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Circular business models in the wind industry

Potential sustainability benefits and industrial challenges

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Abstract (50 words)

The deployment of wind energy technologies is key for a sustainable energy transition. However, circular economy strategies, driven by circular business models (CBMs), must be implemented to ensure the deployment of resource-efficient and sustainable wind energy systems. This paper summarises the potential sustainability benefits for 14 CBMs with application to the wind industry.

Extended Abstract (250 words)

The deployment of wind energy technologies is instrumental to support a sustainable energy transition. However, the manufacturing, operation and end-of-life management of wind turbines (WTs) entail the consumption of a significant amount of energy and material resources contributing to environmental impacts. Thus, much of the ongoing sustainability research on WTs have been concentrated on material innovation (e.g. substitution of rare earth elements in the generators) and technology innovation (e.g. new recycling technologies for blade composites) to increase resource security and efficiency. Nevertheless, there is a lack of research analysing the role circular business models (CBMs) can have in driving implementation of circular economy (CE) strategies for narrowing, slowing and closing resource loops in the wind industry. Accordingly, this paper summarises the key potential sustainability benefits related to 14 CBMs with application to the wind industry, including the main industrial challenges that should be overcome to facilitate the upscaling of sustainable CBMs and value chains. A description of how CBMs can be implemented to support the resource-efficient management of wind energy projects at different stages of development and operation is also provided with the aim of guiding CE-oriented decision-making processes.

Keywords

Business models, circular economy, circular value chain, renewable energy, wind turbines.

Introduction (2500 words, without references)

Wind is a key renewable energy source (RES) to support a sustainable energy transition, accompanied with demand-side resource efficiency improvements driven by circular economy (CE) strategies (UNEP 2019).

However, wind energy is not exempt from resource and environmental impacts. For instance, a review of 79 life cycle assessment studies on RES performed by Amponsah et al. (2014), concludes that wind energy greenhouse gas (GHG) emissions can range between a minimum of 1.7 g CO_2 eq./kWh to up to 123.7 g CO_2 eq./kWh (+7,100%), where the materials used to manufacture the wind turbines (WTs) account for 50% to 80% of the environmental impacts (Amponsah et al. 2014, Jensen 2019).

A conventional WT can have around 25,000 components, weighing more than 3,400 tonnes; 680 tonnes corresponding to the weight of a single (4.2 MW) WT (Razdan and Garrett 2019). Over 90% of the materials used in a single WT, comprising a tower, a nacelle, and a rotor with three blades, corresponds to metals (e.g. steels, copper, aluminium). However, rare earth elements (REEs) (e.g. neodymium (Nd) and dysprosium (Dy)) and composites (glass and carbon fibre reinforced polymers) are required to manufacture the permanent magnets of direct drive synchronous generators and the WT blades, respectively.

REEs are critical materials with a very low recovery rate through current conventional recycling systems (Wind Europe 2020). Likewise, recycling the blades is inefficient and costly due to the technical complexity in separating the various materials in the composite construction (Jensen and Skelton 2018). Both aspects represent relevant challenges for the wind industry. Whereas REE supply might not be able to meet the ambitious wind power deployment scenarios due to geopolitical and environmental constraints (Li et al. 2020), large amounts of blade waste will be generated in the short to medium term due to wind farms decommissioning and repowering projects (Liu and Barlow 2017).

Accordingly, much of the material and technology environmental innovation taking place globally concentrates on finding solutions to reduce the dependence on REEs and facilitate effective composite recycling to increase the overall resource efficiency of wind energy technologies (e.g. European Commission 2022). However, little attention has been placed so far on the role and relevance of circular business models (CBMs) to facilitate the configuration of circular value chains toward narrowing, slowing and closing resource loops (Bocken et al. 2016, Velenturf 2021) from a more integrated and holistic approach than focusing only on material and technology innovation.

CBMs are oriented to narrowing, slowing, closing and regenerating resource loops to mitigate negative impacts (Konietko et al. 2020, EEA 2021), while generating higher socio-economic benefits compared to linear business models based on take-make-use-dispose (Rosa et al. 2019). However, despite the benefits of developing CBMs in the wind industry, research with a focus on CBMs is scarce and limited in scope, as the studies available do not provide an overview of the type of CBMs that can be implemented by the wind industry to deploy more sustainable wind energy systems (e.g. Velenturf et al. 2021, Lobregt et al. 2021, Nichifor 2015).

As far as the authors were aware at the time of writing this contribution, there is only one scientific paper available in the literature (Mendoza et al. 2022) that has addressed a comprehensive categorisation and characterisation of CBMs with application to the wind industry. Building upon Mendoza et al. (2022), this short paper concisely summarises and discusses the potential sustainability benefits and industrial trade-offs related to 14 CBMs applicable to the wind industry, including the provision of guidelines for future research.

