Circular supply chain management in the renewable energy sector: a case study on wind turbine parts

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Abstract

This study delves into the industrial context of the renewable energy sector, particularly wind turbines, as crucial for providing sustainable energy systems. It addresses the pressing need for durable, recyclable product designs and effective waste management within this sector. The research, rooted in a case study of an industrial service provider specialising in wind turbine solutions in the UK and Ireland, investigates the transition towards Circular Supply Chain Management (CSCM) for the Yaw and Pitch Gearboxes. It focuses on understanding the implementation of CSCM practices, evaluating the challenges and opportunities of shifting from a linear to a circular supply chain model and assessing the environmental, economic, and social outcomes of this transition, with special emphasis on the Yaw and Pitch gearboxes of wind turbines. The learning points from this research paves the way for a more sustainable future in the renewable energy sector.

Keywords: Circular economy, Supply chain management, Renewable energy sector

Introduction

In the current era, where environmental sustainability is of utmost importance, the role of supply chain management within businesses is undergoing a significant transformation. This is particularly true in sectors like renewable energy, where environmental considerations are paramount. This study delves into the integration of circular economy principles in the wind energy sector, specifically focusing on a case study of an industrial services provider in the UK and Ireland specialising in renewable energy solutions, particularly wind turbines.

The industrial context of renewable energy, specifically wind turbines, requires a strategic shift towards circular supply chain management (CSCM). The imminent decommissioning of numerous wind turbines across Europe underscores the urgency of this shift. By 2035, around 584 GW of wind capacity, served by approximately 120,000 turbines, will be operational, presenting significant challenges and opportunities for sustainable end-of-life strategies (BVGAssociate, 2023). In the UK, the costly and carbon-intensive nature of decommissioning call for extending the life of wind turbines beyond their original operating lifespan from 20 to 25 years (Butler et al., 2023). With a significant number of turbines nearing the end of their lifespan, the opportunity for recirculating turbine components through circular economy principles emerges as a critical option to reduce costs and carbon footprint and to address the sector's waste management challenges. The transition to CSCM addresses these challenges and holds the promise of a more sustainable and efficient future for the renewable energy sector.

In the wind energy sector, the traditional linear 'take-make-dispose' model prevalent in the industry is increasingly at odds with environmental sustainability goals. This paradox has sparked a shift towards circular economy practices, emphasising the importance of end-of-life strategies for wind turbines, including reusing, recycling, or refurbishing components like gearboxes, blades, and towers (Chhimwal et al., 2021).

The complexity of wind turbine components, such as Yaw and Pitch gearboxes, presents both a challenge and an opportunity for the industry. These components, responsible for the functioning of wind turbines, are expensive and resource-intensive to manufacture. As turbines reach the end of their operational life, the industry faces the daunting task of either disposing of these components, which are neither environmentally nor economically viable or finding ways to refurbish and recycle them. The shift towards circular economy approaches in the wind sector thus centres around finding sustainable ways to manage these components at the end of their lifecycle (Singh and Ordoñez, 2016).

In practice, the industry must also address the challenges associated with the complex composition of components. Recycling and repurposing these components require innovative approaches and technologies, given their composite materials and intricate design. Developing new materials and using complex composites in wind turbines further complicate efforts to reclaim the recycling value of end-of-life products (Psomopoulos et al., 2019). Innovation in design and manufacturing is integral to the sector’s transition, as the industry is increasingly required to design more easily refurbished, repaired, or recycled turbines and components. Such design innovations could significantly reduce the environmental impact of turbines over their lifecycle and enhance the feasibility of circular economy practices (Jensen and Skelton, 2018).

The circular economy offers significant economic and commercial opportunities, emphasising resource reuse and waste minimisation. By reducing reliance on finite resources, creating new job opportunities, saving costs on materials and waste disposal, generating new revenue streams, gaining competitive advantages, fostering innovation, accessing new markets, and building stronger stakeholder relationships, the circular economy offers a transformative pathway for the renewable energy sector (Korniejenko et al., 2021). However, various perceived barriers hinder wider industry adoption, such as concerns about the quality and reliability of recirculated components and insufficient collaboration and information sharing (Butler et al., 2023).

This research develops a case study to analyse a company's transition towards a circular supply chain model within the renewable energy sector. The key research questions for the study are: 1. How is the company implementing CSCM practices within its operations? 2. What are the key challenges and opportunities associated with transitioning from a linear to a circular supply chain model in the renewable energy sector, particularly for Yaw and Pitch gearboxes for wind turbines? 3. What are the environmental, economic, and social outcomes of adopting circular supply chain practices for the company in the Yaw and Pitch gearbox project context?

