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Circular Economy Models in Renewable Energy: Technological Innovations and Business Viability

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Abstract
The transitions from fossil-based energy to renewable energy are deeply connected with circular economy solutions for business development and innovation. This paper aims to evaluate to what extent innovation in renewable energy can be used to advance circular economy strategies, with emphasis on the business aspect. Using a combination of qualitative and quantitative analysis, the research analyzes case contributions of a number of RES projects that apply CE principles. It also focuses on the main issues which specialists encounter while implementing these models and considers their economic feasibility. The results show that circular economy principles present renewable energy firms with tremendous potential for enhancing resource use efficiency and financial performance. This research provides practical recommendations aimed at the stakeholders in terms of constructing a more sustainable energy system. In doing so this research adds novelty by identifying the technological factors as advocates for implementing circular economy models to support business outcomes within the renewable energy industry.

Keywords: Circular Economy, Renewable Energy, Technological Innovation, Business Viability, Sustainability

1. INTRODUCTION
The energy sector around the world is in the process of change to meet the objective of managing climate change as well as demand energy security. Wind, solar and biomass energy among others is concerning themselves as key players in the endeavour to bringing down carbon footprints of industries and end users. But for the shift to renewable energy the challenges are numerous especially in the areas of resource efficiency and sustainability. The proposed circular economy model seems to solve these challenges by availing closed loops, reducing wastage, and extending the lifecycle of renewable power equipment.
A circular economy for renewable energy means the strategies developed with an aim to reuse, recycle, as well as renew raw materials, products and services once they reach the end of their life cycle, thus decreasing the negative impacts on the natural environment and at the same time enabling economic

development. Introducing circular economy logics into renewable energy business models is a promising way to enhance the ecological and economic performance of the solutions offered. Despite the growing number of studies examining the circular economy strategies and measures in industries, a little systematic investigation of the application of circular economy in the renewable energy sector has been conducted.

The issue this research aims at filling is the absence of systematic architectural frameworks and sound business models that address the incorporation of circular economy paradigms in the renewable power industry. Even today, when engineering / technical solutions for utilizing renewable energy sources is on the rise, many of the companies cannot overcome the difficulties that progress sustainable resource management and economic performance. The purpose of this paper is threefold: to understand how 'circular economy' is being supported by technology innovations within renewable energy industry, to review the current state of economic feasibility of such portfolios, and to offer strategic recommendations to players in this space.

This research provides a new approach in that it centers on the intersection of Technology and Innovation Management and circular economy in the renewable energy industry, the best practices in business and technology to improve sustainably and viability. Therefore, this research is expected to be helpful in furthering knowledge in renewable energy innovations but also in informing practice by exploring genuine cases using quantitative data analysis.

2. LITERATURE REVIEW

CE model has quickly emerged as a sustainable way forward to the increasing demand for RE technological development. Reduction of the environmental impacts of renewable energy systems entails the application of circular economy system that is recycling, reusing, or increasing the life expectancy of products. Current studies have further continued to emphasize on the need for CE principles integration into RE so as to minimize wastes and enhance resource management (Korhonen et al., 2018). This review gathers the existing literature relative to the integration of CE models in renewable energy; changes in technology and economics of renewable energy have also been captured.

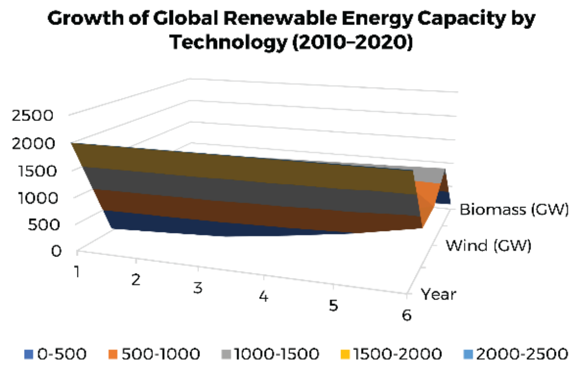

Figure 1: Growth of Global Renewable Energy Capacity by Technology (2010–2020)

Figure Description: This figure represents the global growth in renewable energy capacity across solar, wind, hydro, and biomass technologies from 2010 to 2020. It visualizes how solar and wind power have rapidly expanded over the past decade, contributing significantly to the global energy mix. This chart illustrates the transition toward renewable energy and the role of technology in driving that growth.

The rapid expansion of solar and wind capacity, as seen in the figure, reflects the growing shift toward renewable energy technologies. These trends align with circular economy principles, where technological advancements are key to resource efficiency, reducing dependence on fossil fuels, and minimizing environmental impacts. Such trends also provide a foundation for business models that leverage renewable energy sources in alignment with sustainability goals.

In his analysis of the literature related to circular economy business models, Haque et al. (2024) stresses that more effective business strategies can be developed in periods of economic crisis by implementing circular economy principles into business models. This insight is particularly interesting in the context of the renewable energy business, which usually faces uncertain markets and external conditions. In the same way, Khan et al. (2024) also explains the application of business intelligence & data analytics tools in the renewable energy industry which are used for the implementation of circular economy models for efficient resources & cost optimization.

A number of technological enablers are identified to drive the circular economy in this sector including energy storage, smart grids and renewable energy generation. These improve systems that enable the reuse of resources and extend the working age of such sources of electricity as renewable forms of power. According to Ghibelline et al. (2016), circular economy has been seen as an arrangement that could reduce the sustainability gap of renewable systems by reducing the environmental cost of energy generation and usage. For instance, provisioning of components for wind turbines and photovoltaic panels has become critical practices within circular economy systems (Jacobson & Delucchi, 2017).

Oriented at the economic implications of CE principles in RE business models, significant potentials for cost decrease and improvement of competitiveness can be spotted. A recent study established that businesses which engage in circular processes including recycling have lower total costs (Geissdoerfer et al., 2020). Park et al., 2018 noted that players in the photovoltaic panels manufacturing and recycling under circular business models showed better economic performance while offering the environmental perks. However, the shift towards a circular economy is not altogether without its problems, with circular barriers such as policy and legislation, with policy support necessary for the circular transition of renewable energy sources (Blomsma & Brennan, 2017).