Circular business models in the wind industry

Building upon the approaches proposed by Blomsma et al. (2019) and Pieroni et al. (2020) for the identification, categorisation and characterisation of CE strategies and CBMs, Mendoza et al. (2022) performed a systematic literature review of 125 journal papers and industrial reports leading to the definition of 14 CBMs with application to the wind industry. A CBM canvas was used to define the business offering, the value creation, delivery and capture mechanisms, the potential sustainability benefits and the industrial challenges and opportunities, by relying on the findings from the literature review. However, due to space limitations, only a summary of the main goal, key resource requirements and potential sustainability benefits of the 14 CBMs with application to the wind industry are presented in Table 1.

As shown in Table 1, digitalisation, reverse logistics, and specialised materials, equipment and facilities, are the most relevant requirements to implement CBMs in the wind industry, which must be managed by specialised technicians and engineers. Likewise, strategic partnerships between original equipment manufacturers (OEMs), materials and equipment suppliers, wind farm owners and operators, and waste managers is crucial to design, implement and manage CBMs over time, as each actor depends on the other and CBMs cannot be driven by a single company nor operate in silos. Finally, although wind park owners and operators are the main customer segments, local businesses and communities (from developed and developing countries), looking for the implementation of low-cost renewable energy production systems, also represent relevant customer segments for the deployment of resource-efficient and environmentally sustainable solutions. High energy and carbon intensive industries demanding clean energy (gas or liquid) carriers can also benefit from the hybridisation of wind farms (Table 1).

CE strategy	CBM typologies			Business goal	Key requirements	Sustainability potential		
						Economic sustainability	**Environmental sustainability**	**Social sustainability**
Narrowing resource flows	Demand reduction services			Mitigating resource consumption by delivering service-based solutions	• Digitalisation • Data analytics • Internet of things (IoT)	• Increased profit from reliable asset outputs	• Greater and consistent renewable energy • Lower resource use due to fewer parts replacement	• Increase in skilled component performance modelling careers
	Cleaner production			Reducing resource consumption, wastes and impacts through best available technologies	• Advanced materials and manufacturing equipment	• Substantial reduction in manufacturing costs	• Substantial reduction in resource consumption for WT manufacturing	• Training and skilling new workers in highly specialised and technical jobs
	Collaborative consumption	Community-owned wind park		Decentralisation, democratisation and decarbonisation of electricity generation through community engagement	• Renewable energy certificates • Energy cooperatives • Local investment	• Transparency in the shared economic benefits	• Climate change mitigation through increased use of renewable energy	• Investment returns in the local economy through the development of energy projects • Recruitment of local staff
		Aggregator platform		Balancing energy production and consumption through flexibility services that ensure grid stability, while increasing consumers' awareness in energy sufficiency.	• Software platforms • Virtual energy storage systems • Prosumers	• More efficient use of technologies and physical storage systems		• New job opportunities with consumers becoming active subjects in the energy market
	Wind farm hybridisation	PV-WT-Battery		Combination of photovoltaic panels, wind turbines and batteries in a single location to improve resource efficiency	• WTs, PV panels, storage batteries • Supporting infrastructure	• System performance optimisation through efficient use of surplus energy to minimise power curtailment	• Reduced use of fossil-based fuels, GHG emissions and reduced waste generation	• New employment opportunities as the hybridisation of wind farms requires more labour and new skills
		Power-to-X	Power-to-Gas (PtG)	Convert renewable energy into gaseous energy carriers (e.g. hydrogen, methane) to substitute fossil-based gas fuels.	• Electrolysers & storage tanks • Air capture systems & combined cycle gas turbines	• Same plus act as renewable energy storage system for use to decarbonise energy-intensive industrial processes.		
			Power-to-Liquid (PtL)	Convert renewable energy into liquid energy carriers (e.g. methanol, Fischer-Tropsch fuels) to substitute fossil-based liquid fuels.	• Methanation plant • Reverse water-gas shift plant & heat exchangers • Storage tanks & distribution networks			