Literature Review

Circular economy concepts and practices provide a transformative approach to economic activity, pivoting towards sustainability and resource efficiency. Within supply chains, this paradigm shift manifests as Circular Supply Chain Management (CSCM), which fosters closed-loop systems to minimise waste and optimise resource reutilization

(Batista et al., 2018). This approach is particularly relevant in the renewable energy sector, where sustainability is integral.

Supply Chain Management (SCM) has transitioned from a traditional linear model, characterised by resource extraction, product manufacturing, and disposal, to a more sustainable and integrated approach. This shift reflects a growing awareness of the need to align supply chain processes with environmental sustainability, with the renewable energy sector playing a critical role in this transition (Nasir et al., 2017).

The integration of sustainability within SCM, evolving into Sustainable Supply Chain Management (SSCM), focuses on adopting eco-friendly practices and rethinking supply chain operations to balance economic goals with environmental and social responsibilities, particularly pertinent in the renewable energy sector (Farooque et al., 2019).

In the renewable energy sector, applying CSCM, especially in managing components like wind turbine gearboxes, addresses crucial sustainability challenges. Practices such as extending the life cycle of turbine parts through refurbishing and remanufacturing align with circular economy principles, enhancing the sector's sustainability (Jensen and Skelton, 2018).

CSCM implementation in renewable energy drives triple-bottom-line benefits. Economically, it offers cost savings and resource efficiency. Environmentally, it fosters waste reduction and resource conservation. Socially, CSCM aligns with broader sustainability goals, impacting societal well-being (Jensen et al., 2020).

Regenerative and restorative approaches within CSCM emphasise sustainability beyond traditional practices. For instance, the meticulous disassembly and assessment of used gearboxes allows components to be refurbished, remanufactured, or recycled, effectively minimising waste. This not only reduces environmental harm but also restores ecosystems and resources. These practices align with industrial ecology principles, focusing on closed-loop systems and enabling natural cycles in industrial processes (McDonough and Braungart, 2010).

By prioritising remanufacturing and refurbishment, companies contribute to resource regeneration, extending material life cycles and reducing the need for new material extraction. This aligns with regenerative design principles, seeking to create inherently sustainable systems that contribute positively to the environment (Mang and Reed, 2012).

Methodology

This study employed a mixed-method approach to investigate CSCM in the renewable energy sector, focusing on wind turbine parts. This methodology was selected for its effectiveness in providing a comprehensive understanding of the strategic and operational aspects of CSCM practices within a real-world context.

The research was centred around a single case study of an industrial service provider in the UK and Ireland specialising in renewable energy solutions, particularly wind turbines. The company was chosen due to its role in the renewable energy sector and its efforts to implement CSCM practices, which offer an opportunity to explore practical applications and challenges of CSCM in an industry critical to global sustainability efforts (Yin, 2018).

Data collection combined qualitative and quantitative methods to comprehensively explore CSCM practices in the renewable energy sector. Semi-structured interviews with seven high ranked managers provided in-depth insights into CSCM strategies and challenges (Kvale and Brinkmann, 2009). Field observations complemented these interviews, offering a practical view of CSCM implementation (Robson and McCartan, 2016). Document analysis of internal reports and sustainability documents further enriched the understanding of the company's CSCM approach (Bowen, 2009). Quantitatively, industry reports related to the circular economy in the renewable energy sector were analysed, focusing on metrics like Gross Value Added (GVA), Full-Time Equivalent (FTE) impacts, and waste reduction rates (Saunders et al., 2009).

Accordingly, data analysis involved both qualitative and quantitative techniques. The qualitative data, comprising interview transcripts and documents, underwent thematic analysis (Braun and Clarke, 2012), where coding was used to identify key themes and patterns. This approach allowed an in-depth understanding of the company's operational strategies, challenges, and outcomes in implementing CSCM. Quantitative techniques such as descriptive statistics and time series analysis were applied to the data collected from industry reports and internal company metrics (Field, 2013). This quantitative analysis provided a view of the economic, environmental, and social impacts of CSCM practices, thereby offering a well-rounded perspective on the effectiveness of these practices within the renewable energy sector.