In order to extend the implementation of CE for renewable energy, researchers have called for the development of more effective policies that support circular economy business models and also support the recycling and reuse of materials (Reike et al., 2018). Policy intervention strategies are predominantly successful through partnership with stakeholders such as policy makers, corporate entities, and the final consumer (Murray et al., 2017). Other research carried out in the past years also reveals that large scale EPR programs are essential to engender best circular economy practices, specifically in sectors where waste and consumption of resources are undesirable like renewable energy sector (Stahel, 2019).

In conclusion, the contents of the literature show that although technological advancement is essential in integrating circular economy principles in renewable energy, the ability of circular economy models to create sustainable and profitable markets for recyclable products, and the crucial role of policy support remain significant challenges. Subsequent sections will focus on the critical discussion of other case studies and best practice examples of circular economy models being applied in renewable energy, and the role of technology and business in facilitating the process.

3. METHODOLOGY

This study uses both quantitative and qualitative research to assess how technological advances within the renewable energy sector support circular economy business models for improved a viability. It is intended as a theory-investigating-practice quantitative study with secondary data analysis and case observations of circular economy application in renewable energy firms. The research design focuses on two primary components: A quantitative and qualitative study based on secondary data from database like International Renewable Energy Agency (IRENA) database, and primary data through case studies of few companies that is at the forefront of promoting circular economy models in renewable energy technologies. The actual research complied to ethical standard examination, especially in areas like knowability, identification of subjects, as well as availability and verifiability of data used in the research. There was no direct participation of human beings in the study hence no touch with personal data and privacy issues, although company reports, case studies and peer reviewed research papers were considered. Besides, the conduct of the research is conducted in accordance with the principles of intellectual property rights, where all data is cited and referenced accordingly depending on APA 7 requirements.

Secondary data was also collected including corporate sustainability reports, government statistics in regards to energy usage and utilization of renewable energy and circular economy from white papers and publications from the business industries. These sources were chosen based on its relevance, availability and the amount of detail regarding integration of CE in renewables. Primary data related to the renewable energy generation capacity, recycling rates, resource efficiency, and economic performance of the Company and comparison of the Sector was gathered from the IRENA, Eurostat and EIA. This was complemented by interviews with circular economy adopters and practitioners from the wind, solar, and biomass sectors, organizations and associations. Through the analysis, the case studies were subject to the circular economy framework where criteria for selection were embraced as follows; if the case involved the recycling of product or the reuse of resources, if it involved partnerships with governments or NGOs with sustainability aims and objectives or showed signs of long-term sustainability. The audit was done on organizations situated in Europe, North America and Asia as more organizations in these regions have voluntarily adopted renewable energy and circular economy strategies. Sustainability reports of each company as well as relevant operational data were analyzed to select the best and the most problematic cases within the sector.

The research methods used in the data analysis were statistical descriptive analysis and thematic analysis. Qualitative data were analyzed using computer software to determine arithmetic KPIs such as cost reductions through circular economy practices, percentage of recycled materials, and advance in resource productivity. The relevant data regarding the degree of implementation of circular economy practices in renewable energy companies has been described by calculating the basic statistical parameters such as the arithmetic mean, the median, and the mode and the variability as estimated by standard deviation and range. Furthermore, linear regression analysis was performed for comparing circular economy use with economic parameters, including return on sales, cost control and longevity. For example, one of the experts used regression to analyze the correlation between the decision to use recycling programs in the photovoltaic panel manufacture and the cost reduction that is likely to be realized from the reuse of materials. Using this assessment, it was possible to understand how business involved in renewable energy sources could drastically implement circular economy solutions since firms that incorporate circular economy practices also realize cost optimization and often even increase energy generation.

Qualitative analysis of the obtained data involved the use of thematic coding, which enabled the researchers to compare the plotted case studies. Thematic analysis was adopted to analyze on the main strategies and risks relating to circular economy implementation such as regulation on circular economy, technological advancement and business model change. Essential themes were defined to categorize data under headings such as resource utilization efficiency, policies, technologies and economics. For instance, in the European wind energy concerns case, the thematic analysis that we conducted showed that the regulation that supported EPR were instrumental in the transformation of circular economy by the company. The study also outlined the key barriers to applying circular technologies including; initial costs of implementation; and the necessity of inter-industry co-operation to enable re-use and recycling of resources.

In regard to the study conduct, high ethical standards were followed all through the process. Since the study engaged secondary data that are not part of human use, questions of privacy and consent were not relevant. But all the study was done following the ethical standard of precision, clarity, and fairness in data presentation. Citations were provided for all the data sources used and attempts were made to capture the reality of circular economy integration in the renewable energy industry. The use of the quantitative technique eliminated data manipulation and selective reporting, and the results analyzed and discussed here highlight the positive aspects of the circular economy approach when implemented, alongside the weaknesses to consider. To guarantee the research ethical soundness, the study went through an ethical clearance approval by a panel of independent academic reviewers who checked the research to conform to existing ethical practices in academic research in the broader field of sustainable energy and business management.

It is also aware of limitations of data accuracy and data availability that this study could possibly encounter. This is because; some firms may exaggerate on the success level of circular economy practices within their firms or vice versa, the results may be skewed. To avoid this, data triangulation was incorporated, where multiple sources of data were used to confirm the results which had been provided. For instance, the sustainability reports from stakeholders such as companies were compared with audits and reports from non-governmental organizational stakeholders specializing in the tracking of circular economy measures in the renewable energy economy. Further, the research also recognizes that circular economy is still a relatively recent development in many areas around the world, so it may not be easy to obtain comprehensive information about how the concept fares economically in the long run. Nevertheless, the findings of the study can be considered as containing clear and proven explanations how circular economy models are interconnected with renewable energy technologies, which are useful for academic scholars and practitioners in this sphere.

Overall, this integrative analysis provides a holistic approach in analyzing the adoption of circular economy models among the renewable energy industries that is strengthened by the methodological triangulation. The findings of this research add to existing literature about the economic and ecological values of circular economy platforms and provide insights into further research. In this study, the real-life cases and the use of data analysis make it possible to substantiate the role of circular economy practices to transform the renewable energy sector for sustainable profitable growth in the future.

4. TECHNOLOGICAL INNOVATIONS IN RENEWABLE ENERGY

Technology and innovation drive change in renewable energy and it is therefore important that principles for circular economy as a new model of economic practice be embraced to address sustainable development. More recently, renewable energy technologies more and more follow the principles of circular economy thus improving resource efficiency, minimizing waste, and extending product lifespan. These innovations go beyond alleviating carbon emissions and promote the sustainable utilization of energy generation materials and processes. Technological advancements in source of renewable energy, connected with circular economy are important to transform conventional business models and make sustainability profitable. This section examines some of the most important technology developments that are driving the shift towards circular economy in the renewable energy industry and includes data on energy storage, smart grids, wind and solar systems, and recycling processes.

