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Circular economy meets smart energy grids: designing systems for resource optimization and carbon reduction

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This study examines the integration of Circular Economy (CE) principles with Smart Energy Grids (SEG) as a strategy to advance sustainable, low-carbon energy systems. The CE emphasizes minimizing waste, recovering resources, and prolonging material lifecycles, while SEG focuses on improving energy efficiency, supporting renewable energy integration, and enhancing grid resilience. These frameworks offer significant potential for optimizing resource use and reducing environmental impacts in the energy sector. However, several challenges hinder their full integration, such as technological barriers, regulatory constraints, and the lack of market incentives. Technological obstacles include the need for advanced recycling and energy storage solutions, particularly for renewable energy systems and electric vehicles. Regulatory frameworks are often insufficiently adaptable to the decentralized energy systems central to both CE and SEG. Additionally, policy frameworks that incentivize circular practices in energy infrastructure are essential for fostering innovation. This paper recommends targeted policy measures, including tax incentives for renewable energy technologies, regulatory reforms to support decentralized energy systems, and public-private partnerships (PPP) to mitigate financial risks in research and development. By addressing these challenges, the integration of CE and SEG can facilitate a transition to a sustainable, low-carbon future, benefiting both the environment and society.

KEYWORDS

circular economy, smart energy grids, sustainability, renewable energy, policy recommendations

1 Introduction

The accelerating need for a transition to sustainable energy systems and the reduction of global carbon emissions has created an urgent demand for innovative solutions. Climate change, resource depletion, and the growing pressure to meet global energy demands are all critical challenges that require urgent action (Ho et al., 2024; Upadhayay et al., 2024; Rios et al., 2022). To address these pressing issues, innovative, sustainable solutions are paramount. Among these, the principles of the circular economy (CE) and the deployment of smart energy grids (SEG) represent two pivotal components in the drive toward a low-carbon, sustainable future (Mendoza et al., 2017; Ghisellini et al., 2016; Van Berkel, 2007). The circular economy offers an alternative economic model that decouples growth from resource consumption by promoting the continuous use of resources, minimizing waste, and regenerating natural systems. This approach contrasts sharply with the traditional linear economy, which is based on a "take, make, dispose" model that encourages overconsumption and environmental degradation (Mendoza et al., 2017; Ellen MacArthur Foundation, 2013). On the other hand, smart energy grids, equipped with information and communication technologies (ICT), provide an intelligent and integrated approach to energy management, facilitating the efficient distribution, integration, and consumption of energy (Lund et al., 2014; Gungor et al., 2011; Pursiheimo et al., 2019). Together, these strategies hold the potential to revolutionize energy systems, contributing to carbon reduction and resource optimization in ways that are both environmentally and economically sustainable.

The concept of the circular economy can be defined as an economic system that aims to reduce waste and the continual use of resources through processes such as recycling, reusing, and remanufacturing (Ghisellini et al., 2016; Schwarz and Steininger, 1997). In energy systems, the circular economy calls for rethinking energy production, distribution, and consumption processes. Traditional energy systems, which often rely on finite fossil fuel resources, are inherently unsustainable due to the depletion of resources and the harmful environmental impacts of extraction and burning (Ghisellini et al., 2016; Tukker, 2015). In contrast, the circular economy emphasizes the need to shift toward renewable energy sources, such as solar, wind, and geothermal, which are abundant and sustainable. This also includes the importance of energy storage solutions, which facilitate the efficient use of renewable energy by ensuring energy availability even when production is intermittent. Moreover, circular economy principles in the energy sector also promote the integration of technologies such as smart grids, which enable the real-time management and distribution of energy, helping to enhance the overall efficiency of the energy system (Buchholz and Styczynski, 2020; Dileep, 2020).

Smart energy grids play a crucial role in achieving sustainable energy systems by enabling more efficient energy management. A smart grid is an advanced electrical grid that uses digital communications and automated systems to manage and optimize the production, distribution, and consumption of electricity. Smart grids provide numerous benefits, such as reducing energy losses, improving energy efficiency, and integrating renewable energy sources more effectively (Lund et al., 2017; Gungor et al., 2011; Pursiheimo et al., 2019). These grids facilitate two-way communication between electricity producers, consumers, and distributors, enabling a more responsive energy system that can balance supply and demand dynamically. Additionally, smart grids enable consumers to better manage their energy consumption, often leading to cost savings and reduced carbon footprints (Ohanu et al., 2024; Khalid, 2024). By integrating demand-side management and energy storage, smart grids allow for greater resilience against energy disruptions and fluctuations in renewable energy production, thus supporting a more stable and reliable energy system (Gungor et al., 2011; Howlader et al., 2016).

The intersection of circular economy principles and smart energy grids offers an exciting pathway to optimizing resource use and reducing carbon emissions. One of the most significant ways these two systems work together is by facilitating the transition from a centralized energy production model to a decentralized one. Smart grids enable energy consumers, such as homes and businesses, to become active participants in the energy market by generating, storing, and distributing energy, a concept known as prosumerism (Gimeno et al., 2020; Khatua et al., 2020; Ho et al., 2024). Through the integration of renewable energy technologies, such as rooftop solar panels and small-scale wind turbines, prosumers can contribute to the overall energy supply, reducing the need for energy from fossil fuels. In turn, the circular economy ensures that these energy systems operate in a manner that reduces waste and maximizes resource efficiency by encouraging recycling and the reuse of materials, such as the batteries used in renewable energy storage systems (Islam and Iyer-Raniga, 2022; Antony Jose et al., 2024).

The circular economy also promotes the concept of energy storage, which plays a critical role in the effective integration of renewable energy sources into the grid. Energy storage solutions, such as batteries, can store excess energy generated during periods of high production (e.g., sunny or windy days) and release it during periods of low production, ensuring a steady, and reliable energy supply (Howlader et al., 2016; Augustyn and Mikulik, 2024). Moreover, the circular economy principles can guide the development of more sustainable energy storage solutions, such as the recycling of lithium-ion batteries, to reduce the environmental impact of energy storage technologies (Srinivasan et al., 2025; Islam and Iyer-Raniga, 2022; Upadhayay et al., 2024).

This paper explores the synergies between circular economy principles and smart energy grids, analyzing how their integration can lead to a more sustainable, low-carbon energy system. It will examine the foundational principles of the circular economy and outline the role of smart grids in energy systems, emphasizing how their integration can contribute to a more efficient, sustainable energy future (Mendoza et al., 2017; Gungor et al., 2011; Harper et al., 2023). A particular focus will be placed on the ways these concepts can be applied to the development of sustainable energy infrastructure, with case studies from various regions and sectors (Howlader et al., 2016; Dileep, 2020). These case studies will highlight the benefits, challenges, and opportunities of integrating circular economic principles into smart grid systems. Challenges such as technological barriers, regulatory frameworks, and economic considerations will be examined, along with potential solutions to overcome them. Furthermore, the paper will offer policy recommendations and practical steps for advancing the integration of these systems globally, emphasizing the need for coordinated efforts between governments, businesses, and consumers (Danish and Senjyu, 2023; Reindl, 2024). Through leveraging both smart grids and the circular economy, it is possible to create energy systems that are not only more sustainable but also economically viable, socially inclusive, and resilient to future challenges.

2 The circular economy: key principles and applications

The circular economy (CE) is grounded in a systemic approach to economic activity, where resource efficiency, sustainability, and waste reduction are paramount (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Lieder and Rashid, 2016). It is an alternative to the traditional linear economy, which follows the pattern of "take, make, dispose," resulting in overconsumption of resources, waste generation, and environmental degradation (Kirchherr et al., 2017; Ghisellini et al., 2016; Tukker, 2015). This linear model, heavily reliant on finite resources, encourages a consumption-based economy where products are used once and discarded, often leading to significant ecological damage. In stark contrast, the circular economy focuses on maintaining the value of products, materials, and resources in the economy for as long as possible, thereby reducing waste and resource depletion (Mendoza et al., 2017; Ghisellini et al., 2016; Stahel, 2013; Rios et al., 2022). This is achieved by maximizing the lifecycle of products through strategies such as reuse, refurbishment, remanufacturing, and recycling. In essence, CE seeks to create closed-loop systems that minimize the intake of new resources and optimize the utility of existing materials.

