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Circular economy business models and technology management strategies in the wind industry: Sustainability potential, industrial challenges and opportunities

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ABSTRACT

Circular business models, aimed at narrowing, slowing, and closing resource loops, can potentially generate significant economic and social benefits, promote resource security and improve environmental performance. However, within the wind power industry, sustainability research, including life cycle assessments, has been focused mostly on technology innovation at the material (e.g. permanent magnets), components (e.g. blades) or product level (e.g. new assets). Research analysing the implementation of circular business models in the wind industry is scarce. Such information could, however, support more robust decision-making in the development of system-level innovations for the deployment of more resource-efficient and sustainable wind energy infrastructure. Building upon practical methods for the identification, categorisation and characterisation of business models, 14 circular business models with application to the wind industry were comprehensively evaluated through the revision of 125 documents, including 56 journal papers, 46 industrial business cases and 23 wind technology management reports. Each circular business model is examined according to i) business offering and drivers, ii) value creation, delivery and capture mechanisms, iii) sustainability benefits and trade-offs, and iv) industrial challenges and opportunities. Accordingly, comprehensive guidelines to drive political (legislation design and implementation), industrial (technology and business innovation) and academic (further research) actions, are provided. Though the results are focussed on the wind industry, the general findings and recommendations are relevant across the renewable and low-carbon energy sector.

1. Introduction

Global average temperature is likely to rise by 2.4–2.7 °C during the 21st century unless greenhouse gas (GHG) emissions are significantly cut in the coming decades [1,2]. Accordingly, many countries have announced GHG emission reduction targets for 2030 and 2050 [3], with the deployment of renewable energy sources considered key to a sustainable energy transition [4].

Of all renewable energy sources available, wind power is the fastest growing. Renewable energy accounted for more than a third of the gross European Union (EU) electricity generation and consumption in 2019. However, by 2030, installed EU wind turbine capacity could amount to 327 GW, almost a 4-fold growth compared to 2010, and contributing up to 42% (783 TWh) of renewable electricity generation [5]. By 2050,

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Abbreviations: CAPEX, Capital Expenditure; CBM, Circular Business Models; CE, Circular Economy; EoL, End-of-Life; EU, European Union; GHG, Greenhouse Gases; LCOE, Levelized Cost of Electricity; OEM, Original Equipment Manufacturer; OPEX, Operational Expenses; O&M, Operation and Maintenance; PtG, Power-to-Gas; PtL, Power-to-Liquid; PV, Photovoltaic Panels; PtX, Power-to-X; REE, Rare Earth Elements; R&D, Research and Development; WT, Wind Turbines.

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forecasts suggest that EU wind power could reach 3500 TWh (+447% compared to 2030) [6].

A wind farm consists of multiple wind turbines (WTs) installed on- or off-shore. WTs typically comprise a foundation, a tower, a nacelle, and a rotor with three blades, which can house approximately 25,000 elements weighing over 650 tonnes (t) [7]. The net material requirements to build a 100 MW onshore wind farm, composed of 4.2 MW WTs (as an example), can amount to more than 67,850 t of material, including foundations and site cables, switchgears and transformers [7]. These numbers can be much greater for larger (8–14 MW) offshore wind farms [8]. Thus, WTs are material intensive renewable energy technologies and represent a relevant emerging waste stream.

From a waste management perspective, the most concerning materials used in WTs, are i) rare earth elements (REEs) used in the permanent magnets of modern generators, and ii) the composites used to produce rotor blades [9]. Whereas REE supply might not be able to meet ambitious wind power deployment scenarios due to geopolitical, technical and environmental constraints [10], significant amounts of composite blade waste will be generated in the short to medium term due to wind farm decommissioning [11]. Indeed, composite blade waste generation during this decade (2020–2030) is expected to account for 570 Mt just in the EU [12]. Consequently, WT blade waste management is forecast to become a critical global problem by 2028 [11] due to the complexity of separating materials into different streams for efficient recycling and resource recovery [13].

The use of metals also imposes technical and environmental challenges [14,15], as metal use in WTs (especially steel) is the greatest source of materials-related environmental impacts [16]. Although the recyclability of WTs is assumed to be 85%–95% [17,18] mostly due to their metal content (up to 88% of the mass) [19], it does not mean that WTs are actually recycled at such rate due to high dissipation processes [20]. For instance, actual recycling rates for steel, copper and aluminium can correspond to just 44%, 45% and 60%, respectively [21]. Other WT components, such as electronics and electrical materials, are recycled at 50%, while other materials, such as polyvinyl chloride, fibreglass, lubricants, paints and adhesives, are commonly sent to landfill [22].

Due to significant WT manufacturing resource requirements, and the waste management challenges at their end-of-life (EoL), wind power is not exempt from environmental impacts despite being considered a clean energy source [14]. While modern WTs produce more energy per unit, they tend to produce this energy with a greater environmental impact due to the higher material requirements in manufacturing and the construction of wind farms; the stages together determine over 85% of the life cycle impacts [23].

This underlines the importance of keeping materials in use for as long as possible. Ensuring optimal WT design and life cycle management by applying resource conserving circular economy (CE) thinking, is therefore crucial for transitioning towards high resource-efficient and sustainable wind energy systems [24]. However, this approach needs to be supported by the development and implementation of circular business models (CBMs) and value chains.

A CE for the wind industry can potentially i) narrow resource loops by reducing material consumption to levels that fall within planetary boundaries [25], ii) slow resource loops by keeping technologies and infrastructure in use for longer through design for durability and/or strategic maintenance and repair, reuse, retrofitting, refurbishment, remanufacturing and repurposing, and iii) close resource loops through effective disassembly, recycling and material recovery when technologies and infrastructures reach the EoL [26,27].