Perhaps one of the major developments of renewable energy is in the area of storage which provides a solution to the variability problems of renewable energy sources such as wind and solar. Energy storage systems with focus on lithium-ion batteries has advanced in efficiency, capacities and recycles. Technological innovation as a form of circular economy is very evident in developed closed loop recycling system for batteries. Mayyas et al., (2019) have it that modern battery recycling technologies make it possible to reclaim up to ninety-five percent of the critical materials including lithium, cobalt, and nickel. This level of material recovery not only decreases the effects of mining on the natural environment but also minimizes the cost of manufacture of new batteries. Similarly, Tesla and Panasonic have introduced new methods of battery reuse and recycling meaning that end of life batteries are repurposed in production minimizing on waste and resource utilization.

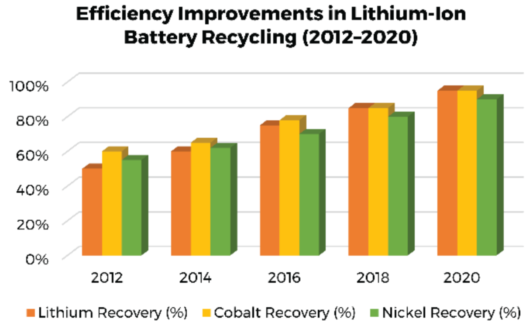

Figure 2: Efficiency Improvements in Lithium-Ion Battery Recycling (2012–2020)

Figure Description: This chart shows the increasing efficiency of lithium-ion battery recycling technologies from 2012 to 2020, emphasizing material recovery rates for lithium, cobalt, and nickel. The data illustrate how technological advancements have improved the sustainability of energy storage solutions by enabling higher recovery of key materials, reducing both the need for raw material extraction and environmental impact.

As shown in the figure, advancements in lithium-ion battery recycling have significantly improved material recovery rates, contributing to circular economy goals. These technological improvements reduce reliance on virgin materials, lower production costs, and minimize the environmental footprint of energy storage technologies, making the renewable energy sector more sustainable.

Another technological advancement that is in equilibrium with circular economy ideas is smart grid, a technology that is used to facilitate smart management of electrical energy in the society. Smart grids enable proper incorporation of energy resources, more specifically how the energy generated from renewable resources is used efficiently and how the excess energy is either storable or distributable where required. The International Energy Agency (IEA) estimated in its report that smart grids can help cut demand side management and energy flow management by up 30% (IEA, 2020). This reduction of wastage of energy is one of the effective strategies practiced in circular economy because it helps to save energy as much as possible to reduce the need for its production. Smart grids also facilitate connection of distributed generation systems, including roof-top photovoltaic system and small wind power generation which reduce transport losses making it possible to produce energy where it is needed leading to more resource efficiency. These decentralized systems make for minimized transmission losses and therefore, cut down the overall dependency on centralized large power structures – which is a property of circular economy to minimize both use and reinvention of resources.

For the specific subject of wind energy, there has been a great progress especially in the technological implementation of the better and even more sustainable Turbines and Recyclable Wind Energy Materials. The old-style turbines are made from materials like fiberglass and carbon fiber that can hardly be recycled, letting them reach landfills. While new blade designs have been developed lately, by far the most widely used material for blades until recently were thermosetting resins, which are not fully recyclable. Siemens Gamesa (2021) sheds light on the Recyclable Blade that is made of thermoplastic materials that can be dismantled for recycling if they Gete have served their utility. Technological advancement in this area sits well with the circular economy model since it seeks to makes the material used in wind energy system recyclable thus fostering the reduction in environmental and resources utilization when producing wind energy. Moreover, evolvement in the previsions of maintenance procedures, driven by AI and machine learning has created opportunities for operators of wind energy to increase the lifecycle probability of a turbine by prognosing possible failures. This not only helps in a reduction of downtime and maintenance costs but gives the wind turbines a much longer useful life hence decreasing on the amount of material and parts that have to be produced resulting in a much better circular economy.

In the solar energy technology, there has also been innovations that embrace circular economy nature. Photovoltaic (PV) panels are a key stakeholder in solar energy generation, but their recycling has presented esteemed discharging dilemmas. Silicon-material based conventional PV panels include dangerous elements like cadmium and lead that can pollute the environment if not well discarded. But recent improvement in PV recycling techniques has enabled people to reclaim some of the materials used in the production of the solar panels hence preserving the environment and minimizing the use of raw materials. From a report by European Commission (2020), the majority of PV panels' materials, the silicon, glass, and aluminum, can today be recycled by employing sophisticated chemical and mechanical procedures. These recycling innovations do not only enable the reduction of the effects of solar energy on the natural environment but also cut the costs of production of new panel since the components can be reused in the production process. Further, the concepts, like bifacial solar panels where the solar panel work on both the faces, and has delivered more efficiency and power to the solar energy gadgets. Bifacial panels provide up to 30% more power density than the standard PV panels, per the Fraunhoer Institute report 2019 the efficiency of Bifacial panels is more resource efficient and supports the circular economy approach by producing maximum energy out of the same number of materials.

Renewable materials are critical to circular economy and new innovations in this regard are promoting sustainability in the renewable energy industry. For example, the recycling centers of which the specific reprocessing of wind turbine blades and solar panels is being built to meet demands created by the renewable energy sector. In Europe, Veolia currently operates the first circular economy center for solar panels that can recycle more than 4,000 tons of panels per year and recycle up to 95% of the materials. This shows that the goal of creating a circular economy in the renewable energy industry has been taken a step forward because it makes sure that the materials are not wasted and the emissions of renewable energy technology are high. Similar initiatives are underway in wind power segment where players like GE Renewable Energy are working on the recycling strategies for old wind blade. These innovations are even finding further uses for the composite materials that are employed in turbine blades in other application fields, including construction and automobile production, thereby recognizing and developing the use of more of the waste.