The transition from a linear to a circular economy has profound implications across various sectors, especially in industries where resource consumption and waste generation are significant challenges. Industries like manufacturing, energy, and construction are prime candidates for the implementation of CE principles, as they are responsible for substantial resource use and environmental degradation. For instance, the energy sector, which has traditionally been dependent on fossil fuels, offers ample opportunity for the adoption of CE principles. The application of CE within the energy sector includes reducing the carbon footprint, optimizing resource use, and supporting the shift to renewable energy, all of which are essential for achieving global sustainability goals (Gimeno et al., 2020; Lund et al., 2017; Ghisellini et al., 2016). In the energy sector, CE principles can be applied in various ways to optimize resource use, reduce waste, and support carbon reduction efforts. Energy efficiency stands as one of the most important areas where CE strategies can be implemented. By adopting energy-efficient technologies in manufacturing, transport, and construction, the overall demand for energy can be significantly reduced, leading to lower carbon emissions and energy consumption (Ghisellini et al., 2016; Gungor et al., 2011; Howlader et al., 2016). These energy-efficient technologies may include high-efficiency engines, smart lighting systems, and more efficient heating, ventilation, and air conditioning (HVAC) systems. The adoption of such technologies directly supports the overarching goal of reducing energy consumption while enhancing productivity and economic performance. The circular economy can also contribute to the sustainability of renewable energy production through practices such as the reuse, repair, and recycling of materials used in renewable energy technologies. Wind turbines, solar panels, and energy storage systems, which are central to the transition to a low-carbon energy system, often rely on rare and precious materials. For instance, the production of wind turbines and solar panels involves materials like rare earth metals, including neodymium and dysprosium, which are often extracted through environmentally damaging mining processes (Harper et al., 2023; Ahi and Searcy, 2015; Morrison et al., 2019). The recycling of these materials at the end of their life cycle can significantly reduce the environmental impact associated with their extraction (Ahi and Searcy, 2015; Morrison et al., 2019; Gungor et al., 2011). Additionally, as the demand for renewable energy technologies grows, the recycling of rare earth metals becomes an increasingly important strategy for reducing dependence on virgin materials and minimizing the environmental impact of resource extraction (Morrison et al., 2019; Ahi and Searcy, 2015; Srinivasan et al., 2025). The development of effective recycling processes for these materials will be essential for the continued growth of renewable energy markets.

Another key aspect of the circular economy is the promotion of decentralized energy systems. In contrast to centralized energy systems, where power is generated at large-scale plants and transmitted over long distances, decentralized energy systems focus on local energy production and consumption (Mendoza et al., 2017; Lund et al., 2017; Gungor et al., 2011). This approach can significantly reduce the need for long-distance transmission, minimizing associated energy losses and increasing the overall efficiency of the energy system. Decentralized systems also provide greater resilience to disruptions, as energy production is spread across smaller, more localized units. This decentralization overlaps with circular economy principles by reducing the reliance on centralized infrastructures and promoting more sustainable, localized energy solutions. A crucial component of the circular economy in the energy sector is the creation of closed-loop systems. In these systems, the waste generated by one process becomes an input for another, creating a circular flow of resources and reducing environmental impact (Srinivasan et al., 2025; Ghisellini et al., 2016; Khatua et al., 2020). For example, waste heat recovery technologies, which capture, and reuse heat generated during industrial processes, can significantly reduce the energy consumption and carbon emissions of energy-intensive industries such as steel, cement, and chemical manufacturing (Morrison et al., 2019; Ghisellini et al., 2016; Gungor et al., 2011). Waste-to-energy technologies, which convert organic waste into usable energy, also represent a valuable tool in promoting circularity within the energy sector (Tukker, 2015; Morrison et al., 2019; Tukker, 2015). Through repurposed waste products into new forms of energy, these technologies minimize the need for external resources and contribute to waste reduction. These applications exemplify the core principles of the circular economy, offering the potential to reduce carbon footprints while enhancing the sustainability and efficiency of industrial processes.

Nevertheless, as global demand for renewable energy technologies and electric vehicles continues to rise, so too does the need for materials such as lithium, cobalt, and nickel, which are critical for energy storage systems and batteries (Tukker, 2015; Islam and Iyer-Raniga, 2022; Antony Jose et al., 2024). However, the extraction of these materials often has significant environmental and social impacts, including habitat destruction, pollution, and human rights violations. In light of these challenges, the circular economy encourages the design of products and technologies that prioritize the reuse and recycling of materials (Tukker, 2015; Islam and Iyer-Raniga, 2022; Antony Jose et al., 2024). For example, the lifecycle of batteries can be extended by recycling the metals contained within them, reducing the need for new mining operations and minimizing the environmental impact of battery production (Islam and Iyer-Raniga, 2022; Antony Jose et al., 2024; Ghisellini et al., 2016). Similarly, the circular economy promotes the repair and refurbishment of products, allowing materials to be reused rather than discarded (Antony Jose et al., 2024; Islam and Iyer-Raniga, 2022; Ghisellini et al., 2016). Incorporating these principles into the design and production of

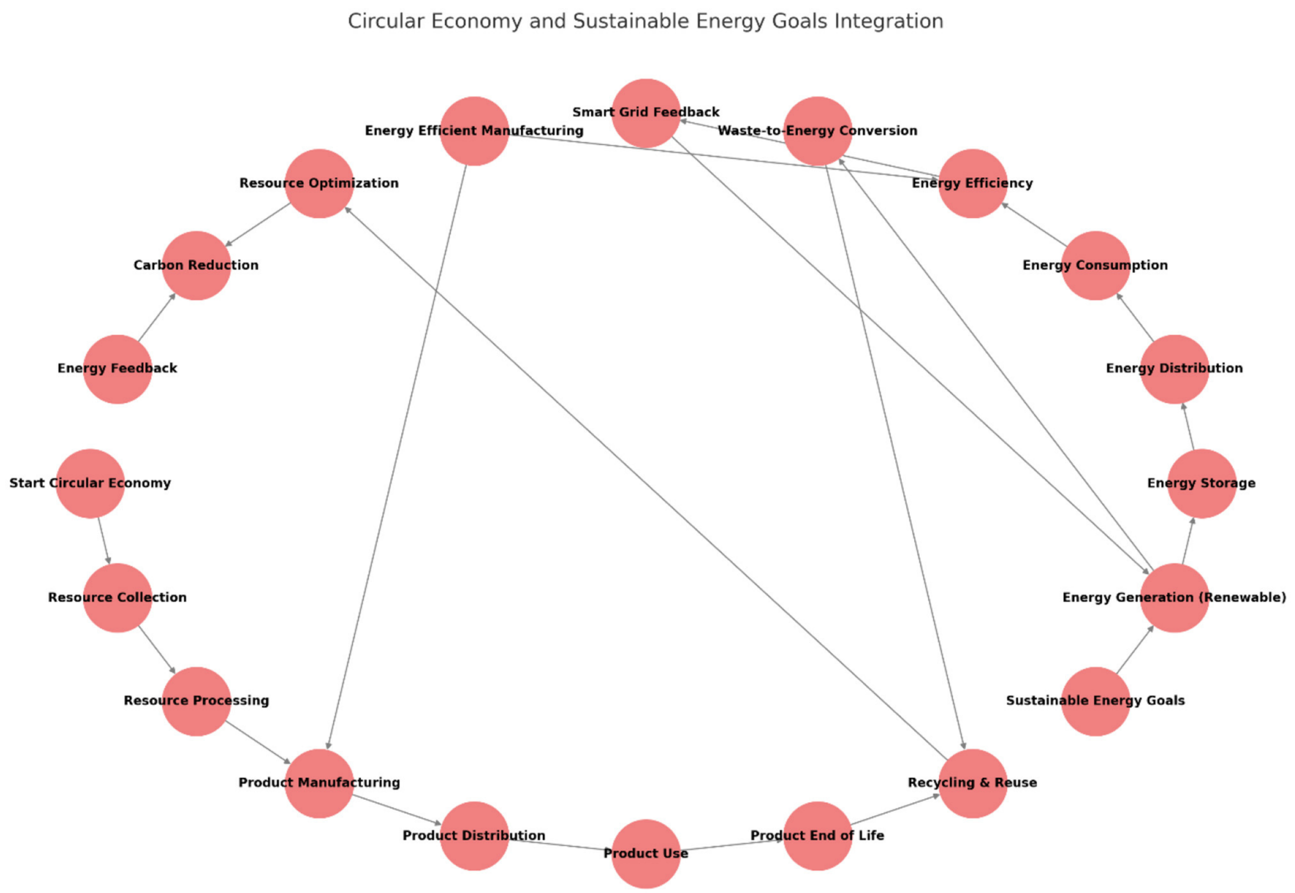

FIGURE 1
Demonstrates the interconnected relationship between the circular economy and sustainable energy goals, illustrating how these two systems mutually reinforce each other to promote sustainability, resource optimization, and carbon reduction.