Accordingly, CBMs are understood as "business models that are cycling, extending, intensifying, and/or dematerialising material and energy loops to reduce the resource inputs into and the waste and emission leakage out of an organisational system" [28, p.7]. Consequently, the re-configuration of current linear business models (based on take-make-use-dispose) towards CBMs, could boost sustainable innovations which capitalise on business competitive advantages (e.g. a reduction in the amount of materials used and waste generated) and significant risks reductions (e.g. lower dependency on scarce resources) [29]. CBMs could also bring greater sustainability improvements to businesses as they generate more economic, social and environmental value per unit of resource used [30,31], while mitigating resource scarcity [32].

Analysing wind industries from a CBM perspective is, therefore, essential to implement technology design and life cycle management practices that could positively impact upon the availability and sustainability of resource use in the wind industry. This has been recently suggested by several authors [33–37], who highlight that the mitigation of environmental impacts in the wind energy sector requires developing CBMs to maintain producer responsibility and facilitate components reuse and material recovery. Thus, increasing the understanding of CE strategies and CBMs in the wind industry is crucial to drive industrial sustainable technology innovation and policy development [35].

Despite the clear benefits of developing CBMs in the wind industry, most environmental-oriented research, including WT life cycle assessments [38–40], focusses on technology innovation at the material (e.g. composites), component (e.g. blades) or product level (e.g. new technologies) [41,42]. Research with a focus on CBM innovation is scarce, and the limited literature available has a narrow scope.

For instance, Graulich et al. [43] propose a number of alternatives to increase the circularity performance of WTs through waste prevention, eco-design, reuse and recycling. However, only a few examples of business cases are provided, lacking a structured CBM analysis. Likewise, Velenturf et al. [44] evaluate how CBMs can help reduce material criticality in the wind industry but the authors only focus on discussing the challenges and opportunities related to REE recycling and recovery, rather than considering WT management as a whole.

Although, Nichifor [45] attempted to provide an overview of sustainable business models for wind energy companies in Romania, the author does not present any categorisation, characterisation and sustainability analysis of circular and/or sustainable business models. Instead, the findings from interviewing wind energy experts regarding their current business strategies, priorities and future trends, are reported. Finally, Lobregt et al. [34] and Vielen-Kallio et al. [35] discusses how the circularity performance of the wind sector can be improved through the implementation of circular permit and tender criteria, modular and collaborative design, extended product responsibility and stakeholder collaboration, data management and material recycling and recovery alternatives. However, the authors do not evaluate what type of CBMs can be developed and how they should be configured to support these strategies as well as the role CBMs can play in facilitating the creation of circular value chains to improve the industry sustainability.

While there is an urgent need for a comprehensive overview of CBM solutions relevant to the wind industry, including analyses of the potential economic, environmental and social sustainability benefits and trade-offs to overcome industrial challenges, such overview does not yet exist [46]. Access to such information, including guidance on how CBMs can be implemented in practice, could support robust decision-making for the development of more systemic innovations for the deployment and management of circular and sustainable wind energy systems.

This paper responds to this gap in the literature by providing a unique and comprehensive characterisation of CBMs with application to the wind industry, as described in section 2. Each circular business model is examined in Section 3 according to i) business offerings and drivers, ii) value creation, delivery and capture mechanisms, iii) potential sustainability benefits, and iv) industrial challenges and opportunities. The paper concludes by providing guidelines and recommendations for policy, industrial and academic action (Section 4).