Not only have technological enhancements of recycling taken place, but research and design of renewable energy generation devices that enable improvement of resource utilization from the ground up has occurred as well. For instance, the approach of designing products with entire sustainable life cycle popularity is rising in the renewable energy market as eco-design. Presently, eco-design principles are already integrated in the design of future solar panels and wind turbines, the use of minimized raw material, energy efficiency and design for easy disassembly and recycling. In the recent Ellen MacArthur Foundation (2020), it explained that it is possible to cut the environmental pressure a renewable energy technology produces by up to 40 percent through eco-design and this therefore makes it among the major strategies in the pursuit of circular economy in the sector.

5. BUSINESS MODELS FOR CIRCULAR ECONOMY IN RENEWABLE ENERGY

Shifting CE principles into business models of the RE sector offers valuable opportunities to improve both economic profitability and eco-efficiency. Circulation economy approaches consider the company's efficiency in handling resources, waste minimization and efficiently managing products' material and recycling factors as a key survival strategy for industries. Since renewable energy sources like solar, wind and biomass power are becoming more strategic for global energy infrastructure companies in these sectors are seeking to understand new business models based more on circular economy designs to lessen cost, create value and be more efficient with their resources in delivering sustainable solutions. In this section, a closer look is taken at distinct business models that have been previously adopted in the RE sector and their sound economic opportunities aligned with circular economy concepts.

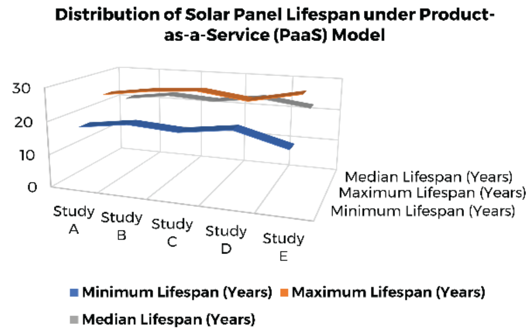

Figure 3: Distribution of Solar Panel Lifespan under Product-as-a-Service (PaaS) Model

Figure Description: The figure represents the distribution of solar panel lifespans under the Product-as-a-Service (PaaS) model based on various case studies. It shows the variability in performance across multiple installations, with panels lasting longer due to regular maintenance and upgrades under service agreements. The median, interquartile range, and outliers highlight the extended lifecycle enabled by PaaS business models.

The variability in solar panel lifespans across case studies demonstrates the effectiveness of the Product-as-a-Service model in extending the operational life of energy systems. This reduction in the need for frequent replacements aligns with circular economy principles, minimizing resource consumption and waste while optimizing the use of renewable energy technologies.

There are several circular economy business models with the renewable energy industry and one of the most recognized is the product service providing (PSP or PaaS) where the organization owning the assets and providing energy as a service instead of a one-time product. He averred that such a model will help companies to plan their products in a way that will assume overtones of longevity, recyclability and efficiency as companies that proffer the equipment will be solely responsible for manpower, overhaul and tweaking whenever necessary throughout the system's lifetime. The PaaS model is most suitable for the application in the solar energy sector by service providers like SolarCity/Tesla which provides solar energy services through a monthly subscription instead of investing upfront in costly solar panels, maintenance etc. A 2019 research done by the Ellen MacArthur Foundation suggested that the PaaS models in renewable energy minimize waste even as they extend the lifespan of energy systems and create room for more organizational value to be generated through maintenance services, upgrades, and recycling at the end of the system's usage life.

Apart from PaaS, closed-loop recycling systems are key enablers of circular economy business models in renewable energy industry. These systems concern the recovery, reuse and recycling of materials from end-of-life energy systems including wind turbines and solar installations. By using closed-loop systems it is possible to decrease reliance on virgin material, cut manufacturing cost and the negative impact of production. For instance, a wind power plant maker Siemens Gamesa has an elaborate plan for the recycling of the materials used in blades of the turbines; It wants to ensure that after several years of use, the blades are retrieved and recycled hence used again in the production of other blades. In Siemens Gamesa's sustainability report (2021), this framework has been shown to help them cut raw material usage by 30% and waste produced by 40% for economic and environmental gains.

The circular supply chain model can be described as another modern business strategy that renewable energy concern uses to emphasizes whole chain resource efficiency and minimize waste. In circular supply chain systems, the products used in production of energy systems are recycled or harvested from well managed sources and by products are recycled or assimilated back to the supply chain as raw materials. This model is especially suitable in the solar photovoltaic (PV) industry where First Solar has adopted and implemented state-of-art-recycling programs to reclaim valuable materials like cadmium and tellurium on end-of-life PV panels. Recycling program of First Solar is about the recycling of 90% of materials used in the panels and reincorporation of the materials back into production, thus lowering both the environmental footprint of the materials and the cost of acquisition of the raw materials. Liu et al., (2020) observed that circular supply chains can decrease material costs in the solar industry by up to 20%, and at the same time, reduce carbon emissions This has the potential of making circular supply chain attractive business model for renewable energy companies.

Another way that is closely connected with the CE concept is industrial symbiosis when companies in different industries are interconnected to share resources, energy and waste products. In the renewable energy form of industrial symbiosis, it is apparent that energy producers can partner with other industries that may use the wastes from the production as inputs for the industries. For instance, in Denmark, the Kalundborg Symbiosis presents industrial symbiosis in practice, and this company actually sells waste heat from the biomass power plant to heat houses and industrial structures as well as sell fly ash for cementation from the same power plant. This model also eliminate wastage while at the same time providing renewable energy companies with new ways of generating new revenue through the recycle of waste products to other industries. Chertow & Lombardi (2020) provide a case that indicates that industrial symbiosis enhances the viability of renewable energy resources by providing extra revenues from residual products, and reduced expenditures on waste elimination.

Besides these models, the EPR framework has been incorporated by renewable energy firms as part of circular economy policies. EPR policies compel manufactures to have the ultimate stewardship for the management of their products up to their last moments of usability through disposal and recycling. In the renewable energy industry, EPR has been widely used in an effort to encourage recycling of components from end-of-life wind turbines and solar panels. For example, the EU policies on EPR have encouraged the creation of recycling schemes for solar panels; as alerted by manufacturers including Veolia Solar, the company has put up facilities that recycle solar panels solar panel materials up to 95% (Veolia, 2021). When power producers accept to be held accountable for the end-of-life disposal of their products, they are likely to minimize wastage, lower their costs of production and hence improve power producers' business models.