renewable energy technologies and electric vehicles, it is possible to reduce reliance on virgin resources, support the sustainable use of materials, and mitigate the environmental impacts of extraction. Ultimately, the integration of circular economy principles into the energy sector represents a transformative approach to addressing global sustainability challenges. However, through prioritizing energy efficiency, renewable energy production, and the recycling of materials, the circular economy can help decouple economic growth from resource consumption, creating a regenerative and sustainable energy system that benefits both the environment and the economy (Ghisellini et al., 2016; Tukker, 2015; Stahel, 2013). The key to achieving this vision lies in the adoption of circular economy practices across industries and the collaboration of governments, businesses, and individuals in supporting this transition (Ghisellini et al., 2016; Tukker, 2015; Stahel, 2013). As the world continues to embrace the potential of circular economy strategies, it is crucial to focus on the creation of closed-loop systems that promote sustainability, efficiency, and resilience across all sectors of society (Stahel, 2013; Tukker, 2015; Ghisellini et al., 2016). Thus, the circular economy offers a compelling framework for reshaping the way energy systems are designed, produced, and consumed. However, applying the principles of circularity, it is possible to enhance resource efficiency, reduce waste, and support the transition to a low-carbon, sustainable energy future (Ghisellini et al., 2016; Tukker, 2015; Stahel, 2013). Therefore, as technologies advance and the global community becomes more committed to achieving sustainability goals, the circular economy will play an increasingly central role in shaping the future of the energy sector and beyond (Stahel, 2013; Tukker, 2015; Ghisellini et al., 2016). Integrated circular energy systems are essential for sustainable energy goals. Prioritizing resource efficiency, waste reduction, and energy recovery, these systems support resilient infrastructures, optimize energy use, and reduce carbon footprints. This approach advances renewable energy adoption, minimizes environmental impacts, and enhances energy security (Figure 1).

3 Smart energy grids: a technological revolution for sustainable energy

Smart energy grids represent a transformative shift in the way electricity is generated, transmitted, and consumed. Traditional power grids, characterized by centralized generation and one-way distribution, often result in inefficiencies, energy losses, and a heavy reliance on fossil fuels, which significantly contribute to

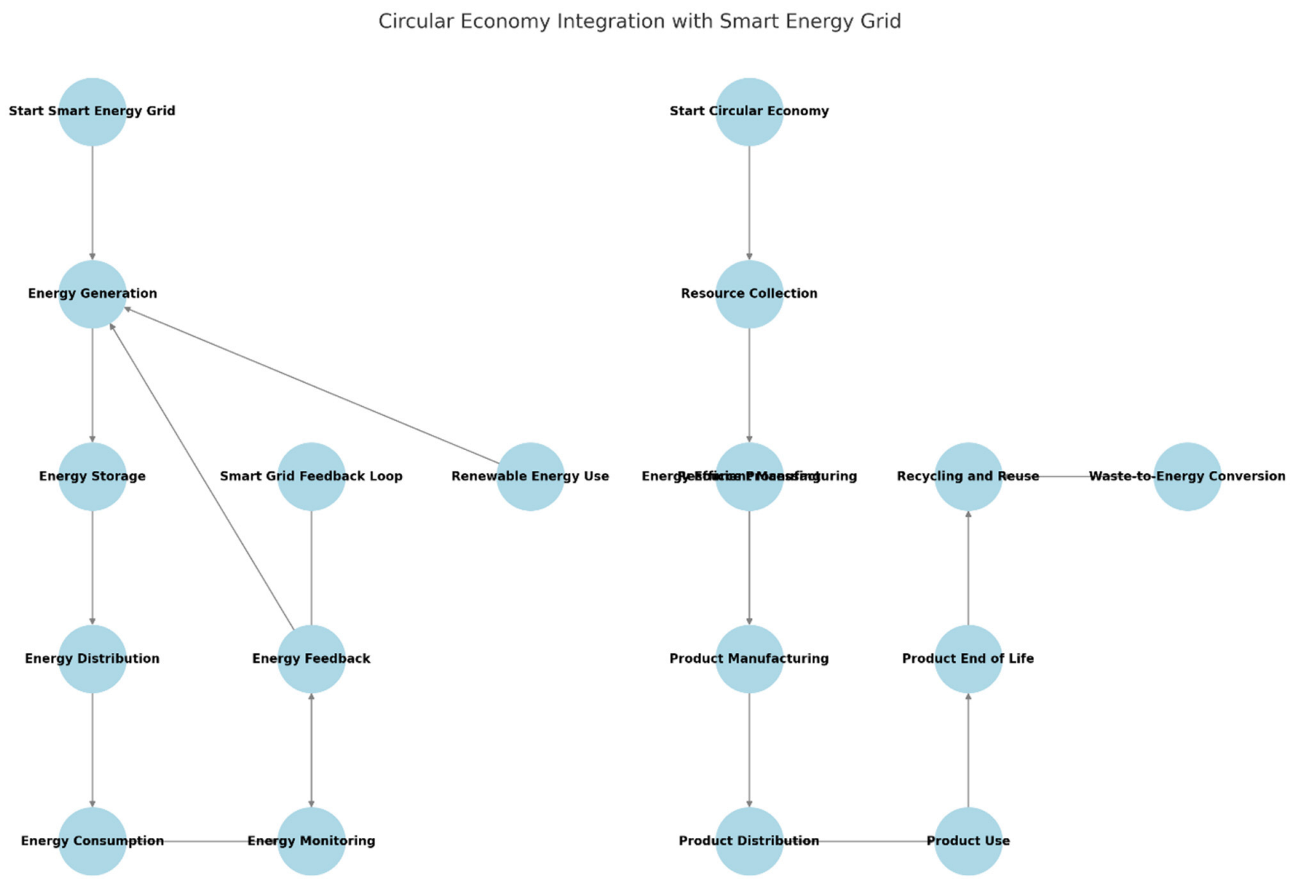

FIGURE 2
Illustrates the integration of the circular economy with the smart energy grid, showcasing how both systems work together to optimize resources, enhance energy efficiency, and reduce carbon emissions.

carbon emissions (Ohanu et al., 2024; Schwarz and Steininger, 1997). Unlike traditional grids, smart grids incorporate advanced technologies, such as sensors, communication networks, and data analytics, to create a more responsive, flexible, and decentralized energy system (Ohanu et al., 2024; Reindl, 2024; Khatua et al., 2020). Circular economy integration with smart energy grids enhances resource efficiency, reduces waste, and supports clean energy transitions. This approach optimizes energy use, minimizes carbon emissions, and creates resilient, self-sustaining infrastructures, advancing long-term sustainability and economic resilience (Figure 2). This technological revolution enables smarter energy consumption, facilitates the integration of renewable energy sources, and enhances real-time monitoring and control, ultimately contributing to the reduction of carbon emissions and improving the sustainability of energy systems (Lund et al., 2017; Kumar and Bhimasingu, 2015). The ability of smart grids to adapt to changing demands and incorporate new technologies highlights their importance in the pursuit of a sustainable, low-carbon energy future (Kabeyi and Olanrewaju, 2023; Lah, 2016; Mendoza et al., 2017).