2. Methodology

A four-step methodology (Fig. 1), was applied for the identification,

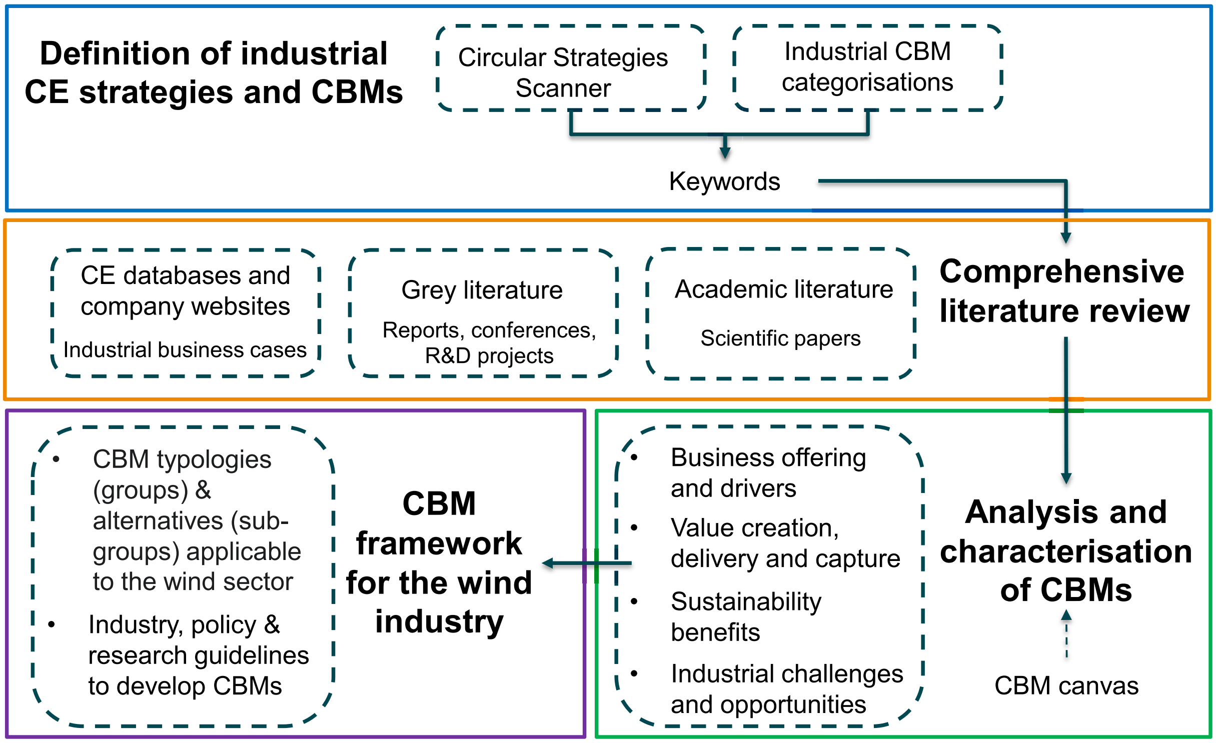

Fig. 1. Research methodology. Acronyms: CBM - circular business models, CE - circular economy, R&D - research and development.

categorisation and characterisation of CBMs with application to the wind industry. The methodology was based on recognised approaches for the development of circular [47] and sustainable [48] business model typologies, which combine both conceptual and empirical methods.

2.1. Definition of circular economy strategies and business models

The definition of business model typologies for a particular sector requires the identification of relevant categorisations from the literature and business model innovations from practice [48]. Consequently, the first methodological step involved an analysis of literature review papers on CE strategies and CBM typologies.

In the context of this paper, a "typology" is understood as a grouping of CBMs [48], whereas an "alternative" represents the configuration options of CBM elements. Thus, each CBM typology integrates a set of alternatives that combine one or more CE strategies and CBM elements to address specific needs [47].

The circular strategies scanner [49] was used to categorise industrial CE strategies. This scanner presents a taxonomy of 30 circular strategies to CE-oriented innovation by manufacturing companies. Thus, it was considered suitable to get an overview of the potential CE strategies for implementation in the wind industry.

The CBM categorisation provided by [50], comprising 20 alternatives organised into seven CBM typologies (dematerialise, collaborative consumption, product-service systems, long life, next life, circular sourcing, and circular production and distribution) was used as a baseline to get an overview of industrial CBMs. These two frameworks were developed by i) focusing on the industrial manufacturing sector, ii) analysing the most relevant literature on the topics at the time of conducting their research, and iii) validating the research outcomes through several interaction cycles with industrial stakeholders, making them practical and meaningful to support CE research and drive industrial CE-innovation processes, as demonstrated by follow up papers [e.g. 51, 52].

Likewise, the list of CBM typologies provided by [50] was compared to the CBM categorisations provided by other authors who published their results previously [e.g. 47] simultaneously (same year) [e.g. 53–55] or afterwards [e.g. 52,56], in order to validate and further complete the list of features that define an industrial CBM.

Table S1 in the Supplementary File (SF), presents the resulting CBM categorisation used as a baseline to gather keywords to perform the comprehensive literature review described in the following section.

2.2. Comprehensive literature review and examination of circular economy databases

A three-stage literature review, including the analysis of i) academic literature, ii) grey literature, and iii) CE databases and company websites, was performed. This led to the identification of 125 resources for a comprehensive evaluation to define and characterise CBMs in the wind industry, as illustrated in Fig. 2.

Table S2 in the SF presents the complete list and combination of keywords used to identify scientific papers on the topic, employing SCOPUS as search engine. In all cases, wind energy-related keywords (first search stream) were crossed-linked with keywords related to CE strategies [49] or CBMs (Table S1 in the SF) (second search stream) and business model-related keywords [58,59] (third search stream). Accordingly, three searches of academic papers were performed in April 2021, filtering by article title, abstract and keywords. Only journal and review articles written in English and published between 2010 and 2021 were considered in order to analyse a decade of research, and to evaluate journal papers developed within the current notion of CE, which gained momentum since 2010 [60].

Detailed information about the literature sources consulted, including academic papers, grey literature (conference proceedings, industrial reports, MSc and MEng thesis and R&D projects), and CE databases and Original Equipment Manufacturers (OEM) company websites, is provided in section S2 of the SF.