Case Study Subject

The company chosen for this case study actively explores and implements initiatives to transition towards a CSCM model. The company is a specialised industrial service provider. It offers solutions to various industry sectors in the UK and Ireland, including the renewable energy sector, focusing on wind energy services. The company's technical and supply specialists work with businesses across the region to enhance productivity and reliability and ensure cost-effective solutions along their lifespan. In this transformative phase, the company implements a sustainable Yaw and Pitch gearboxes project for wind turbines onshore and offshore. These gearboxes, critical components of wind turbines, are responsible for the yawing motion—rotating the turbine head to align with wind direction, maximising efficiency and energy capture. The pitch gearboxes adjust the angle of the blades, optimising their position to control the turbine's rotational speed and power generation. The company is implementing circular strategies in a controlled setting. The implemented practices exemplify how circular economy principles can be applied to critical industrial components within the company and the industry, paving the way for more sustainable practices in the renewable energy sector.

Findings

Implementation of Circular Supply Chain Management Practices

The CSCM practices at the company mainly focus on refurbishing, remanufacturing, and recycling wind turbine's Yaw and Pitch gearboxes, marking a significant transition from the traditional linear model to one emphasising product longevity and sustainability. This shift was rooted in a systematic process of disassembling and assessing used or worn-out gearboxes, with each component undergoing a thorough examination to determine its suitability for refurbishing, remanufacturing, or recycling. The Chief Operating Officer (COO) highlighted this strategic change, stating,

> *"Our focus has significantly shifted towards extending the life of gearboxes. We invest more in refurbishing and remanufacturing processes than just replacing old with new for our customers."* (COO)

This strategic shift was implemented by operational initiatives involving procedures where gearboxes were systematically examined for refurbishment, remanufacturing, or recycling rather than mere replacement. The company's operations carried out refurbishment following complete certification requirements, ensuring the refurbished gearboxes met the same standards as the new ones. This sustainable approach to gearbox management is depicted in Figure 1, which illustrates the company's practice in implementing CSCM for the Yaw and Pitch gearboxes. The figure highlights the process of preparing gearboxes suitable for refurbishment, remanufacturing, or recycling.

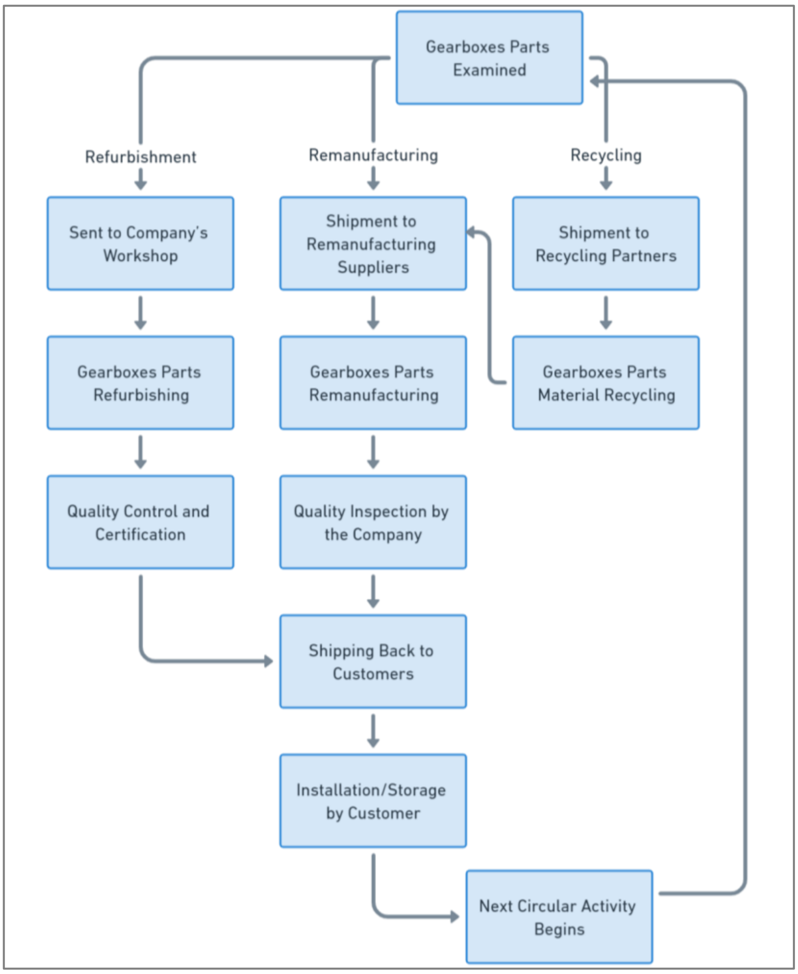

Figure 1 - Representation of CSCM practice for the Gearboxes Lifecycle.