A central advantage of smart grids is their ability to integrate renewable energy sources, which are often intermittent and variable in nature (Mirletz et al., 2022; Reindl, 2024; Stahel, 2013). Traditional energy systems struggle with accommodating renewable energy due to their fluctuating availability, which can lead to imbalances between supply and demand. In contrast, smart grids use energy storage systems, such as batteries, alongside advanced demand-response systems to balance supply and demand more effectively (Berechet et al., 2019; Tukker, 2015; Van Berkel et al., 1997). For example, during periods of high renewable energy generation, excess electricity can be stored for later use when renewable generation is low, helping smooth out fluctuations in supply (Veleva et al., 2015; Dileep, 2020; Bilibin and Capitanescu, 2014). This capacity for storage and demand management reduces the need for conventional fossil-fuel-based power generation, which is typically used to balance supply and demand in traditional grids. As such, smart grids contribute to lowering carbon emissions by minimizing reliance on non-renewable energy sources, which are a major contributor to climate change (Gimeno et al., 2020; Gungor et al., 2011; Ahmed et al., 2023).

Moreover, the decentralized nature of smart grids plays a pivotal role in supporting sustainable energy systems (Ahmed et al., 2023; Azizi et al., 2019). In traditional power grids, electricity is typically generated at centralized power plants and transmitted over long distances to consumers (Danish and Senjyu, 2023; Albadi and El-Saadany, 2008; Upadhayay et al., 2024). This process results in significant energy losses, especially as electricity travels across vast distances, and increases the carbon footprint of energy production. In contrast, smart grids enable decentralized energy systems, where power is generated locally and consumed nearby, reducing the need for long-distance transmission and minimizing associated energy losses (Gungor et al., 2011; Ghisellini et al., 2016; Harper et al., 2023). The decentralization of energy production fosters local energy resilience, ensuring that communities are less reliant on distant power plants and enabling the integration of small-scale, renewable energy generation sources such as solar panels and wind turbines (Kabeyi and Olanrewaju, 2023; Gimeno et al., 2020). Furthermore, smart grids facilitate peer-to-peer energy trading, allowing consumers to produce and sell excess energy to others in their community, and further enhancing the sustainability of energy systems (Gungor et al., 2011; Harper et al., 2023; Howlader et al., 2016).

In addition to renewable energy integration and decentralization, smart grids also bring significant improvements in energy efficiency. The utilization of real-time data and advanced analytics empowers smart grids to identify inefficiencies in energy distribution and consumption (Lund et al., 2017; Lah, 2016; Kumar and Bhimasingu, 2015; Ohanu et al., 2024). These technologies enable utilities to optimize energy usage by dynamically adjusting energy flows to meet demand while avoiding overproduction and waste. Through demand-response programs, consumers are incentivized to shift their energy consumption to off-peak periods, reducing the need for peaking power plants, which are typically inefficient and more polluting than base-load plants (Lund et al., 2017; Reindl, 2024; Mirletz et al., 2022). As a result, energy efficiency is enhanced, and the overall carbon emissions of the energy system are reduced. Additionally, the integration of smart meters and monitoring technologies provides consumers with more accurate billing information and the ability to track their energy consumption in real-time, fostering more informed energy usage decisions, and ultimately leading to reduced overall demand (Kullmann et al., 2021; Islam and Iyer-Raniga, 2022; Khatua et al., 2020).

The ability of smart grids to enhance the resilience of energy systems is another key feature that contributes to their sustainability. Traditional power grids are vulnerable to disruptions, such as extreme weather events or technical failures, which can result in widespread blackouts. In contrast, smart grids use sensors and real-time data to monitor grid health and quickly detect faults (Lund et al., 2017; Kabeyi and Olanrewaju, 2023; Cheung et al., 2010). When a disruption occurs, smart grids can isolate the affected area and reroute power to minimize the impact on consumers, significantly reducing the need for manual intervention and improving overall reliability (Gungor et al., 2011; Kabeyi and Olanrewaju, 2023; Khalid, 2024). Furthermore, predictive maintenance is enabled by real-time data, allowing utilities to detect potential failures before they occur. This proactive approach to grid management reduces downtime and operational costs while enhancing the stability of the energy system (Lund et al., 2017; Howlader et al., 2016). As energy systems become more complex and interconnected, the ability of smart grids to maintain stable operations and adapt to disruptions is crucial for ensuring long-term sustainability and reliability (Lund et al., 2017; Rios et al., 2022).

The integration of smart grids into energy infrastructure also facilitates the development of microgrids, which are smaller, localized grids that can operate independently or in conjunction with the main grid. Microgrids are particularly useful for integrating renewable energy sources, as they allow for the efficient use of locally generated energy, including solar, wind, and biomass (Cheng et al., 2019; Upadhayay et al., 2024). Microgrids can also be equipped with energy storage systems to store excess renewable energy and provide backup power in case of grid disruptions. This further enhances the resilience and sustainability of the energy system, as communities can continue to generate and consume energy even in the face of grid failures or extreme weather events (Cheung et al., 2010; Danish and Senjyu, 2023). The adoption of microgrids is expected to play a significant role in the future of energy systems, providing greater energy autonomy and improving the integration of distributed energy resources.

Nevertheless, the widespread adoption of smart grids is expected to have significant social and economic benefits. Which can be achieved through improving energy efficiency, reducing waste, and promoting the use of renewable energy, smart grids can help lower energy costs for consumers while simultaneously reducing carbon emissions (Pan and Hashemizadeh, 2023; Lavrijssen, 2017; Sovacool et al., 2018). Additionally, the ability to integrate distributed energy resources can create new business opportunities, such as local energy production, storage, and trading, which can stimulate economic growth in the renewable energy sector (Gungor et al., 2011; Albadi and El-Saadany, 2008). As countries strive to meet climate targets and reduce reliance on fossil fuels, smart grids offer a promising path toward a more sustainable and resilient energy future (Thomas and Mishra, 2022; Wilson et al., 2022; Ho et al., 2024).

Consequently, smart energy grids represent a key innovation in the transition toward a low-carbon, sustainable energy system. Other studies can adapt this approach by integrating renewable energy sources, improving energy efficiency, and enhancing resilience. Smart grids offer a technological solution to many of the challenges facing traditional energy systems. Through the incorporation of real-time data, decentralized energy production, and advanced grid management techniques, smart grids can optimize energy consumption, reduce waste, and improve the overall sustainability of energy systems.

The Circular Economy starts with Resource Collection, where raw materials are gathered for production. These materials undergo Resource Processing and are then converted into products through Product Manufacturing. After products are distributed, they are used by consumers (Product Use) and eventually reach their End of Life, where they enter the Recycling & Reuse phase, minimizing waste and extending product lifecycles.

Simultaneously, the Sustainable Energy Goals involve Energy Generation (Renewable), where energy is produced primarily from sustainable sources like wind, solar, and hydro. This energy is stored (Energy Storage) and distributed (Energy Distribution) across the grid. Energy Consumption occurs as industries, homes, and businesses use this energy, which is then optimized for Energy Efficiency. The integration of Smart Grid Feedback ensures real-time adjustments to maximize energy use and improve efficiency.

Key interactions between the two systems include Energy Efficient Manufacturing, where energy usage is minimized during production, and Waste-to-Energy Conversion, which converts waste into energy, supporting both energy generation and recycling processes. Ultimately, the entire system focuses on Resource Optimization and Carbon Reduction, advancing the transition toward a sustainable, low-carbon economy.

4 Integrating circular economy with smart grids: a path to resource optimization and carbon reduction

The integration of circular economy (CE) strategies with smart energy grids presents a powerful approach to optimizing resource use and reducing carbon emissions, essential in achieving a sustainable energy future (Ho et al., 2024; Upadhayay et al., 2024). This fusion of CE principles with smart grid technology offers a holistic approach to addressing the challenges of energy generation, distribution, and consumption (Masanet et al., 2020; Eyo-Udo et al., 2024). The ability to combine the two systems ensures the efficient use of resources, the minimization of waste, and supports the decarbonization of energy production and consumption (Ghisellini et al., 2016; Abdmouleh et al., 2018; Ohanu et al., 2024). Through this synergy, the overall sustainability of energy systems can be improved, overlapping with global goals of reducing environmental impacts while maintaining the efficiency and stability of energy infrastructure (Khan and Nasir, 2023; Konietzko et al., 2020).