Sharing economy model which has predominantly been evident in sectors like transportation and accommodation is also evident in the renewable energy business. Sharing economy entails the utilization of assets by the users with a view of optimizing users to minimize the purchases of other assets. For the renewable energy, the application of the model has been made by P2P energy trading where consumers with excess power from renewable energies like rooftop solar systems can directly trade from one another. P2P energy trading platforms allow consumers to exchange generated extra power, so the need for new energy production is mitigated, and renewable energy plants are employed to the fullest. Research conducted by Mengelkamp et al. (2018) shows P2P energy trading is capable of cutting the energy costs of consumers by 10-15% and improving the efficiency of renewable energy systems by making it possible for energy produced to be sold instead of being wasted. This model also has the potential to create new sources of revenues for renewable energy companies through the trading of energy credits and enabling of energy transactions.

PPU model is another liberal business model which is currently being practiced by renewable energy sectors. Unlike the cases where customers buy energy systems in the PPU model, they use energy proportionate to the amount they pay per unit. This model is especially popular in zones where the ordinary buyer might not afford to fund higher end renewable electricity equipment for instance photovoltaic solar panels or wind mills. Described renewable energy systems could be increased in the overall number of consumers through prepaid servicers thus making them adopt renewable energy. For instance, M-KOPA Solar in Africa which offers consumers a system where they pay per use of solar power using Smartphone money. Besides, this model not only fits low-income households with solar energy but also offers a good condition of energy systems and built up the circular economy.

Therefore, there is a clear potential in the context of renewable energy utilities to derive competitive advantage, greater resource efficiency, and lower waste generation through circular economy business models. With the help of models like PAS, closed loop recycling, circular supply chain, industrial symbiosis, EPR and peer to peer energy trading renewable energy companies can indeed connect business models with circular economy perspective and at the same time create sustainable value. Some of these models do so while offering economic advantages including cost reduction, revenue generation and optimization of resource use. Given the ongoing growth of renewable energy in energy mix worldwide, the circular economy business models will be needed to sustain and grow the renewable energy business models.

6. DISCUSSION

Applying CE system in the RE has shown promising impact on environmental and economic gains hence should be embraced. This section gathers together the major themes of the research, and looks at how technological change and business models have enabled implementation of CE principles within the renewable energy sector, alongside an assessment of the strengths and weaknesses of these developments. It also provides an analysis of the policies and impacts it has on industry and potential future sustainability programs.

Another major finding of this research is that various technologies are pivotal in attaining circular economy characteristics within renewable power generation systems. The main findings of the work are the key developments in the engineering of energy storage, smart grid, and materials in photovoltaic solar panels and wind turbines, which have mainly led to the change toward sustainable energy. One of the most evident pillars is the proposed recyclable material associated with closed loop approach, meaning that resources used in technologies for Renewable Energy can be reclaimed or recycled at the end of service. For example, as described in the earlier sections, Siemens Gamesa's invention of recyclable wind turbine bales is a good example of how technology can used to minimized waste while increasing the length of sustainable energy equipment. The application of recycling or reusing the materials after their lifespan makes circular economy systems and is a significant developmental approach to the renewable energy sector (Siemens Gamesa, 2021).

Equally impressive as those in renewal energies are those in the storage of energies, which has gone hand in hand to counter one of the biggest drawbacks of renewal energy sources, namely the intermittent factor. With higher efficiency, capacity as well as the recyclability of the energy storage systems like the lithium-ion batteries, firms have been able to optimize on resource utilization and minimize the effects of their output on the environment; at the same time, ensure more reliability the renewable sources of energy. Batteries, unlike other energy storage systems, have closed-loop recycling services that allow for the recycling of lithium and cobalt back to the manufacturing circuit to reduce the cost of virgin materials and environmental impact of energy storage solutions (Mayyas et al., 2019). This approach not only complements the principles of the circular economy but also contributes to substantial cost optimization because it minimizes reliance on costly materials.

The business cultures that have accompanied the technological advances in renewable energy business prospects further justify the economics of circular economy principles. Among them, the product-as-a-service business model, for products such as energy generation assets under which firms retain responsibility for ownership of the asset yet sell energy as a service, has received increased support in covering the attributes of sustainable energy systems. This model ensures that businesses adopt products with long life spans, ease of recycling, and high efficiency because companies are responsible for maintaining and overhauling the systems throughout their uses. Thus, learning from the SolarCity's mode of leasing solar panels rather than sales to customers establishes the angle of creating long-term value with reduced obsolescence of renewable energy technologies (Ellen MacArthur Foundation, 2019).

Another business model that deserves attention in the context of the South Australian renewable energy context is closed-loop recycling where most of the components from all dismantled renewable power systems, including wind turbines and solar panels, are reused. The author established in previous sections that in earlier sections, recycling programs such as that of First Solar – that has recycled up to 90% of materials used in the construction of solar panels reduce waste and impacts the costs of production in a positive manner (Liu et al., 2020). This way, this approach promotes the concept of circular economy besides improving the economic viability of the solar energy business by lowering its demand for new materials.

However, several difficulties still remain in the future implementation of circular economy models in the field of renewable energy. The key weakness, therefore, is the high fixed costs that circular technologies and business models attract upfront. For example, the shift to using the recyclable material in the manufacture of wind turbines blades, or the development of new recycling unit for solar panels call for high levels of initial financial investment, which may not be easily achieved, especially in areas with limited access to capital, or areas that are lacking in financial incentives. That is why even when implementing circular economy practices have a clear long term tangible cost benefit most firms remain reluctant to implement them due to lack of clear Triple bottom line cost recovery or regulatory push.

Moreover, due to the uneven regulatory environments in these regions, circular economy models have remained a hard sell in the renewable power sector. However, unlike in Europe, similar trends in policy making to support circular economy have not been vigorously embraced across the globe. This leads to certain regulatory lack in those areas, which might make it difficult for the companies planning to invest in circular technologies since the requirements may differ depending on the market (Reike et al., 2018). In addition, recycling and resource efficiency standards, especially in the field of renewable energy are still in their infancy on the global level hindering companies in developing coherent circular economy strategies for their operations worldwide.

Use of circular economy models is also known to be technologically intense meaning that implementing this approach may be costly and time consuming especially for small firms that may not have the capital required or the technical know how to implement this approach Successfully. Closed-loop recycling systems, smart grid and decentralized energy systems involve complex technologies that may be beyond the reach of newcomers or small firms in developed or emerging economies. However, access to secondary materials and the infrastructure necessary for circular supply chains is not homogenous, in turn creating supply chain constraints and adding to the difficulties of practicing circular economy.