The Engineering Manager emphasised the evolution of their engineering processes, noting,

> *"Our engineering processes are now evolving. We prioritise design elements that make disassembly and refurbishment more feasible."*

This was complemented by an enhanced focus on supplier engagement, ensuring the use of sustainable and recyclable materials, as described by the Service Manager:

> *"We're working closely with our suppliers to ensure that the materials we use are sustainable and that our entire supply chain reflects circular economy principles."* (Service Manager)

Additionally, the company implemented advanced tracking and management systems to enhance the efficiency of the refurbishment process. The COO added,

> *"Technology plays a crucial role in our operational shift. It allows us to track each component, predict maintenance schedules, and efficiently manage the refurbishment and remanufacture process."* (COO)

Quality assurance was also a key focus, with the Quality Manager highlighting,

> *"We're enhancing our quality control measures. Refurbished and remanufactured gearboxes must meet stringent standards to ensure they perform as well as new ones."* (Quality Manager)

Challenges and Opportunities in the Transition

A major challenge identified was overcoming technical and design barriers inherent in traditional gearbox designs. These designs often do not lend themselves easily to disassembly and recycling, posing hurdles to achieving true circularity. The COO highlighted this challenge:

> *"To make the gearboxes fit for a circular economy, we must innovate at every level. This means using more durable materials, choosing the right design for disassembly, and finding ways to give old gearboxes new life through refurbishing and remanufacturing."* (COO)

Another significant aspect of the transition involved realigning supply chain processes, particularly establishing efficient reverse logistics systems. The Project Innovation Manager pointed out the complexity of this endeavour:

> *"Setting up efficient reverse logistics is a complex task. It requires new infrastructure and a shift in how we think about products at the end of their life."* (Project Innovation Manager)

Stakeholder engagement emerged as both a challenge and an opportunity. Resistance to change from some suppliers, customers, and community members initially impeded collaborative efforts. However, the company viewed these interactions as vital opportunities for innovation and partnership, focusing on building an ecosystem of partners that supports the circular objectives.

Quality management in a circular supply chain also posed significant challenges, necessitating stringent control measures to ensure that refurbished or remanufactured products met the highest standards. The Quality Manager emphasised the importance of maintaining high customer trust and long-term viability standards.

Despite these challenges, the transition opened up opportunities for innovation in product design and process optimisation, which the company recognised as crucial for continuous improvement in a rapidly evolving market. The COO reflected on this innovation drive:

> *"Embracing circular practices has spurred a wave of innovation within our company."* (COO)

Transitioning to a circular model led to new business models and revenue streams. For instance, the market size and margin data revealed significant opportunities in remanufacturing and refurbishment. The Regional Manager noted the growing demand for sustainable solutions among customers:

> *"Our customers are increasingly sustainability-conscious. They appreciate the environmental benefits of refurbished and remanufactured gearboxes and the cost savings they bring."* (Regional Manager)

Table 1 summarises these challenges and opportunities, providing a concise overview of the critical aspects of the transition. This table encapsulates the multifaceted nature of transitioning to CSCM, illustrating this shift's hurdles and potential gains.

Table 1 - Summary of the Challenges and Opportunities

Challenges	**Opportunities**

• Technical and Design Barriers • Adapting Supply Chain Processes • Reverse Logistics Complexity • Balancing Change and Collaboration Among Stakeholders • Stakeholder Engagement Resistance • Quality Management Requirements • Investment in Infrastructure and Technology	• Innovation in Product Design and Process • New Business Models and Revenue Streams • Market Growth Potential • Responding to Regulatory Pressures • Sustainable Solution Demand Increase • Operational Efficiency and Cost Saving • Overcoming Long Lead Times • Improved Customer Relations

Expected TBL Outcomes: Environmental, Economic, and Social

The research identified multi-dimensional sustainability outcomes encompassing environmental, economic, and social benefits. Economically, the operational changes led to significant impacts, as evidenced in the UK's GVA for Yaw and Pitch Gearboxes, projected from 2025 to 2035. The cumulative GVA over this period is estimated at £38.9 million, indicating a substantial economic contribution. This benefit directly results from the company's innovative practices in extending the life of gearboxes, which saves costs and adds economic value. A yearly breakdown of GVA shows a consistent increase, reflecting the growing adoption and refinement of circular practices over time. In 2025, the GVA is expected to be £5.55 million, increasing to £7.34 million by 2035. This growth illustrates the long-term economic benefits of transitioning to a circular supply chain (see Figure 2).

