchain technology, ensuring seamless traceability from the initial raw materials, such as monomers and polymers, to the various stages of manufacturing, sales, utilization, and product recycling. Similarly, Porsche, Borealis, Domo Chemicals, and Covestro have initiated a blockchain traceability project. Furthermore, Solvay has commenced trials of blockchain technology to effectively track its products across the entire value chain in conjunction with Chemchain (Lawson, 2022).

Overall, from a conceptual standpoint, the transition to a circular economy holds several potential advantages. These are mitigation of environmental pressures and consequences and cost savings related to materials, reduced susceptibility to price fluctuations, and enhanced supply security. Governments view the circular economy as an appealing alternative to the conventional linear economic model. This shift can uncouple economic growth from resource consumption, stimulating innovation and employment opportunities. For businesses, the transition offers practical benefits, such as diminishing the risk of resource shortages and creating new revenue streams, alongside technological advantages facilitated by emerging technologies that facilitate circular principles (Wautelet, 2018). From a social point of view, it means an increase in jobs and stable income that can guarantee maintaining the necessary level of life. Nevertheless, the circular economy is not ideal has some threats and could be subjected to small-scale failures due to being a new concept. For example, many linear economy workplaces could be lost in transition. Regular people should keep an emergency fund to offset these implications. Experts recommend having enough money to cover up for at least 6 months (Morgan, 2023). Illustrated in Table 2, this context delineates the business prospects emerging within a circular economy, the driving trends that expedite its integration, and the challenges that restrain its adoption.

Table 2. Opportunities and threats of circular economic transition

OPPORTUNITIES	THREATS
• Easing supply risks for critical resources • Amplifying government pressures and incentives *Enabling Trends:* • Urbanization • Evolving consumer perspectives on value and materialism • Emphasis on access over ownership and sharing economy • Proliferation of transformational technologies	• Competitiveness of linear business models • Competition from alternatives to scarce materials • Higher initial investment costs and longer revenue generation timelines for service models • Constraints of Waste Transportation Regulations • Insufficient awareness of the urgency to adopt sustainable production and consumption patterns

Source: compiled by the authors based on PriceWaterhouseCoopers (2018)

However, it is worth noting that while digital technology is promising for transitioning to a circular economy, it is not a universal solution and is not without environmental consequences. The emergence of digital technologies has contributed to resource depletion, with the material footprint of digital equipment quadrupling between 1995 and 2015. Extracting raw materials, such as precious metals and rare-earth elements for this equipment caused significant environmental damage, including land degradation, water scarcity, and loss of biodiversity. Additionally, the production of digital equipment generates substantial waste, with a 3 kg laptop being responsible for producing 1,200 kg of waste. The frequent replacement cycle of such equipment exacerbates the waste issue. Furthermore, estimates suggest that digital technologies contribute to approximately 3.7% of global greenhouse gas emissions, and projections for France indicate that these technologies might account for 7% of total greenhouse gas emissions by 2040. Remarkably, the proliferation of digital technologies has correlated with an uptick in CO_2 emissions over the last half-century (Moigne, 2021). Consequently, the notion that the environmental drawbacks associated with digital technology can be balanced by the benefits they offer remains unconfirmed. Industries considering investments in new digital technologies must rigorously assess that any negative impacts throughout the lifecycle of these technologies fade with the gains they bring.

The concept of the circular economy has undergone a transformative evolution since 1980, gaining increased attention in the 21st century in both academic and non-academic literature. This surge in interest has primarily focused on macro and meso levels, delving into national and European scales, identifying obstacles and catalysts for circular economy adoption, constructing comprehensive policy structures, analysing the finance sector's role, and understanding the ramifications of reverse loops on supply chains. Many scholars have contributed to the understanding of the circular economy's implications for environmental and economic systems. Critical examinations by M. Geissdoerfer *et al.* (2017) and J. Korhonen *et al.* (2018) addressed sustainability, diverse perspectives, advantages, and potential limitations of circular approaches. These findings resonate with the conducted research, which also highlights the transformative potential of technology integration in fostering circular economy practices and promoting economic development.

The research findings underscore a compelling positive correlation between the integration of technology, circular economy practices, and economic development. The same opinion is shared by Y. Kalmykova *et al.* (2018). The study also reveals that as businesses adopt advanced technologies to embrace circular economy principles, significant improvements in various aspects are noted. These include enhanced resource efficiency, reduced waste generation, increased recycling rates, and the creation of new revenue streams through innovative business models. N.M.P. Bocken *et al*. (2016) and M. Lewandowski (2016) addressed product design, business models, and practical implementation, showcasing the complex nature of the circular economy concept. In line with these studies, the conducted research also underscores the importance of a common understanding, collaborative efforts, and innovative strategies for facilitating the transition to a circular economy.

On a micro level, scholars have concentrated on prerequisites for product design within a circular economy context, outlining strategic approaches, establishing frameworks for business models conducive to circular thinking, and classifying circular business models (CBMs). Notably, this aligns with findings in the current study, where exploration into the multifaceted role of technology demonstrated its potential to accelerate the adoption of circular economy principles across various sectors. However, the practical limitations of achieving absolute circulatory perfection in the circular economy concept are acknowledged. Challenges include the difficulty of achieving zero loss of technical material, zero material inputs, endless loops, and endless energy for loops. These constraints highlight the complex interplay of factors hindering the complete elimination of waste. The study by D. Zhong *et al*. (2022) provides a specific example of the use of a business model following the circular economy in China. Although the authors devoted considerable attention to the prospects and recommendations for the development and favourable implementation of the model mentioned in the study, they also point out the unsatisfactory situation in the region, as well as market pressure from the world's leading countries.