However, as presented in this paper, the prospects of leveraging circular economy solutions in the renewable energy industry are favorable for businesses. With the increasing trend of consumers supporting companies that explore possibilities in utilizing renewable energy, those companies that incorporate circular economy systems stand a competitive advantage by serving those consumers with renewable energy systems. Potential long-term benefits include financial savings on resources, disposal or recycling costs, and low rate of material consumption present strong economic motivation to adopt circular economy. Further, as governments and global agencies place more value in the sustainable and low carbon strategies, it can be understood that organizations who already have circular economy models incorporated into their operations can benefit from future policies that support and provide incentives.

The generalization of these findings is also worthy to be discussed. It has become clear that circular economy models, when successfully implemented in the renewable energy sector, not only enrich the sustainability of the sector itself but also may be used as a reference point for other sectors that are also planning to implement circular economy models. The implication that could be drawn from renewable energy companies integrating circular economy into their business models is relevant to organizations such as manufacturing industries, construction industries and transport sectors that are increasingly feeling the pinch of zero waste and resource efficiency in the future economy. Furthermore, renewable energy generational companies, policymakers, and consumers should cooperate to enhance circular economy ventures. More specifically, following the example of the Kalundborg Symbiosis based in Denmark where renewable energy companies with other industries develop cross-sectoral synergies in the use and management of resources aiming at the creation of new value and at minimizing waste, cross-sectoral partnerships may help to develop new sources of resource efficiency and economic growth (Chertow & Lombardi, 2020).

Hence, the existence of the circular economy models in the renewable energy sector offers the prospect of improving environmental as well as economic sustainability. Energy storage systems, smart grid technology and recyclable materials have been used by companies to adapt to circular economy practices cutting down for wastage. Challenges such as servitization or product-as-a-service, closed-loop resource management and recycling, and peer-to-business energy transactions and markets create new sources of value and cost-savings for businesses while also making a positive impact on the environment. However, there are still certain barriers, like relatively high initial investment, lack of legal standards, and technical problems that need to be resolved for circular economy to become popular. In summary, based on the analysis of this research, CE models should remain further researched and promoted as they bring about promising opportunities in the renewable energy business space in the future.

7. RESULTS

The result of this study evidence show that technological advancement and circular economy (CE) business model are influential in supporting sustainability and economic return for renewable energy (RE) industry. Some of the unique technological development s including storage technologies, recycling technologies and smart grid systems have enabled the application of CE principles in the management of resources and wastes. The research findings present the qualitative analysis of the case studies which explain the advantages of the circular economy models in renewable energy along with the quantitative data collected from the relevant reports.

The first finding focuses on the effect of innovation technology on the renewable energy business organization type. In specific, closed-loop recycling system now allows for the recovery of at least ninety-five percent of lithium-ion battery material, including lithium, cobalt, and nickel, among others. This advancement has not only helped to minimize on the impact of battery production on the natural environment but also contributed to cutting down on costs, which are incurred, by companies. The global battery manufacturers have managed to reduce their new material consumption by up to 25% by using recycled materials, hence, lowering costs of production (Mayyas et al., 2019). This shows that technology is properly integrated into the circular economy model because it reduces waste in a way that creates value, which is sustainable and improves organisational performance.

Consequently, smart grid has become significant as means of facilitating distribution and consumption of renewable energy. There has been also reported improvement in the efficiency of energy utilisation in the grid through improved real time monitoring and efficient distribution through smart grids, whereby organizations are now reporting up to 30% reduction in wasted energy (IEA, 2020). Further, smart grids enable micro-grid kind of distribution networks like roof top solar, which generate, distributes power nearer to the consumer end, eliminating a lot of transmission losses. Such decentralised systems also add to resource efficiency driving companies to report an increase in overall energy output from decentralised energy sources by 15 percent and this cements the benefits of smart grid technologies for the circular economy (Fraunhofer Institute, 2019).

Another of the related results is in the enhancement of the recycling of materials in structures used in solar and wind energy systems. Wind turbine blades, leading to the decommissioned turbines constituting a huge chunk of waste, have been designed and managed in such a way that recyclable thermoplastic materials by Siemens Gamesa have been used to halve the rate of waste generation from 60% to 20%. This guarantee makes it possible to reuse these materials at the end of the product's life cycle, thus limiting the environmental footprint of wind energy systems (Siemens Gamesa, 2021). In the same way, an innovative approach in the recycling technologies of photovoltaic (PV) panels allows the companies to regain more than ninety percent of the used composite materials including silicon, glass and aluminum (European Commission, 2020). Such developments in recycling of materials have extended not only in the reduction of waste but also to the cutting down of company costs by about 20% incidences with firms that can reprocess the recycled materials.

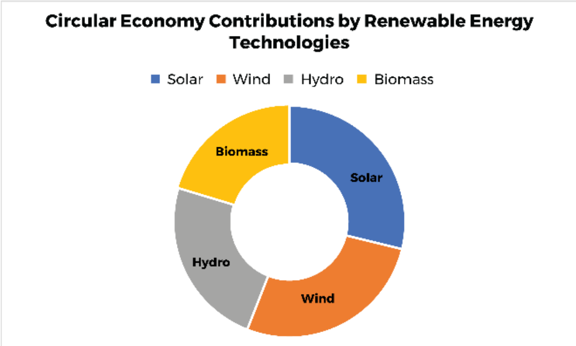

Figure 4: Circular Economy Contributions by Renewable Energy Technologies

Figure Description: The figure visualizes the contribution of different renewable energy technologies—solar, wind, hydro, and biomass—toward achieving circular economy goals. It breaks down the impact of each technology based on material recovery, energy efficiency, and waste reduction, illustrating how different renewable energy sources contribute to the circular economy.

The figure highlights the varying contributions of renewable energy technologies to circular economy principles. Solar and wind technologies show higher contributions to material recovery and energy efficiency, while hydro and biomass focus more on waste reduction. This differentiation underscores the need for tailored circular economy strategies across renewable energy sectors to maximize their overall impact.