The process begins with the Smart Energy Grid, where Energy Generation harnesses renewable energy sources, such as wind, solar, and hydroelectric power. The generated energy is stored in Energy Storage systems like batteries or pumped hydro, ensuring energy availability even when renewable sources are intermittent. This stored energy is then distributed to various sectors, such as residential, industrial, and commercial, where it is consumed for daily needs (Energy Consumption). Energy Monitoring plays a pivotal role by continuously tracking the grid's performance and demand patterns, feeding this data into the Energy Feedback loop. This feedback adjusts Energy Generation, optimizing production to match consumption patterns, and improving grid reliability.

On the Circular Economy side, the flow begins with Resource Collection, where raw materials are sourced for product creation. These materials undergo Resource Processing, turning them into usable inputs for Product Manufacturing. Once the products are made, they are Distributed and used by consumers. After their useful life, the products enter Product End of Life, where they are either reused, recycled, or repurposed, significantly reducing waste. The Recycling & Reuse phase minimizes the need for raw material extraction, reducing environmental impacts.

Key integration points, such as Renewable Energy Use, Smart Grid Feedback, Energy Efficient Manufacturing, and Waste-to-Energy Conversion, connect the two systems. Waste-to-Energy Conversion allows waste materials to be transformed into usable energy, while Energy Efficient Manufacturing ensures that production processes consume less energy. This system drives Resource Optimization by efficiently managing both materials and energy, leading to Carbon Reduction. Ultimately, this integrated model ensures a sustainable, closed-loop system where resources are reused, waste is minimized, and carbon emissions are reduced, supporting long-term environmental and economic sustainability (Source: Author own as inspired by Ho et al., 2024 and Rios et al., 2022).

Therefore, one of the primary areas where the integration of CE principles into smart grids can significantly impact sustainability is in the recycling and reuse of materials used in renewable energy infrastructure. Renewable energy technologies, such as wind turbines, solar panels, and energy storage batteries, are integral to the transition away from fossil fuels. However, these technologies have finite lifecycles, and as they age or become obsolete, they may contribute to a growing amount of electronic waste and resource depletion (Srinivasan et al., 2025; Islam and Iyer-Raniga, 2022; Antony Jose et al., 2024). Circular economy strategies can be applied to mitigate these impacts by promoting the reuse, refurbishment, and recycling of materials used in these technologies. For instance, the recycling of rare earth metals from decommissioned wind turbines can alleviate the environmental burden associated with mining and reduce the need for new resource extraction (Srinivasan et al., 2025; Ghisellini et al., 2016; Upadhayay et al., 2024). As wind turbine technology continues to evolve and older turbines are decommissioned, valuable metals like neodymium and dysprosium, used in magnets for turbine motors, can be recovered, which reduces the environmental damage caused by resource extraction (Srinivasan et al., 2025). Similarly, solar panels can be designed to allow for efficient disassembly and material recovery at the end of their operational life, contributing to a circular system where the materials are continuously reused rather than disposed of Srinivasan et al. (2025), Mirletz et al. (2022), and Ho et al. (2024).

In the realm of energy storage systems, batteries are becoming an essential component of smart grids, helping to balance the intermittent nature of renewable energy sources like solar and wind. However, battery production is resource-intensive and has environmental implications, particularly with the mining of materials such as lithium, cobalt, and nickel (Srinivasan et al., 2025; Howlader et al., 2016). Circular economy principles can be applied to battery design and use to enhance sustainability. Batteries can be engineered for easier disassembly, allowing for the efficient recovery and reuse of valuable components and materials. Additionally, the reuse of batteries from electric vehicles in stationary storage applications has gained traction as a circular solution. These batteries, which still have considerable capacity after their use in vehicles, can be repurposed for use in stationary energy storage, thereby extending their useful life and reducing the need for new batteries (Lund et al., 2017; Antony Jose et al., 2024). This approach reduces waste and lessens the demand for new raw materials, contributing to the circular economy's goal of minimizing resource extraction.

Another essential aspect of integrating circular economy practices with smart grids is the optimization of energy flows through decentralized and distributed energy resources (DERs). Smart grids facilitate the integration of a variety of DERs, including rooftop solar panels, small-scale wind turbines, electric vehicles, and home energy storage systems (Danish and Senjyu, 2023; Kabeyi and Olanrewaju, 2023; Khatua et al., 2020). These DERs are key components of a decentralized energy network, where energy production, storage, and consumption occur closer to the point of use. This decentralized approach not only reduces the need for extensive, long-distance transmission but also minimizes associated energy losses. Energy produced from renewable sources can be consumed locally, reducing the reliance on centralized power plants and the environmental impact of energy transportation (Gungor et al., 2011; Kabeyi and Olanrewaju, 2023). Furthermore, the ability of smart grids to monitor and manage energy usage through advanced metering infrastructure (AMI) and real-time data analytics enables consumers to optimize their energy consumption, shift usage to off-peak hours, and participate in demand-response programs (Albadi and El-Saadany, 2008; Gungor et al., 2011). These measures reduce energy waste and decrease the strain on the grid, contributing to the overall goal of carbon reduction.

The integration of circular economy principles also strengthens the resilience and adaptability of energy systems. Traditional energy systems, especially centralized grids, can be vulnerable to disruptions such as extreme weather events or fluctuations in energy supply and demand. In contrast, smart grids are designed with built-in flexibility and the ability to make real-time adjustments to energy flows, making them more resilient to such disruptions (Gungor et al., 2011; Howlader et al., 2016). Circular economy practices further enhance this resilience by emphasizing the need for energy infrastructure that is durable, adaptable, and repairable. For example, rather than discarding outdated components, smart grids that adhere to circular economy principles can incorporate systems designed for refurbishment and reuse, ensuring that components remain functional for longer periods (Ghisellini et al., 2016; Rios et al., 2022). Additionally, energy storage systems integrated into smart grids provide backup power during outages and can help maintain a steady energy supply during peak demand periods, ensuring grid stability even in the face of challenges (Lund et al., 2017; Ho et al., 2024; Rios et al., 2022).

The decentralized nature of smart grids also supports greater local energy resilience. In the event of a grid failure, microgrids, which are small-scale, localized energy networks, can operate independently of the main grid, ensuring continued energy supply for critical services and households. Microgrids can integrate renewable energy sources, such as solar or wind, along with energy storage systems, enabling them to function autonomously. The ability to isolate these microgrids from the larger grid during an outage enhances energy security and reduces the potential for widespread disruptions (Lund et al., 2017; Kabeyi and Olanrewaju, 2023). Moreover, local energy production and consumption, coupled with energy storage, increase the resilience of communities by reducing their dependence on centralized power sources and providing greater control over their energy needs.

The integration of circular economy principles within smart grids also contributes to the broader goals of environmental sustainability and carbon reduction. Smart grids optimize energy efficiency and minimize waste, which reduces overall energy consumption and lowers carbon emissions. As more renewable energy sources are integrated into the grid, carbon emissions associated with energy generation will decrease, especially when paired with energy storage and demand-response systems that optimize the use of renewable energy (Moraga et al., 2019; Ahmed et al., 2023; Rios et al., 2022). The circular economy's focus on reducing resource extraction and minimizing waste complements these efforts, ensuring that energy systems are not only more sustainable but also regenerative in nature, working in harmony with the environment (Ghisellini et al., 2016; Tukker, 2015; Upadhayay et al., 2024).

Looking circumspectly, integrating circular economy principles with smart grids offers a comprehensive and innovative solution to the challenges of resource optimization, energy efficiency, and carbon reduction. The combination of decentralized energy systems, the recycling and reuse of materials, and the optimization of energy flows through real-time data analytics helps create a more sustainable and resilient energy future. As the demand for clean energy continues to rise, the synergy between circular economy strategies and smart grids will play a crucial role in achieving a low-carbon, sustainable energy system for the future.