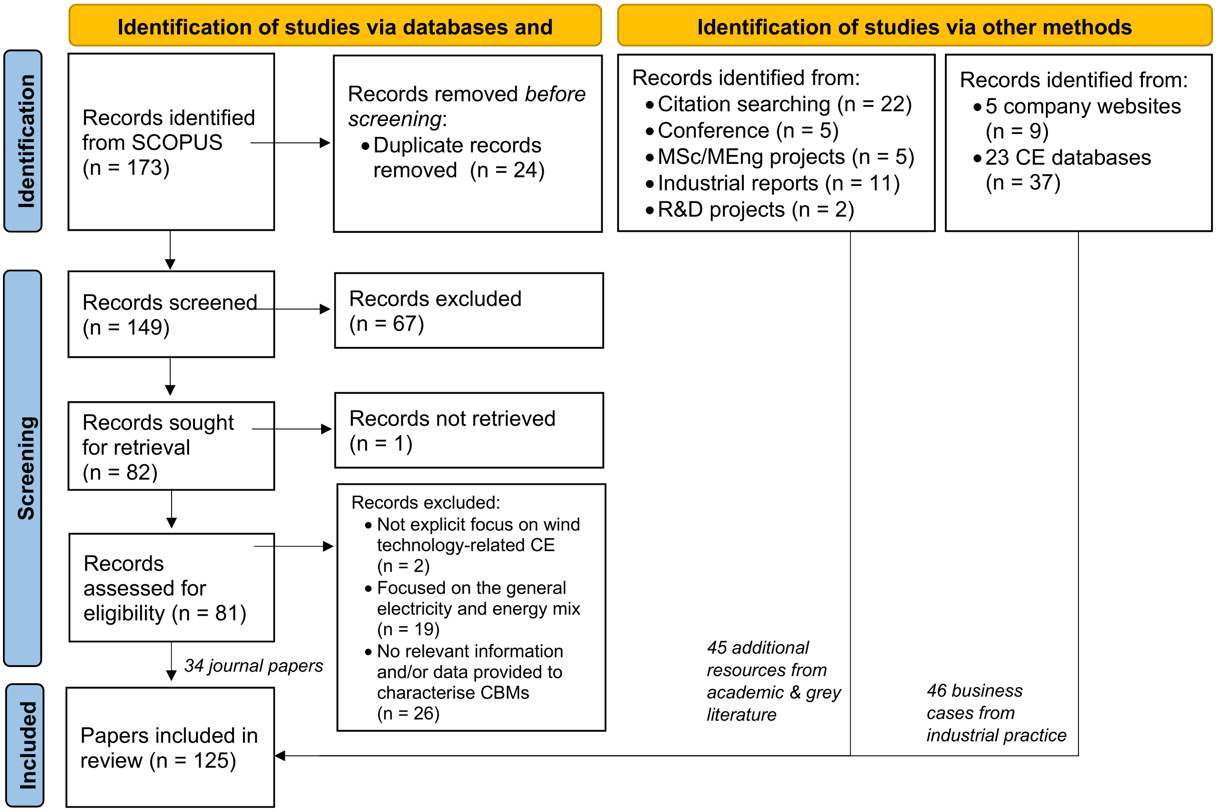

Fig. 2. Systematic literature review procedure and outcomes. Based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram [57].

2.3. Analysis, classification and characterisation of CBMs

The effectiveness of using canvases to structure the analysis and characterisation of business models has been widely acknowledged between academics [e.g. 61] and practitioners [e.g. 62]. Accordingly, a simple CBM canvas was designed (Table S3) to structure the analysis of the literature outcomes (section 2.2) based on available templates [52, 63,64], which are all grounded on the original structure proposed by the business model generation handbook [65]. The resulting CBM canvas integrated three main analytical blocks:

i) CE business approach, including CBM typology, alternatives and CE strategies, and the main actor driving each particular CBM;
ii) CBM building blocks, including value proposition (need/problem addressed, business offering and products/services), value creation (key activities, resources/assets and partners/collaborators), value delivery (customer segments, channels and customer relationships), and value capture (cost structure and revenue streams); and
iii) Sustainability screening, including potential benefits and/or impacts related to people (society), profit (share value) and planet (resource decoupling) within and beyond the company boundaries.

A description of what is understood as value creation, delivery and capture is provided in S3 of the SF. Likewise, a brief description of each analytical block of the canvas is presented in comments embedded in each cell of Table S3 (CBM canvas tab).

2.4. Proposal of a CBM framework for the wind industry

The research outcomes (sections 2.1-2.3) were analysed from an integrated perspective to build a comprehensive list and characterisation of CBM typologies (groups) and alternatives (subgroups) applicable to the wind sector. This was accompanied with the provision of a set of guidelines for industrial, policy and academic action to facilitate the development and upscaling of sustainable CBMs. Accordingly, the results can be used as a baseline what, - and how, to do guide by wind energy professionals, and other renewable energy companies and actors, interested in building sustainable energy systems.

3. Results and discussion

Fig. 3 provides an overview of 14 CBM alternatives with direct application to the wind industry, as identified in the literature review (sections 2.1-2.2). CBMs are articulated around the WTs' life cycle stages and grouped by typology based on their main end-goal and scope.

As illustrated in Fig. 3, various CE strategies, driven by CBMs, can be implemented throughout the entire life cycle of wind farms. CBMs addressing or affecting the early wind farm life cycle stages (especially WT design and manufacturing) can lead to higher circularity (resource efficiency) than CBMs tackling the EoL stage of WTs, where resource management possibilities are determined by the condition and quality of the assets.

A description of each CBM is presented in the next section (section 3.1.), followed by the characterisation of their value creation, delivery and capture mechanisms (section 3.2), their sustainability benefits (section 3.3.) and the industrial challenges to facilitate implementation and upscaling (section 3.4.).

3.1. CBMs categories with application to the wind industry

Section S4 (Figure S1) in the SF presents a summary of the literature review findings organised per type of literature source and the resulting CBM alternatives, including the re-arrangement of the original list of industrial CBMs (section 2.1, Table S1) according to the reality of the