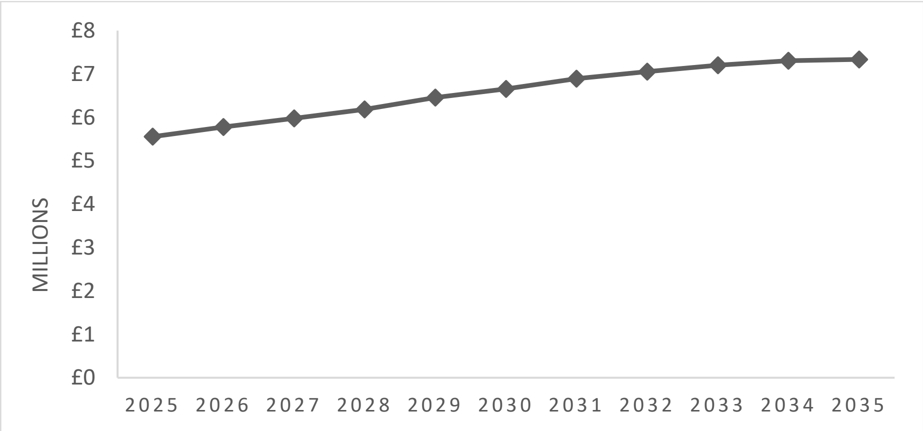

Figure 2 - GVA Projection for Yaw and Pitch Gearboxes. Source:(BVGAssociate, 2023).

Socially, the transition impacts job creation and demands new skills and competencies in the workforce. The company invests in training and development programs, fostering a culture of continuous learning and adaptation. The shift is expected to support many jobs, with an estimated 1324 FTE positions cumulatively from 2025 to 2035. This research finding reflects the potential of CSCM practices to contribute to regional economic development and social cohesion (see Figure 3).

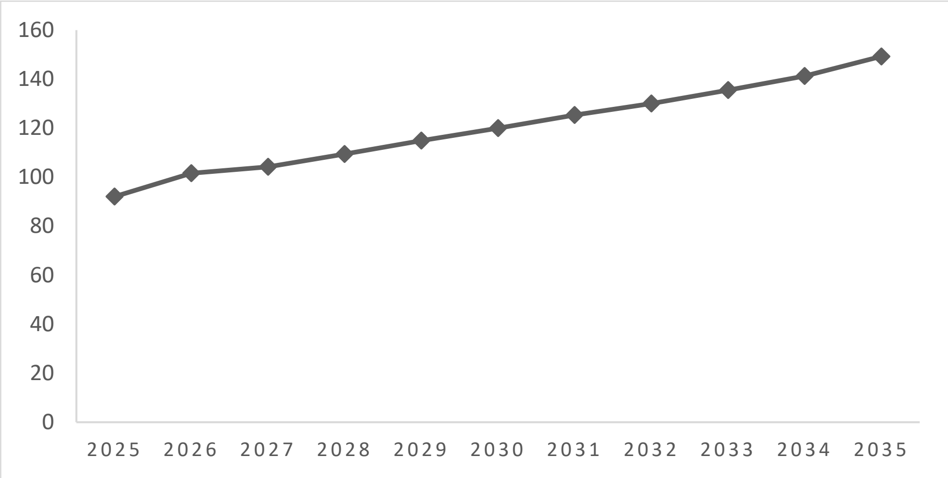

Figure 3 - FTE Projection for Yaw and Pitch Gearboxes. Source:(BVGAssociate, 2023).

Environmentally, the transition has significant benefits. The company's commitment to refurbishing and remanufacturing gearboxes aligns with the principles of a circular economy, aiming to maximise the utility of every component and minimise the need for disposal. Quantitative data indicates a total estimated avoided waste of 4,489,418 kg over 2025-2035 for Yaw and Pitch Gearboxes in the UK. In 2025 alone, 344,473 kilograms of waste is expected to be avoided, aligning with the company's goal of reducing the waste-to-scrap ratio (see Figure 4).