CE strategy	CBM typologies	Business goal	Key requirements	Sustainability potential		
				Economic sustainability	Environmental sustainability	Social sustainability
Slowing resource loops	Retrofitting (upgrading)	Improving assets´ efficiency, capacity and performance by fitting components upgrading solutions	• Software and data analytics • Technology adds on	• Reduction in the LCOE • Increase revenue generation through adds-on	• Increase annual energy production • Reduction in noise levels	• Need for skilled engineers • Positive corporate reputation (by rising environ. awareness)
	Reuse	Second-hand use (same application) of WT components that are in a good condition.	• Software (trading platforms) • Decommissioning tools & storage areas • Redistribution logistics	• Cost savings in purchasing and operating WTs • Development of local markets for reused products	• Notable reduction in waste generation and GHG emissions	• Employment opportunities in second-hand markets
	Refurbishment	Partially restoring the WT operational capacity by repairing and replacing worn or damaged components	• Workshops & tools • Testing equipment • High quality spares	• Market diversification • Reduced capital costs, payback times and LCOE	• Substantial reduction in material use and GHG emissions per asset	• As refurbishment activities are labour intensive, they can open new markets and job opportunities • Serve educational purposes • Meeting social needs in less developed RES markets
	Remanufacturing	Fully restoring the WT functionality, resulting in final WTs comparable, or even better, to brand-new units	• Reverse logistics • Remanufacturing plants and equipment • Spare parts	• Project cost improvement for secondary users due to reduced capital investment	• Preserve the material value • Save energy and avoid GHG emissions • Improve energy output.	
	Repurposing	Reusing a product or its parts (after reprocessing) for different applications than the original	• Specialised facilities • Software tools • Warehouses • Redistribution logistics	• Blade-based products can be very profitable • Reduce the economic cost of some civil engineering projects • Improvement in brand image and reputation.	• Blade-based solutions have a reduced environmental footprint compared to standard solutions. • Product lifetime can be extended greatly	• Local jobs in communities close to wind farms. • Education and training programmes for students and industry professionals through design studios and labs
Closing resource loops	Open loop recycling	Extending resource value through material recovery for use in the development of new components and products (downcycling)	• Recycling facilities, technologies and tools • Material storage units	• Lower disposal rates • New business opportunities • More resilient supply chains by reduced demand on imports	• Reduced pressure on virgin materials and imports. • Improved environ. performance against landfilling	• Potential to create new jobs in material recovery activities.
	Closed loop recycling	Implementation of reverse logistics and reprocessing systems for material recovery and use in the manufacture of WT components (upcycling).	• Dismantling, collection & recycling equipment and facilities • Reverse logistics	• Optimised recovery routes for some materials can generate substantial economic benefits (e.g. REEs)	• Significant GHG reductions by recovering some materials (e.g. REEs) • Optimised reverse logistic routes can help to reduce the transportation GHG emissions	• New highly specialised jobs • Local community development through the installation of collection and recovery facilities

Table 1. Overview of circular business models with application to the wind industry. Acronyms: GHG – greenhouse gases, LCOE – levelised cost of electricity, OEM – original equipment manufacturer, PtG – power to gas, PtL – power to liquid, PV – photovoltaic panels, REE – rare earth elements, WT – wind turbine.

However, CBMs should be properly planned, designed and deployed in the value chain to ensure sustainability benefits (or net positive impacts) are achieved. This requires action to be taken in the following areas (Mendoza et al. 2022):

1. Development of servitisation and digitalisation capabilities
2. Build robust business cases, including value chain considerations within and beyond the wind industry, for an accurate balance of costs and benefits
3. Address technical constraints for the implementation of CE solutions
4. Develop suitable markets for secondary products and materials
5. Reduce the complexity of forward and reverse logistics
6. Rationalise supply and demand mismatches
7. Diversify industrial know-how and capabilities
8. Encourage policy development and incentives
9. Define and implement circular design and technology management criteria
10. Use robust sustainability assessment frameworks, tools and indicators

Main conclusions

As discussed by Mendoza et al. (2022), the dematerialization and servitization of wind farms should be considered from the early project planning stage to minimise overall resource consumption and negative impacts related to WTs and infrastructure manufacturing, installation and maintenance over time. As an absolute dematerialisation of wind farms is not a realistic solution nowadays, cleaner production techniques and closed-loop recycling systems should be pursue to complement the implementation of digital solutions to mitigate WTs life cycle resource consumption and environmental impacts.

Alternatively, collaborative consumption models can be deployed for a more efficient production and consumption of wind energy through the optimisation of the system operational performance, which can be further pursue through the hybridisation of wind farms by integrating multiple technologies for renewable energy generation in combination with energy storage systems. Once in operation, the lifespan of WTs can be extended through retrofitting CBMs.

When a wind farm reaches the end of its service life, dismantled WTs and components can be i) reused in other wind farms if they are in an appropriate condition, ii) refurbished and/or remanufactured for a second and/or multiple subsequent use cycles (e.g. towers, gearboxes and/or entire WTs), iii) repurposed for reuse in different industrial and/or urban applications (e.g. wind turbine blades), or iv) recycled to recover some materials (e.g. mostly metals and plastics).

Nevertheless, each wind energy project is unique and the decision to foster one or several CE strategies driven by CBMs is highly project-specific, as it depends on the site constraints, safety issues, technologies performance and reliability, and the whole economic balance. Accordingly, building robust CE business cases is essential to demonstrate the sustainability benefits of implementing CBMs in the wind industry. This requires active collaboration between OEMs, suppliers, wind park owners, asset managers, operation and maintenance service providers, off-takers, policymakers and researchers.

Indeed, a CE plan should be prepared from the early stage of project conceptualisation and design, and address the whole life cycle of wind farms, based on a shared vision on the best CE strategies with the goal of maximising sustainability benefits. In this process, it is essential to address and respond properly to the 10 challenges highlighted above.

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