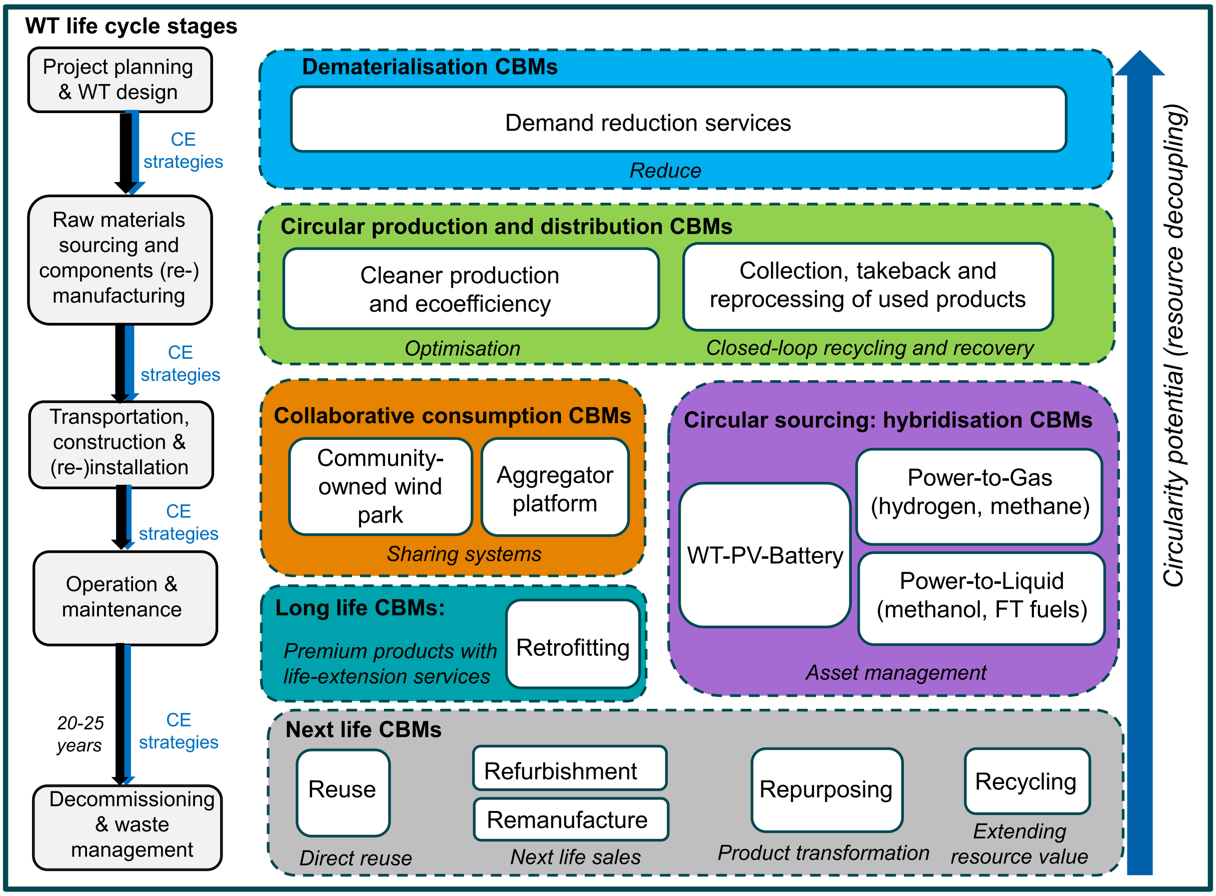

Fig. 3. CBMs with application in the wind industry. Coloured boxes: CBM typologies and end-goals; white boxes: CBM alternatives. Acronyms: CBM - circular business models; CE - circular economy; FT - Fischer-Tropsch; PV - photovoltaic panels; WT - wind turbine.

wind industry. Building upon the review findings, a general description of the 14 CBM alternatives with application to the wind industry is provided in this section. Likewise, an example of industrial business cases for each CBM alternative is presented in Table 1. Information about the business offerings, main drivers for each CBM alternative, including further business cases, can be consulted in Table S3 (section S5).

3.1.1. Dematerialisation CBMs

Dematerialisation CBMs are aimed at replacing or mitigating resource consumption by delivering resource decoupling solutions, usually in the form of digital services. Despite the progress in the technological development of WTs (Watson et al., 2019), academic literature covering the physical point of production dematerialisation is lacking [46]. Some insights into activities that could reduce resource consumption are provided in Table 1 [66,67] but they cannot be considered absolute dematerialisation strategies as products are still required to be manufactured, installed and managed over time. Accordingly, dematerialisation CBMs characterised in this paper refer to businesses that promote long-term operational efficiency of assets through the provision of demand reduction services. This includes innovations focused on system efficiency optimisation that can be derived from smart data driven operations (e.g. data analytics), including preventive maintenance. For instance, 'big data' [99,100] and the 'Internet of Things' [101] can support the development of solutions that limit unnecessary servicing, increasing the reliability of WT outputs and reducing resource use and environmental impacts over its operational lifetime.

3.1.2. Circular production and distribution CBMs

This CBM's typology is built around cleaner production innovations and take back solutions for closed-loop recycling and recovery. Cleaner production CBMs are focused on reducing material and energy consumption and mitigating pollution and waste generation during WT manufacturing by installing the best available technologies [50]. However, cleaner production innovations can also influence the circularity performance of WT operation by increasing wind energy production. Thus, these CBMs are usually aimed at delivering technical and manufacturing solutions to solve production and operational challenges [102]. This includes the provision of improved materials, components and WTs designs for use in different locations under different conditions, regimes and requirements (Table S3). With regard to collection, take back and reprocessing CBMs, they are aimed at closing material loops by facilitating collaboration between different stakeholders of the WT supply chain to improve the efficiency of forward and reverse logistics [103,104] and reprocessing practices for the recovery of materials [105]. These CBMs are particularly relevant to address the challenges related to the supply and recovery of REEs used in WTs [106,107].

3.1.3. Collaborative consumption CBMs

These CBMs create and deliver shared value to customers and communities by offering cost-efficient solutions for the integration of renewable energy into local electricity systems [100]. There are two collaborative consumption CBMs applicable to the wind industry: i) community-owned wind parks and ii) aggregator platforms. Community-owned wind farms are usually promoted by groups of citizens who adopt a legal form, such as a cooperative [109]. Accordingly, they promote the decentralisation, democratisation and decarbonisation of electricity through community engagement (project planning, investment and revenue sharing), empowerment and capacity building, which, in turn, increases the acceptance of wind farms [74,110].