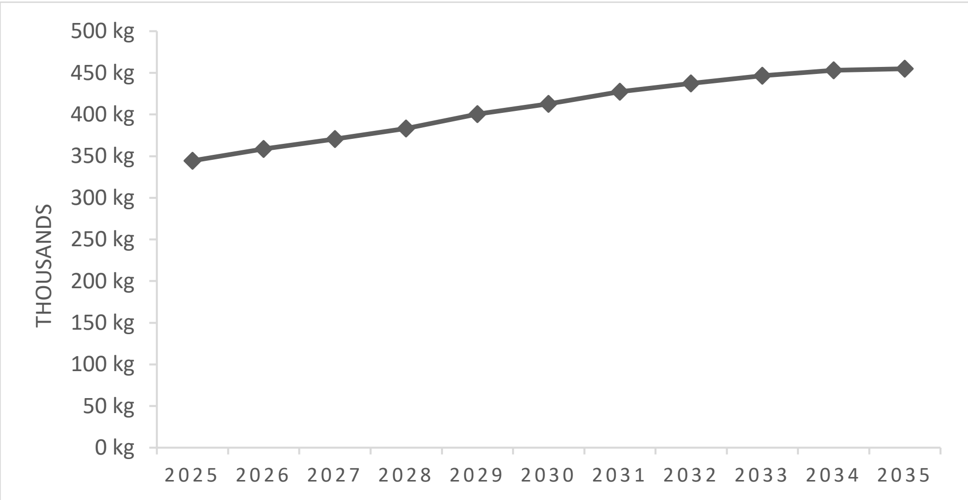

Figure 4 - Avoided Waste to Scrape projection for Yaw and Pitch Gearboxes in (kg) (BVGAssociate, 2023).

Discussion

This study explores CSCM within the renewable energy sector, mainly focusing on wind turbine parts. It reveals significant alignments between regenerative and restorative approaches, which are essential for transitioning to a circular economy.

Regenerative and restorative approaches within the company's CSCM practices contribute to improving restoration and resource efficiency. By prioritising the remanufacturing and refurbishment of components, the company extends the life cycle of materials, reducing the need for new material extraction, which has significant environmental benefits (McDonough and Braungart, 2010). These approaches go beyond reducing negative impacts to actively contributing to ecological restoration, aligning with regenerative design principles (Mang and Reed, 2012).

Literature on circular economy and resource efficiency supports the economic and environmental efficiency of these regenerative and restorative practices (Webster, 2015; Stahel, 2016). By demonstrating the viability of these approaches, the company sets a precedent for industry-wide adoption, contributing to a more sustainable and circular economy.

Economically, the GVA projections illustrate the economic viability of regenerative and restorative practices. This increase reflects the potential economic benefits that circular supply chain practices can offer, contributing to environmental sustainability while driving economic growth (Porter and Kramer, 2006). Such findings align with the growing discourse on the economic opportunities that circular economy models enable.

From a social perspective, the study underscores the positive impacts of CSCM on job creation and skill development. This aspect of CSCM aligns with restorative approaches that extend beyond environmental benefits to foster social well-being. The increase in FTE jobs and emphasis on workforce development highlight CSCM's role in creating opportunities for skill enhancement and promoting social inclusion (Savitz, 2013).

Environmentally, the significant reduction in waste and improved resource efficiency achieved by the company's CSCM practices exemplify the environmental benefits of circular economy approaches. These findings demonstrate the potential of CSCM practices to address global environmental challenges effectively (Pachauri et al., 2014).

Conclusion

This research outcomes offer significant insights and practical implications. The case study of the industrial service provider in the UK and Ireland exemplifies the integration of CSCM into business operations, highlighting the multifaceted impact of this transition.

The study points out the challenges and opportunities that renewable energy providers have in transitioning from a linear to a circular model. It demonstrates the economic, environmental, and social benefits of adopting CSCM practices, particularly in extending the lifespan and enhancing the sustainability of wind turbine gearboxes. The research underscores the potential of CSCM to foster a more sustainable, efficient, and socially responsible renewable energy sector.

Looking ahead, there is considerable scope for further exploration in the field of CSCM. Future research opportunities include investigating the long-term impacts of CSCM, exploring cross-industry applications, examining consumer responses to circular practices, and developing advanced tools and metrics for evaluating CSCM effectiveness. This study invites further academic inquiry and collaboration with industry partners, offering a comprehensive understanding of CSCM's challenges and opportunities.

In-depth assessments of CSCM's long-term impacts and scalability across different regions are crucial. Future research should build upon this study's findings, exploring how CSCM can be adapted and implemented in various contexts and industries. Additionally, consumer responses to circular practices in the renewable energy sector warrant exploration, providing insights into market dynamics and the potential for broader adoption of circular models.

Overall, the research outcomes provide useful examples of sustainability practices in the renewable energy sector, contributing to the broader discourse on sustainability and the circular economy.

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