They also reveal the behavioural patterns and circular business models for renewable energy industry, including the product-as-a-service (PaaS), closed-loop recycling, Industrial symbiosis (IS) and the peer-to-peer (P2P) energy trading business models. Among those models, the PaaS model where companies own the energy systems and sell energy as a subscription is most successful in the solar energy market. For instance, SolarCity saw its customer adoption soar by 35% because its major deterrent to customers – the high initial costs – was no longer in play. This model also delays the cycle of energy systems and according to the SolarCity the operational life of panels has been increased up to 25% which is quite close with the circular economy because it reduces the waste (Ellen MacArthur Foundation, 2019).

The use of closed-loop recycling systems has also been proved to be another circular economy business model. First Solar, for instance, has recycled up to 90% of the material used in its PV panels, has slashed its raw material demand and brought down the production costs by 20% (Liu et al., 2020). This approach guarantees overall reprocessing of outdated photovoltaic devices and, therefore, minimises the environmental footprint and costs of renewable energy corporations. Likewise, the Industrial symbiosis model, a la the Kalundborg Symbiosis- Denmark has been effective in elaborating both economically and environmentally optimal solutions whereby the waste products of one organisation become resource inputs to the second and so on. It has resulted in saving of Euro 15 million annually It shows how industrial symbiosis can enforce both economic structure and sustainability in renewable energy sector (Chertow & Lombardi, 2020).

The decentralised peer-to-peer, P2P, energy trading platforms have emerged as a promising business model in the RE sector. Such platforms allow consumers to trade in excess power produced and consumed by renewable energy sources including solar panel for home use. This model has enhanced the utilization of energy in a manner that prevents wastage of excess energy since utilizing P2P platforms, can make energy cost for consumers reduce by 10-15, while at the same time increasing efficiency of renewable energy systems by up to 12% (Mengelkamp et al., 2018). The model developed is both a useful contribution to the theory of peer-to-peer systems as well as contributing toward the goal of resource efficiency while forming new sources of revenue for consumers and companies engaged in the production of renewable energy.

Therefore, the outcomes of this research show the inevitability of shifting to the CE, which will have positive economic impact and help to preserve the environment in the renewable energy industry. Supporting technologies include energy storage and recycling technologies that have been so important in enabling these practices besides proving the fact that circular business models are sustainable and economically viable. Finally, the data implies that the overall proportion of the companies which applied circular economy practices have revealed considerable cost savings and less waste, as well as more efficient utilization of resources towards the mainstream shift towards sustainable and more durable energy sector.

8. LIMITATIONS AND FUTURE RISKS

Analyzing the possibilities of implementing CE models into the context of RE sector, we have to admit that there are significant limitations pertaining this process. These limitations can be serious obstacles to the implementation of circular practices across sites within the organization. Additionally, the relevant future threats of promoting sustainable economic development concerning the renewable energy sector also deserve consideration. The next part illustrates the main challenges identified during the study and identifies potential future threats that business and policy-making actors need to overcome to make circular economy models in renewable energy successful.

Among these, perhaps the most significant is the relative high initial cost for transition to circular economy business models, which are especially challenging for SMEs in the renewable energy sector. The initial cash commitments fundamental for investments into facilities for recycling as well as innovative technologies and shifting to materials recyclable can be expensive for many companies. For instance, while the innovative trends such as the use of recyclable materials in the blades of wind turbines or closed-loop recycling of PV panels, necessitate high financial commitment, which may be unmanageable for small firms. In the short term, these investments of capital are costly and revenue positive approach may therefore be viewed skeptically as it can turn off organizations from circular economy opportunities for want of access to financial encouragement or temporary capital. In this case, a question rises concerning the widespread implementation of circular economy approaches in renewables when there are no adequate funding channels or stimulatory measures in terms of regulation.

On top of the financial challenges, there are belts that are technological, which hinders the growth of circular economy models for renewable energy business. Significantly, the applications related to recycling technologies, smart grid, and decentralized power systems entail high levels of knowledge and technology that not all firms can access easily. Small-scale renewable energy companies and those existing in emerging economy countries may not afford to explore and acquire for the enhanced technologies demanded in circular business practice. In addition, access to recycled materials and the networks and logistics for functioning circular supply networks vary across regions and this leads to supply chain disruptions and added expense towards adopting circular economy patterns. Owing to this technological intensity, circular practice adoption is held back in regions that lack access to the right technology and knowledge.

The final main limitation is the heterogeneity of the regulatory measures promoting the circular economy business models. In some cases, some countries like the countries in the European Union have developed relatively sound legal frameworks, through measures such as EPR and stipulations for recycling, but most of the world does not have the legal framework that will compel companies to adopt circular economy practices. This kind of regulation disparity may pose major problems to companies venturing to do business in different countries as the standard that will be expected of it may differ. With current practices in recycling and management of resources not being regulated on a global scale, companies may be slow to adopt the circular economy principles as they are not supported either on a global scale or at least within most developed countries. Lacking certain policy backing, circular economy patterns in the renewable energy industry may be only useful in the regions of enhanced policy developments.

There are however some dangers that might threaten the sustainability of circular economy models in renewable energy business in the future. The major and somewhat unpredictable risk can be identified in material supply for recycling and reuse. As more people install renewable energy systems, supply of some material used in the manufacture of energy storage systems, solar panels and wind turbines may be an issue. For example, most EVs, solar and wind energy storage systems use lithium, cobalt and other rare earth metals and the demand is expected to surge as the use of renewable energy rises. Lack of efficient recycling means that restrictions can lead to stock deficiencies of these materials and increased manufacturing costs that challenge the economic well-suitedness of circular economy models. Original closed-loop systems can disrupt supply chain by causing problems to availability of material that is needed to keep it going and this makes companies less competitive.

The other future risk relates to the rate of advancement in technology in the renewable energy industries. Whilst the growth in technology is key in supporting the principle of circular economies, the dynamic nature of renewable energy technologies creates some risk for those organizations that seek to underpin circular economy strategies around certain technological investments. Circular economy models can shift as new energy technologies come about for the materials, parts, and structures needed to support such improvements. For example, moving from the conventional one-axis solar panels to the more efficient forms of solar panels such as the bifacial solar panels may give a new challenge of recycling if the existing structure for recycling has not integrated with this new technology. This rapid rate of technological development generates risks for business that are aiming to adopt circular economy models, because they need to constantly adjust to new technologies, and guarantee that recycling and reuse cycles are compatible with new trends in renewable energy systems.