Table 1
Industrial business cases per CBM alternative with application to the wind industry. Acronyms: CBM – circular business model, OEM – original equipment manufacturer, PM – permanent magnets, PtG – Power-to-Gas, PtL – Power-to-Liquid, LCOE - levelized cost of electricity, R&D – research and development, PV – photovoltaic panels, VPP – virtual power plants, WT – wind turbine.

CBM typologies	CBM alternatives	Industrial business cases
Dematerialise (section 3.1.1)	Demand reduction services	• Small scale 'flutter' power generators with significantly reduced size and omission of rotor blades [66] • Direct drive WTs to reduce weight and moving parts, while improving energy efficiency [67]
Circular production & distribution (section 3.1.2.)	Cleaner production	• High volume low speed fans based on the humpback whale flippers to increase WT efficiency [68] • Blade surface coating where riblets mimic shark denticles, reducing drag and increasing lift, which allows WTs to operate effectively at lower wind speeds, while reducing noise [69] • Siemens's NetCoverter® system for the full conversion of all the power generated in less reliable grids [70]
	Collection, take back & reprocessing	• Mitsubishi, Hitachi, and the Urban Mining Company have begun to enter the NdFeB magnet recovery market by implementing recycling technologies at industrial level [71,72]
Collaborative consumption (section 3.1.3)	Community-owned wind park	• Hepburn Wind's Australia's first community-owned wind farm established in 2007 [73,74]
	Aggregator platform	• FLEXCoop end-to-end interoperable tool suite to segment, classify and cluster demand and storage assets as aggregated resources that can be made available to balance the energy cooperatives own resources or facilitate operators' grid management [75] • Statkraft's AS virtual power plant connecting more than 1300 wind farms and 100 solar energy, hydropower and bioenergy producers in Germany, exceeding 10,000 MW capacity [76]
Circular sourcing (section 3.1.4)	PV-WT-Battery	• BayWa r.e.'s 10 MW solar PV plant connected to the grid of a 24 MW wind farm [77]
	Power-to-Gas (PtG)	• Siemens Gamesa Brande Hydrogen pilot project capable of producing green hydrogen directly from WTs with electrolyzer stacks and batteries [78,79]
	Power-to-Liquid (PtL)	• Methanol synthesised from CO_2 emitted by a coal power plant and hydrogen produced through water electrolysis using surplus electricity from WTs [80,81]
Long life (section 3.1.5)	Retrofitting (upgrading)	• ABB Wind Retrofit packages [82] • PowerCone® Retrofit [83] • SG Energy Trust Solution [84]
Next life (section 3.1.6)	Reuse	• Wind turbine global marketplace [85] • Used wind turbines for sale [86] • The big portal for wind energy [87]
	Refurbishment	• Refurbishment solutions to costs and improve the sustainability of wind turbines [88] • Solvento comprehensive restoration of WTs [89] • Integral solutions to upgrade old WTs with completely new technology [90]
	Remanufacturing	• Vestas Wind Systems and Caterpillar Inc. 10-year agreement to remanufacture components [91] • Gamesa OXiris after-sales re-engineering service [92] • GoldWind Remanufacturing Technology Development Centre [93]
	Repurposing	• Re-Wind Design Atlas [94] • Blade-based urban furniture, playground, sign posts and bus shelter [95] • Blade-based renovated Wikado playground [96]
	Recycling	• Technologies (ionic liquid extraction and high temperature electrolysis) enabling closed loop REE recycling from PMs [97] • Process glass fibre reinforced plastic composite waste into fine granulate used as a cement additive [98]

Complementarily, aggregator platforms enable balancing energy demand and production through flexibility services (demand-side response) that ensure grid stability and alleviation of network constraints, while increasing consumers' awareness in energy self-consumption and self-sufficiency [75]. These CBMs seek to support decentralised green energy production through the introduction of residential prosumers (someone who both produces and consumes energy) [111] as active subjects.

3.1.4. *Circular sourcing CBMs*

Circular sourcing CBMs are focused on creating and capturing value by optimising companies' own assets [50]. Wind farms can be optimised through hybridisation, which refers to merging and managing multiple technologies for renewable energy generation in combination with energy storage systems to increase the flexibility of electricity supply and use [112].

The simplest wind farm hybridisation alternative refers to the combination of photovoltaic (PV) panels, WTs and batteries in a single location (PV-WT-Battery system). This CBM alternative can be extended further by integrating the so-called Power-to-X technologies, which convert renewable energy into gaseous (Power-to-Gas: PtG) or liquid (Power-to-Liquid: PtL) energy carriers [81,113,114]. At the core of the extended PtG and PtL solutions is green hydrogen generation via the electrolysis of water (Power-to-Hydrogen), which can be converted further into another gas, such as methane (Power-to-Methane) or synthesised into liquid energy carriers, such as methanol (Power-to-Methanol) and/or Fischer–Tropsch-fuels (Power-to-FTf). Hybrid wind farms produce and inject electricity into the main grid. However, in times of energy overproduction, the surplus energy can be used in alternative ways to optimise the cost efficiency and profitability of operating wind farms, while producing green energy sources that could displace fossil-fuel use by energy-intensive and high-carbon industries with the corresponding environmental savings (section 3.3.) [115,116].

3.1.5. *Long life CBMs*

Long life CBMs are mostly oriented to WT retrofitting, which entails improving existing assets' efficiency, capacity and performance by fitting technology upgrading solutions [117], such as adds-on, updated control systems and digital solutions, to extend the technology lifetime and optimise operating expenses (OPEX). An example of WT retrofitting is the implementation of rotor blade extensions that maximise energy production by increasing the WT swept area [e.g. 118]. Retrofitting solutions can be also applied to components inside the nacelle [e.g. 119] and tower foundations [120].