The process begins with the Smart Energy Grid, starting with energy generation, followed by storage, distribution, and consumption. Energy monitoring ensures efficient operations, with feedback mechanisms optimizing generation and consumption patterns. The energy feedback loop connects all stages, improving energy efficiency by adjusting production based on real-time data.

On the other side, the Circular Economy starts with resource collection, leading to processing and subsequent manufacturing. After products are made, they are distributed and used by consumers. At the product's end of life, it enters the recycling and reuse stage, closing the loop by reducing waste.

Integration points include the use of renewable energy, ensuring that energy generation is sustainable, and the smart grid feedback loop, which uses data to regulate energy distribution. Other key elements are energy-efficient manufacturing and waste-to-energy conversion, where waste is recycled into energy, fostering a more sustainable and efficient system. This synergy between energy and resource management leads to greater sustainability (Source Authors own as inspired by Rios et al., 2022 and Upadhayay et al., 2024). Circular economy and smart energy grids drive resource optimization and waste reduction by enhancing energy efficiency, minimizing carbon emissions, and promoting renewable integration. This synergy creates resilient systems, reduces resource dependency, and supports sustainable energy transitions for long-term environmental and economic benefits (Figure 3).

5 Technological and regulatory barriers to integrating circular economy principles with smart energy grids

A critical analysis of technological and regulatory barriers reveals several challenges to the effective integration of Circular Economy (CE) principles with Smart Energy Grids (Eyo-Udo et al., 2024; Murray et al., 2017; Upadhayay et al., 2024). These challenges span the realms of technological advancement,

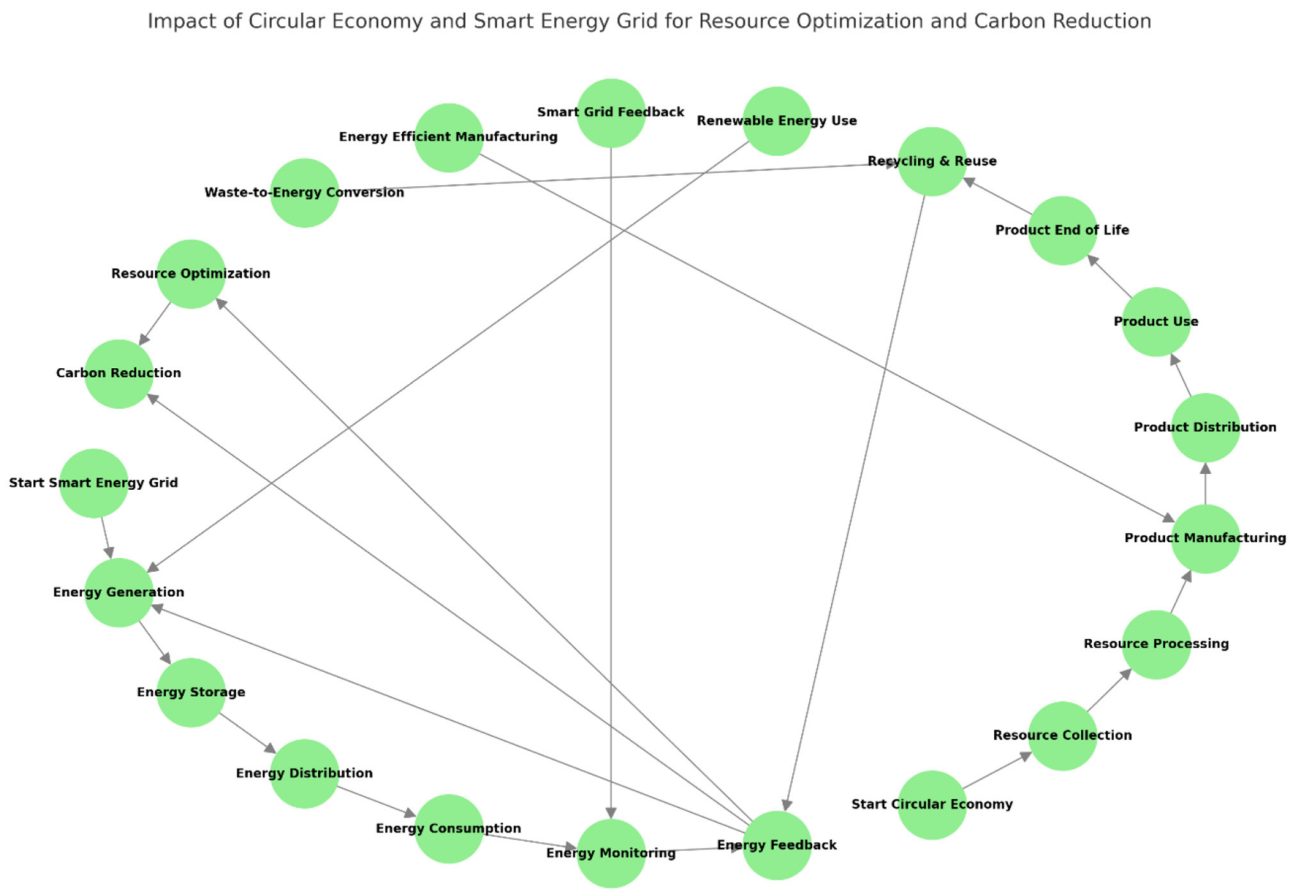

FIGURE 3
Represents the integration of the circular economy with a smart energy grid, illustrating how energy generation and resource management work together in a sustainable ecosystem.

regulatory alignment, and economic feasibility, significantly hindering the seamless adoption of sustainable practices in the energy sector. Addressing these issues requires coordinated efforts across innovation, policy, and financial strategies, ensuring a holistic and future-proof approach to integrating circular economy principles within SEG frameworks (Korhonen et al., 2018; Khan et al., 2021; Bogdanov et al., 2021; Fragkos, 2022).

For instance, a primary technological hurdle in achieving a circular energy system lies in the development of efficient energy storage systems, which are crucial for the integration of renewable energy sources (Sovacool et al., 2018; Zhang et al., 2025; Kirchherr et al., 2023). As highlighted by Zafar et al. (2021), energy storage technologies such as batteries and supercapacitors play a central role in stabilizing energy supply from intermittent renewable resources like wind and solar power. However, the current technological landscape for energy storage remains in a developmental phase, with challenges around efficiency, lifespan, and scalability (Zafar et al., 2021; Bilal et al., 2020; Alshamaila et al., 2023; Rios et al., 2022). Despite their potential to enhance grid reliability, these storage systems struggle to meet the demands of large-scale integration, hindering the realization of smart grids that can autonomously manage fluctuating energy demands.

Another significant barrier is the insufficient recovery of materials from renewable energy infrastructure, which is a core principle of circular economy models. Hao et al. (2020) and Pan and Hashemizadeh (2023) argue that while recycling technologies for materials such as metals, glass, and rare earth elements in wind turbines and solar panels are available, the efficiency of these recovery processes remains low. This is particularly problematic given the anticipated increase in renewable energy infrastructure globally. The lack of effective material recovery undermines the sustainability of renewable energy systems, as many materials used in these technologies, such as rare earth metals, are non-renewable and scarce. Without significant improvements in recycling technologies, the CE principles of reusing and minimizing waste cannot be fully integrated into the energy sector (Mirletz et al., 2022; Albertsen et al., 2021; Gielen et al., 2019).

In addition, the technological complexities of implementing CE within SEG frameworks are compounded by the challenge of retrofitting existing infrastructure. Most current grids were not designed with sustainability or circularity in mind, meaning that substantial technological and engineering innovations are required to adapt them to accommodate both renewable energy integration and circular economy practices (Rios et al., 2022; Ho et al., 2024). The gradual development of these technologies, such as smart meters and energy-efficient grid systems, is critical but faces substantial hurdles due to the need for a coordinated effort across industries and regions (Kumar and Bhimasingu, 2015; Dileep, 2020; Khalid, 2024).