Fundamentally, the investigation of the circular economy plays a pivotal role in formulating strategies and policies to mitigate environmental and economic challenges while harmonizing with sustainability paradigms. The study's results have notable policy implications, suggesting that governments can incentivize technology adoption, and corporations can strategically integrate technology into their operations to enhance resource efficiency and competitiveness. Collaborative efforts between the public and private sectors present an unparalleled opportunity for harmonizing economic expansion, environmental custodianship, and societal well-being within the global interconnected fabric.

CONCLUSIONS

The study findings demonstrate the transformative potential of technology integration in fostering circular economy practices and promoting economic development. The insights gained provide valuable guidance for policymakers, businesses, and researchers seeking to accelerate the adoption of circular principles and technologies for a sustainable future. Through a systematic approach, the study defined the prerequisites for the necessity of transitioning toward a circular economy, such as awareness of resource depletion and mounting environmental concerns stemming from the traditional "take-make-dispose" model. Technological advancements also act as a pivotal driver, shifting economic systems away from fossil resources.

The conducted study allowed to distinguish several separate stages of its development. Stage 0 was around 1966, and Stage 1 encompassed 2 decades: the 70s and 80s, Stage 2 was in place between 1990 and 2010, while the present Stage 3 is still on. Several interconnected concepts and frameworks have been determined to add to the holistic vision of sustainable development within the circular economy discourse, aligning economic, environmental, and social dimensions. The ecological transition guides economic development within planetary boundaries, while frameworks advocate innovative business models and eco-efficient product cycles. Cradle-to-cradle thinking supports sustainable material cycles, shared value aligns capitalism with societal needs, and industrial ecology emphasizes closed-loop systems.

The study findings extend beyond conventional boundaries, illustrating how technology can amplify the global influence of sustainable practices. As industries grapple with the challenge of harmonizing economic growth with environmental responsibility, this research provides empirical evidence of technological efficacy in facilitating the transition to circular economies. Given the growing urgency to address environmental concerns, this study contributes to the existing body of knowledge by shedding light on the critical link between technological development and circular economy transition. The insights gleaned from successful case studies and empirical assessments offer a pragmatic foundation for policymaking, corporate strategies, and future research endeavours. The research underscores the practical viability of transitioning to circular economies by harnessing the power of technology to achieve sustainable economic growth.

Future research directions should include the long-term impacts of technology integration on circular economy practices and economic outcomes. Sector-specific analyses can provide deeper insights into the challenges and opportunities unique to various industries. Additionally, investigating the social and behavioural aspects of technology adoption and circular practices can provide a more comprehensive understanding of the transition process.

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CONFLICT OF INTEREST

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Стратегічні прогнози переходу до циркулярної економіки: оцінка ролі технологій в економічному розвитку

Анотація. Використання циркулярної економіки, на відміну від лінійного виробництва, дозволяє оптимально утилізувати відходи, зменшити дефіцит ресурсів, знизити негативний вплив на навколишнє середовище та досягти конкурентних переваг за рахунок інновацій. Рушійною силою цього переходу є технологічний розвиток, який уможливлює більш ефективні та швидкі зміни. Метою дослідження є оцінка впливу технологій на перехід до циркулярної економіки, яка набуває все більшого значення на тлі викликів, спричинених зростанням населення, зміною клімату та погіршенням стану довкілля. У дослідженні було використано поєднання кількісних та системних методів аналізу, а саме: вивчення, категоризація та аналіз тематичних досліджень, галузевих звітів та проведення мета-аналізу. Дослідження визначило ключові рушійні сили переходу до циркулярної економіки, зокрема усвідомлення вичерпання ресурсів, екологічні проблеми, технологічний прогрес, зміна споживчих цінностей та державне регулювання. У дослідженні проаналізовано різні визначення циркулярної економіки та класифіковано розвиток її принципів на етапи з 1966 по 2023 рік. Вивчення комплексної ролі технологій продемонструвало їхній потенціал для прискорення впровадження принципів циркулярної економіки в усьому світі. Дослідження вийшло за межі традиційних кордонів, проілюструвавши здатність технологій посилювати вплив сталих практик. Оскільки галузі збалансували економічне зростання з екологічною відповідальністю, дослідження надало емпіричні докази ефективності технологій у сприянні переходу до циркулярної економіки. Це дослідження дало цінне розуміння критично важливого зв'язку між технологічним розвитком і переходом до циркулярної економіки. Успішні тематичні дослідження та емпіричні оцінки запропонували прагматичну основу для формування політики, корпоративних стратегій та поточних досліджень. Дослідження має теоретичне значення для поглиблення розуміння динаміки циркулярної економіки. Водночас воно практично сприяє формулюванню політики та корпоративних стратегій, що сприяють стійкій економічній трансформації

Ключові слова: сталість; циклічність; економіка замкненого циклу; регенеративна економічна система