3.1.6. *Next life CBMs*

Next life CBMs are aimed at ensuring WTs and components can have a second (or multiple) use cycle(s). Differently to long life CBMs, which aim to keep products in use for the longest possible within the same use cycle and application, next life CBMs are articulated around the EoL management of WTs to avoid waste generation by keeping technologies in use within different use cycles, applications or contexts (Table S3).

Next life CBMs can be divided into five alternatives: i) reuse CBMs, ii) refurbishment CBMs, iii) remanufacturing CBMs, iv) repurposing CBMs and v) recycling CBMs, depending on the condition and quality of the WTs, components and materials to be handled.

If ageing WTs and/or components are still in relatively good condition, they can be reused either within the same wind park or in a different location [20]. Reusing in-service WTs and components is currently taking place through second-hand trading e-platforms run by third party operators [13].

If ageing WTs are not in good condition, WT refurbishment or remanufacturing can take place, where the intensity of the restoration effort will depend on the condition of the technology. Whereas refurbishment entails partially restoring the WT operational capacity by repairing and/or replacing only worn or damaged components (such as the tower, bed frame and/or generator), remanufacturing entails fully restoring the WT to OEM specifications, resulting in final WTs comparable, or even with better quality, to brand-new technologies [121]. Accordingly, remanufactured WTs are usually more expensive than refurbished assets. Nevertheless, they are often more reliable, as they have new components integrated with, reducing the likelihood of component failure and downtime, which greatly affects financial performance [121].

When WTs cannot be reused, refurbished or remanufactured, repurposing (also called structural reuse or structural recycling) can be pursued, which refers to reusing a product or its parts (after reprocessing) for functions or applications other than the original [122]. Most of the research and industrial practice on WT repurposing concentrates on blades, as they represent a recycling challenge due to their thermoset composite construction [123]. WT blades can be repurposed as a whole (e.g. as noise barriers along highways) or sectioned into parts (root, aerofoil sections and shear webs) for use in different applications (e.g. storage tanks, building roofs or window shutters) [9,124]. This helps to retain the structural and material quality (e.g. engineered properties) of blades through secondary applications [125], instead of reducing them to relatively low-value materials for use as aggregates and/or fillers in other industries (e.g. cement co-processing) [126].

Finally, when WTs and components cannot be managed by the application of any of the CE strategies above, materials can be recycled. Although recycling suffers from a vague definition [46,127], recycling CBMs can be understood as businesses contributing to extending resource value [50] by facilitating material recovery and reprocessing into new components and products, which is aligned with the definition for recycling specified by the EU waste hierarchy [128]. Recycling CBMs can be divided into two main alternatives: i) general recycling of materials, including metals (e.g. steel), concrete and electronics, and ii) composite recycling from WT blades and nacelle shells. Recycling CBMs focused specifically on metals did not come through in the review despite the environmental relevance of steel and REEs in the WT life cycle impacts [16]. Instead, much of the literature refers to WT blade recycling processes [12] that can open up new market opportunities through the delivery of recyclates, such as fibres, filler, resins and oils alongside with energy recovery solutions [127,129].

3.2. CBMs' value creation, delivery and capture mechanisms

A description of relevant aspects related to the value creation, delivery and capture mechanisms of the CBMs with application to the wind industry is provided in this section. More detailed analysis about each individual CBM can be consulted in section S6 and Table S4 in the SF.

3.2.1. CBMs value creation mechanisms

According to the information gathered from the literature review (Table S4), there are three main common requirements between CBMs to create value: i) digitalisation, ii) reverse logistics, and iii) strategic partnership.

Focusing on the former, data can be turned into 'actionable knowledge' [94] to optimise long-term wind farms resource efficiencies through intelligence-based planning and management [130]. Thus, digital solutions are not only relevant for the development of dematerialisation CBMs (section 3.1.1.) but to support also the development of other CBMs, including (Table S4):

i) Design and management of aggregator platforms relying on IoT and big data analytics (collaborative consumption),
ii) Process modelling for the implementation of cleaner production techniques and take back systems to facilitate closed-loop recycling (circular production),
iii) WT retrofitting through the integration of software solutions to improve energy production and extend products lifespans (long life),
iv) Assets management through the hybridisation of wind farms by deploying WT-PV-battery, PtG and PtL solutions that can be monitored and operated virtually (circular sourcing),
v) Refurbishment, remanufacturing and repurposing (next life), where the implementation of preventive maintenance is a prerequisite to reduce costs (section 3.2.3).

Effective reverse logistics, understood as the process of managing products and components from the point of use, back to a point of deposition to recapture material and/or functional value [131], is another relevant prerequisite to facilitate the deployment of several CBMs, including next life CBMs (reuse, refurbishment, remanufacturing and repurposing) and circular production CBMs (collection, take back and reprocessing) (Table S4). Whereas next life CBMs require reverse logistics to enable components management for use in a second (or multiple) life cycle(s), circular production CBMs require reverse logistics to facilitate closed-loop material recycling and recovery [104].

Finally, OEMs (and/or independent specialised operators) are required to partner with wind farm owners and/or operators, components and materials suppliers and waste managers (Table S4). This four-level partnership is essential to offer retrofitting, reuse, refurbishment, remanufacturing and recycling (next life CBMs) solutions to customers. Whereas OEMs (and related actors) have the technical knowledge and expertise to undertake product-level CE strategies, customers (WT owners/operators) must ensure access to used and/or worn assets for CE technology management. Likewise, new materials are usually required to undertake repair and reconditioning activities (need for suppliers), while worn and/or damaged or out-dated components for replacement should be properly handled (by waste managers) to reduce waste landfilling.