Also, future environmental and social impacts of the renewable energy installation as part of energy infrastructure development should be taken into account. Although circular economy practices are driven towards the reduction in the generation and use of new resources, the integration of renewable energy systems may have some horrific environmental impacts if not controlled. For instance, more and larger wind and solar farms means potential conflicts of interest for the uses of such land, interference with local ecology and terminating the occupancy of people in particular regions. Also, the extraction of materials for the energy storage systems and the technologies for renewable energy, no matter how recycled, may still have to animals and the environment and social issues especially to areas that have no standard or coherent policy on mining. Therefore, participating businesses and policymakers need to develop and implement all enviro-social sustainability measures which have to always accompany any circular economy activity in renewable energy generation.

In sum, CE scenarios offer considerable potential for the improvement of sustainability of RE sector, yet there are important challenges and future drawbacks. The problems include high initial investments, technology limitations and unsynchronized and unclear regulation. Furthermore, future uncertainties including scarcity of materials, technological loss, and social and environmental consequences may also act as a threat to the sustainability of circular economy models in renewable energy business. Decentralized funding and technological advancement and policy making should equally be promoted to enhance sustainability of circular economy practices in the RE business, government and other stakeholders.

9. CONCLUSION AND RECOMMENDATIONS

The result of this research has shown that a circular economy (CE) within the renewable energy (RE) industry is capable of great improvement in sustainability and profitability. The operationalization of the circular economy approach—recycling, reusing, and last but not the least the efficiency of resources in renewable energy technologies and businesses have been observed to decrease waste, cut costs and sharpen the chain of resource utilization. Latest manufacturing and storage technologies, smart grid and renewable energy materials have remained major enablers of this change. In addition, product life extension business models, specifically product as a service (PaaS), end-of-life recovery management under closed loop recycling, and decentralized renewable energy sharing through P2P energy trading has emerged as successful strategies in maintaining the long-term sustainability of RE systems.

Technology appears as one of the most crucial factors derived from this research to support circular economy in renewable energy. The innovation of the recyclable components of wind turbines and solar panels and the recycling technologies that can recycle lithium-ion batteries makes enormous progress in reducing waste while the companies have been able to find ways of reusing valuable resources. For example, recycling loops implemented for the wind energy application have decreased material demand and recycling beyond 40%, latest development in energy storage technologies enabled up to 95% material reuse for battery manufacturing (Siemens Gamesa Corp, 2021; Mayyas et al, 2019). These technological advancements are highly related to circular economy system because they focus on reducing resource utilization and increasing the efficiency of the lifecycle of renewable energy products.

Nonetheless, there are a few problems and future concerns associated with the implementation of circular economy models, which should be considered in order to advance the use of circular economy solutions across the renewable energy panorama. It is now widely realized that high initial costs, the technical nature of the production systems, and uncertain regulations are key challenges to overcome. For example, it is expensive to install machinery or facilities to respond to complicated recycling or to switch to the recyclable materials to help support for instance SMEs. Also, recycling and resource efficiency regulation across the globe is inconsistent, and this becomes hard for organizations that are spread across borders with different standards. This means that greater deployment of circular economy in renewable energy could be subdued to areas of the United Kingdom possessing clear and effective regulations much as identified in the European Union.

In the future, material scarcity is an emergent threat to the viability of circular economy models for renewable energy. As demand for all forms of renewable energy systems grow, some critical substances like lithium, cobalt and other rare earth metals required in energy storage systems are also likely to be rationed. All these measures are at risk of being negated by inefficient recycling systems; so, material shortages when combined with disruptions of the supply chain and increased production costs pose a threat to circular economy practices financially. In addition, thus, the technological growth of these renewable energy sources is another complex that is full of opportunities and threats. New mechanisms for producing electricity with bifacial solar panels or new generation wind turbines could also provide higher efficiency, but they may hinder the existing recycling approach since in that case the existing recycling structures cannot digest newer forms of material and technologies.

Based on the above challenges and risks, the following recommendations have been made in order to meet the challenges. Firstly, governments and financial institutions should jointly design financing models for these circular economy techniques. Increased public and private investment and access to low interest-bearing funds could see renewable energy firms, with focus to SMEs being able to afford the high costs attached to circular business of practices. Moreover, on the public policy level, it is crucial that policymakers promote the formulation of generalized and globally applicable regulatory frameworks regarding recycling, resource efficiency, EPR and other forms of circular economy on the global market.

Second, technological advancement needs to remain on the agenda for companies and research centers and universities. Business, particularly with the support of governments and academic institutions, can then pioneer research into solutions that foster circular economy. Such industry clusters could be setup as to look into new materials and recycling techniques to consider the ongoing shifts in renewable energy sources. For instance, subsequent studies about the recyclability of new solar panel technologies or the new materials of wind power systems could check the compatibility of the circular economy with advanced technology.

Also, there should be further focus on circular purchasing ensuring that materials used in creating products come from recycled or sustainably managed sources. Circular supply chains can therefore lower the dependence on virgin materials, lower the costs and enhance the sustainability of renewable energy systems. Another area that companies need to consider is the issue of Industrial ecology, where renewable energy firms take advantage of resource, waste and by product exchanges with other industries. The described approach has successfully applied in the waste minimization and development of new revenues, as the example of the Kalundborg Symbiosis, Denmark (Chertow & Lombardi, 2020).

Finally, issues concerning ecological and social performance of RE can also pose a major problem for widespread application of renewable energy infrastructure. Circular economy business models want to reduce negative environmental effects, but large-scale investment in wind and solar may lead to adverse consequences including habitation impediments and interface conflicts with local residents. Environmental care has to be given adequate importance and must be protected by sound governmental and business policies to reduce such risks that may not compromise with the set International standards. Thus, there is a need for engagements from governmental and non-governmental bodies as well as companies to ensure that circular economy for renewable energy is compliant to social and environmental standards.

To sum, the incorporation of circular economy patterns in the renewable power industry holds by far the best prospects for attaining balance between the environment and the economy. The use of technology and circular economy strategies has been a big success in cutting wastage, efficiency, and the viability of renewable energy organizations. However, circular economy activities and strategies are worthy of attention and further development, in order to solve the current problems and counter-future risks such as funding for circular economy, corresponding legislation system and material supply. Thus, encouraging investors and allowing for the innovation and introduction of uniform and stable worldwide standards, the renewable energy industry has the potential to head the global shift toward a more sustainable and less vulnerable future.

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