Therefore, on the regulatory side, the lack of harmonization across key regions such as the European Union (EU), the United States, and China presents another significant barrier to integrating CE with SEG (Khan et al., 2022; Kirchherr et al., 2023; Korhonen et al., 2018). The EU has made notable strides toward embedding circular economy principles in its policy framework, such as through the Circular Economy Action Plan. However, as Gielen et al. (2019) note, the actual implementation of these policies in the energy sector has been slow. In particular, the lack of standardized regulations across member states makes it challenging to create a cohesive strategy for integrating CE principles with SEG. The absence of coordinated regulatory frameworks impedes the efficiency of cross-border collaborations, which are essential for scaling smart grid and circular economy initiatives at an international level (Konietzko et al., 2020; Leal-Arcas et al., 2017).

In the US, the situation is further complicated by the decentralization of regulatory powers. As Leal-Arcas et al. (2017) argue, energy policies in the US are often governed at the state level, which leads to a fragmented regulatory environment where states adopt divergent strategies. While some states like California have been proactive in adopting ambitious renewable energy and circular economy policies, other states lag behind due to different political priorities and economic conditions (Rios et al., 2022; Upadhayay et al., 2024). This inconsistency in policy development leads to inefficiencies, as ambitious state-level policies do not translate into nationwide strategies, preventing a more cohesive energy transition and the adoption of smart grids (Khatua et al., 2020; Ho et al., 2024).

Conversely, China's centralized approach to governance allows for more uniform policy implementation, but this comes with its own set of challenges. As Sánchez-García et al. (2024) point out; the rigidity of China's top-down regulatory mechanisms may limit the flexibility required for technological innovation and adaptation in the rapidly evolving energy sector. Although China's focus on large-scale implementation ensures significant advances in renewable energy infrastructure, it may stifle innovation that is crucial for the effective integration of circular economy practices within SEG (Stahel, 2013).

Likewise, economic barriers also play a crucial role in hindering the widespread adoption of circular economy principles in smart energy grids. Developing economies face significant financial constraints when it comes to transitioning from linear to circular economic models (Eyo-Udo et al., 2024; Ali et al., 2025). Govindan (2023) highlights that the high upfront costs associated with implementing circular economy strategies such as investing in energy storage systems, smart grid technologies, and the infrastructure necessary for recycling renewable energy components can be prohibitively expensive for countries already grappling with challenges like poverty reduction and economic growth (Eyo-Udo et al., 2024; Sánchez-García et al., 2024; IEA, 2023). This is compounded by the fact that many developing countries are still reliant on traditional energy systems, which may not align with the high costs associated with transitioning to smart, circular grids (Tukker, 2015; Ali et al., 2025; Padmajan Sasikala et al., 2019).

Furthermore, as Gielen et al. (2019) observe, the economic trade-offs involved in implementing CE strategies are particularly pronounced in developing economies. These nations often struggle to balance immediate economic growth needs with long-term sustainability goals. The financial burden of transitioning to sustainable energy systems can overshadow the long-term economic and environmental benefits, making it difficult for governments to justify these expenditures (Khatua et al., 2020; Mendoza et al., 2017; Srinivasan et al., 2025). This gap in financial capability is further exacerbated by the lack of external funding mechanisms, particularly for infrastructure investments in energy storage and recycling technologies (Gimeno et al., 2020; Zhang et al., 2025; Zhou et al., 2023; Lah, 2016).

Moreover, without contradiction, integrating circular economy principles with smart energy grids faces significant technological, regulatory, and economic barriers that hinder the realization of a sustainable, circular energy system (Ali-Toudert et al., 2020; Han et al., 2023). Technologically, energy storage and material recovery systems are not yet optimized for large-scale deployment. Regulatorily, fragmented policies, and inconsistent frameworks across regions prevent the alignment of CE and SEG objectives. Economically, the high upfront costs of transitioning to circular energy systems present challenges, particularly for developing economies. Overcoming these barriers requires technological innovation, the harmonization of regulations, and the development of financial models that prioritize long-term sustainability (Schnitzer and Ulgiati, 2007; Reindl, 2024; Zhang et al., 2025; Zafar et al., 2021).

6 Case studies on the intersection of circular economy and smart energy grids: real-world insights and lessons learned

The convergence of circular economy principles with smart energy grids represents a paradigm shift toward sustainability. However, through harnessing renewable energy technologies, optimizing energy efficiency, and employing advanced resource management strategies, these systems are designed to mitigate carbon emissions while enhancing material circularity through reuse and recycling. Empirical case studies offer tangible insights into both the transformative potential and the complexities of these integrated systems, highlighting the critical roles of digitalization, energy storage solutions, and cutting-edge technological advancements in realizing their full potential.

One notable example of circular economy principles in the smart energy grid context is the implementation of wind turbine recycling in Europe. The recycling of materials used in wind turbine blades, particularly glass fiber and resin, has been a key challenge (Hao et al., 2020; IEA, 2023; Wilson et al., 2022). However, initiatives like the *Circular Wind* project, led by a consortium of European companies, have made significant strides by converting used wind turbine blades into valuable resources, such as recycled glass fiber for use in the construction industry. This initiative has not only reduced waste but also supported the sustainability of wind energy in Europe, contributing to its circular economy.

This example shows how integrating circular economy practices within renewable energy projects can drive both environmental and economic benefits (Gielen et al., 2019; Hao et al., 2020; Zhou et al., 2023).

In the context of smart grids, a compelling case study comes from the energy storage and management systems in the city of Sanaa, Yemen and Pakistan. As part of a broader effort to modernize the energy grid, the integration of distributed generation and energy storage technologies helped improve the resilience and efficiency of the local power grid (Zafar et al., 2021). The implementation of a smart grid system incorporated renewable energy sources, such as solar power, combined with advanced demand response mechanisms. The results were promising: the system improved grid stability, reduced electricity consumption during peak hours, and minimized carbon emissions (Kabeyi and Olanrewaju, 2023; Abdmouleh et al., 2018; Hamidu et al., 2023). The project highlighted the importance of combining renewable energy with efficient energy management systems, a fundamental principle of circular economy strategies (Danish and Senjyu, 2023; Govindan, 2023; Zafar et al., 2021).

Moreover, the concept of resource optimization is further explored in the application of smart grids in the United States, particularly in the state of California. The state's *Pacific Gas and Electric Company (PG&E)* implemented a smart grid system to enhance its energy distribution capabilities. The system employed advanced metering infrastructure (AMI) to allow for real-time monitoring and management of energy flows (Sovacool et al., 2018). This was propelled by facilitating peer-to-peer energy trading, the system optimized energy distribution, reducing waste, and ensuring more efficient use of renewable energy sources (Zhou et al., 2023; Khatua et al., 2020; Howlader et al., 2016). Moreover, this setup supported the circular economy by enhancing grid flexibility, ensuring that energy was sourced from renewable means, and minimizing waste through efficient demand-side management. These efforts are aligned with the global shift toward a circular, sustainable economy, underpinned by innovations in digital technologies (Gimeno et al., 2020; Govindan, 2023; Gimeno et al., 2020).

In contrast, some challenges faced by circular economy initiatives in energy grids can be seen in the case of the *European Union's Smart Grid Deployment* program. Despite significant investments in smart grid technologies, the transition has faced hurdles related to regulatory barriers, insufficient integration of renewable energy, and consumer resistance to new technologies. These challenges were particularly evident in the implementation of smart grids in Eastern Europe, where inconsistent policy frameworks and limited public acceptance delayed the adoption of energy-efficient technologies (Leal-Arcas et al., 2017; Thomas and Mishra, 2022; Ali et al., 2025). These failures highlight the importance of comprehensive policy frameworks that incentivize both innovation and public adoption of smart grid systems.

Furthermore, lessons can be learned from the *Smart Grid Energy Storage Project* in South Korea, which focused on integrating energy storage systems (ESS) into the smart grid infrastructure. By using ESS to store excess renewable energy during off-peak hours and discharge it during peak times, the system helped balance supply and demand, thereby reducing the reliance on non-renewable energy sources (Padmajan Sasikala et al., 2019). However, the project faced challenges due to high initial investment costs and the complexity of managing large-scale ESS systems. Despite these hurdles, the project successfully demonstrated the potential of circular economy practices in optimizing energy use and reducing carbon emissions (Sovacool et al., 2018; Zafar et al., 2021).

Another success story comes from the *Netherlands*, where the integration of electric vehicle (EV) batteries into the smart grid system has enabled energy storage solutions that contribute to grid stability while also supporting the circular economy (Zhang et al., 2025). The *Vehicle-to-Grid (V2G)* technology allows EV batteries to store and release energy to the grid as needed, providing a reliable source of renewable energy. This innovative approach not only optimizes energy use but also promotes the recycling and reuse of EV batteries, reducing the environmental impact of battery disposal (Antony Jose et al., 2024; Zafar et al., 2021). The Dutch case validates the growing role of digitalization and advanced technologies in achieving both energy efficiency and circularity in energy systems (Khan et al., 2022; Zhang et al., 2025).

Mirroring a close reflection, these case studies demonstrate the diverse and evolving ways in which circular economy principles are being integrated into smart energy grids. While real-world applications reveal significant potential for reducing carbon emissions and optimizing resource use, they also address the need for tailored policies, technological advancements, and consumer engagement to overcome existing barriers. The success stories from California, Europe, and South Korea provide valuable insights into how innovation, collaboration, and systemic thinking can drive progress toward a more sustainable and circular energy future.

7 Conclusion and policy recommendations: circular economy meets smart energy grids

The integration of Circular Economy (CE) principles with Smart Energy Grids (SEG) holds transformative potential in driving sustainability. This is attained through optimizing resource use, reducing emissions, and creating resilient systems, CE and SEG together can ensure a low-carbon future (Zhang et al., 2021; Ali et al., 2025). CE emphasizes waste reduction, resource recovery, and the extension of product life cycles, while SEG focuses on enhancing energy efficiency and integrating renewable energy sources. Together, they form a holistic approach to resource optimization that benefits not only the environment but also the economy and society (Abdmouleh et al., 2018; Geissdoerfer et al., 2017; Murray et al., 2017; Masanet et al., 2020).

While both CE and SEG are aligned in their objectives, their full potential can only be realized by addressing significant barriers. These include technological limitations, regulatory frameworks, and market incentives. Technologically, recycling and energy storage systems face challenges that hinder large-scale implementation. Innovative solutions are needed to recycle materials such as lithium-ion batteries, which are central to both energy storage and electric vehicles (Antony Jose et al., 2024; Srinivasan et al., 2025; Sovacool et al., 2018). At the same time, developing energy-efficient and scalable storage solutions remains a critical priority (Islam and Iyer-Raniga, 2022; Dantas et al., 2021; Chen et al., 2022). The large upfront investment required for such technologies requires targeted policy interventions to stimulate research and development in these areas.

Regulatory frameworks must also evolve to facilitate the integration of CE and SEG. Current regulatory structures are often ill-equipped to accommodate the complexities of integrating renewable energy, decentralized grids, and waste-to-energy systems (Chen et al., 2013; Dye and Yang, 2015). Existing laws, such as those governing electricity pricing and energy storage, need to be revisited to ensure that they support emerging smart grid technologies (Kumar and Bhimasingu, 2015; Kabeyi and Olanrewaju, 2023). A regulatory environment conducive to innovation will encourage the adoption of energy-efficient, decentralized systems, and foster circular business models. In this regard, countries that have successfully implemented regulatory reforms, such as Germany's Energiewende, have shown how policy shifts can accelerate the transition toward renewable energy and energy efficiency (Gielen et al., 2019; Moraga et al., 2019).

Additionally, governments should leverage financial incentives, such as tax breaks and subsidies, to encourage innovation in the circular economy and smart grid sectors. For instance, the European Union's Green Deal provides a model for tax incentives and subsidies to foster renewable energy technologies, with a projected €1 trillion investment in sustainable infrastructure (Sovacool et al., 2018). Such investments can stimulate job creation, economic growth, and environmental benefits. For example, Germany's Renewable Energy Sources Act (EEG) has successfully incentivized investments in renewable energy, resulting in over 30% of the country's energy being sourced from renewables as of 2020 (Gielen et al., 2019).

To provide a clearer understanding of the financial impact, tax incentives could reduce the cost of adopting energy storage systems by up to 20%, based on estimates in the U.S. Department of Energy's 2021 report (IEA, 2022). This financial relief encourages private sector investments in CE technologies, which could offset upfront costs for businesses while enabling them to benefit from long-term savings due to lower energy consumption and reduced waste disposal costs.

Market incentives should also include subsidies for research in energy storage, recycling technologies, and the development of waste-to-energy systems. For instance, the Japanese government has implemented various subsidy programs to support smart grid projects, which have resulted in significant reductions in carbon emissions and operational costs (Moraga et al., 2019; Bazan et al., 2015). These kinds of policies create a competitive environment that incentivizes businesses to develop innovative solutions and bring them to market (Ali-Toudert et al., 2020; Govindan, 2023).

Public-private partnerships (PPP) are also crucial in bridging the gap between technological challenges and regulatory reforms. Governments and private firms can share financial risks, leverage each other's expertise, and co-develop infrastructure to support both circular economy and smart grid strategies. Successful examples of PPPs can be found in countries like the U.K., where partnerships between local governments and energy companies have accelerated the rollout of smart meters and renewable energy systems. These collaborations can also provide platforms for testing and refining emerging technologies, ensuring that they are both viable and scalable in real-world applications (Gungor et al., 2011). In addition, pilot projects, such as the "Smart City" initiatives in cities like Barcelona and Amsterdam, can act as living labs for experimenting with CE and SEG integration. These pilot projects can provide valuable lessons in overcoming technological and regulatory challenges and allow for the refinement of business models (Yang et al., 2023; Sánchez-García et al., 2024).

Moreover, a key component in driving this transition is education and awareness. Public understanding of the interconnectedness between circular economy principles and smart grids is crucial to creating demand for sustainable solutions. Education campaigns should aim to inform both consumers and policymakers about the long-term environmental, economic, and social benefits of these integrated systems. For instance, in Sweden, a national campaign on energy efficiency helped reduce household energy consumption by 10% in just 5 years (Kullmann et al., 2021). By promoting energy-efficient behaviors and circular business models in the energy sector, such campaigns can foster a more informed, engaged society that drives demand for sustainable products, and services.

Furthermore, targeted policy measures can incentivize consumers to participate in the transition. For example, countries like Denmark have offered tax reductions on energy-efficient appliances and electric vehicles, making sustainable choices more accessible to households. These policies contribute to both financial savings for consumers and reduced carbon footprints for society (Leal-Arcas et al., 2017; Han et al., 2023). The estimated financial impact of such tax incentives suggests that they can reduce household energy costs by up to 25% annually, thereby enhancing the adoption of energy-efficient technologies at scale (Zhou et al., 2023; Almagtome et al., 2020).

To accelerate the integration of CE and SEG, governments should implement policies that facilitate cross-border collaboration and knowledge-sharing. International platforms such as the Clean Energy Ministerial (CEM) provide valuable opportunities for nations to exchange best practices and scale successful innovations. These collaborations can further drive the global transition to low-carbon energy systems by sharing research findings, funding opportunities, and policy insights (IEA, 2022; Gungor et al., 2011; Ali et al., 2023).

Looking introspectively, integrating circular economy principles with smart energy grids offers significant potential for achieving a sustainable, low-carbon future. Overcoming the technological, regulatory, and market challenges that exist requires well-designed policy frameworks, financial incentives, public-private partnerships, and educational initiatives (Danish and

Senjyu, 2023; Ghisellini et al., 2016; Bogdanov et al., 2021). With these strategic actions, governments can foster the widespread adoption of circular economy and smart grid systems, creating a sustainable energy system that benefits society, the economy, and the environment (Lund et al., 2017; Kullmann et al., 2021; Dantas et al., 2021; Gielen et al., 2019). Likewise, ensuring that these integrated systems are adopted on a large scale, societies can enjoy long-term environmental and economic benefits, including job creation, enhanced energy security, and a reduction in greenhouse gas emissions. With the right policies and investments, the transition to a sustainable, low-carbon future is not only possible but achievable (Tukker, 2015; Stahel, 2013; Khan and Nasir, 2023).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

WM: Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Validation, Writing – original draft, Writing – review & editing.

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

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