However, partners can be more specific to the CBM alternative being deployed, such as those for the hybridisation of wind farms. Partners for these CBMs extend beyond the wind energy sector, as running hybrid wind farms requires involving actors from the energy (e.g. manufacturers of PV panels and energy storage systems, natural gas network operators and transporters of liquid energy carriers), mobility (e.g. hydrogen gas stations) and industrial sectors (e.g. chemical industries) (Table S4) [81,113,116,132,133].

3.2.2. CBMs value delivery mechanisms

Wind park owners and operators are the most relevant customer segments for the analysed CBMs, as they are the actors demanding, purchasing and using WTs and components. However, local businesses and communities, and users from developing countries, looking for the implementation of low-cost solutions, also represent customer segments (and niches) of interest for the industry (Table S4). CBMs targeting these particular customer segments include community-owned wind parks and aggregator platforms (collaborative consumption), reuse, refurbishment, remanufacturing and repurposing CBMs (next life), and asset management through hybridisation (circular sourcing).

For example, community-owned wind farms produce green electricity with renewable energy certificates and sell it to energy retailers that operate within national electricity markets [74]. These cooperatives are usually governed by the "one member one vote" principle, where members get to decide how the profits are used [109]. Accordingly, there is a close relationship between the people and the project, which seeks to build trust, familiarity and knowledge around wind energy. On the other hand, aggregator platforms enhance the value of flexibility (gathering and selling energy to energy buyers) by grouping asset owners (e.g. consumers, producers and prosumers) to act as a single entity in the market, as these actors would be too small to participate in the energy market individually [134].

Moreover, aggregator platforms can complement hybrid CBMs, by improving the management of decentralised energy distribution through Power-to-X solutions (section 3.1.4.), which can help to further improve the wind parks performance and efficiency [116]. For instance, in the case of Power-to-Hydrogen, an electrolysis plant could be powered by geographically close wind farms allowing for the benefits of scalability. A central virtual power plant would distribute the available power between the power market, balancing markets, and the electrolysis plant, which could be located close to potential customers, helping to reduce hydrogen transport costs [116].

However, hybrid wind farms, differently to the rest of the CBMs, are also aimed at satisfying the needs of regional and/or global energy and carbon intensive customers from the energy (e.g. power plants and refineries), mobility (e.g. maritime shipping, long-haul road transport and aviation) and industrial sectors (e.g. cement, steel or chemical plants), who demand cheaper and cleaner energy sources to decarbonise their industrial activities (Table S4). Thus, these CBMs extend beyond the wind industry, in a similar manner as recycling CBMs, where recyclates (e.g. fillers, fibres, resins and hydrocarbon products obtained through blade recycling) are used in other industries, such as construction (cement production), chemical (bulk moulding compounds production) and oil industries (using hydrocarbon products generated through pyrolysis) [9,131,135].

Examples of next life CBMs targeting local communities and developing countries are provided in section S6 of the SF.

3.2.3. CBMs value capture mechanisms

CBMs can make profits through two main income sources: i) material contracts (assets' users pay to the OEM for the product-related CE strategies) and/or ii) service-based contracts (a service level of the WTs is ensured by the OEM at the user site) [136]. Whereas, service fees are usually pursued by dematerialisation, collaborative consumption, and long life CBMs, material contracts are usually pursued by circular production, circular sourcing (hybridisation) and next life CBMs. Nevertheless, larger profit margins and business turnover can be obtained through cost reductions in manufacturing processes (e.g. cleaner production, recycling), shorter lead times for the delivery of WTs (e.g. refurbishment and remanufacturing) (see section S6), and market diversification (refurbishment, hybridisation) [131,137].

Focusing on market diversification, all refurbishment companies offer multi-brand services, which helps optimise logistics and cost efficiencies [88,138]. Another example of market diversification is the production and sale of methanol from surplus energy production in hybrid wind farms, which can increase the wind farms revenue by 33% compared with selling renewable electricity alone [139].

A reduction in CO_2 emission taxes, thanks to the delivery of multiple clean energy sources from hybrid wind farms, also offers additional cost saving opportunities, which further increases profits. For instance, the cost of methanol production supplied by a hybrid wind farm (€1028–1067/tonne) can be higher than the methanol produced with grid electricity (€608–1453/tonne) in Germany [133]. However, CO_2 emission avoidance costs between €365–430/tonne could be achieved. Thus, Germany could reach market parity by 2030–2035 and the price for the avoidance of CO_2 turning from a cost to benefit at around the same time. Accordingly, the hybridisation of wind farms can be effective for implementation in old wind parks without receiving economic incentives [140].

Nevertheless, operating CBMs can be costly and, sometimes, operational costs can be greater than potential revenues [131,141,142]. Pertinent CBM operational costs are usually determined by i) labour (skilled engineers, technicians, software developments, data analysts, and marketing, customer support and financial specialists), ii) infrastructure (e.g. manufacturing plants, and specialised workshops and warehouses), technologies (e.g. processing technologies, machinery and tools, including assets plus operating costs) and material requirements (e.g. advanced, alternative, and standard materials), and iii) dismantling, disassembly and transportation of WTs and components (Table S4). Although the latter is mostly relevant for next life CBMs.

For instance, a refurbished 1.5 MW onshore WTs can retain 20% (≈€350 K) of the value of a new unit (≈€1,700 K) [121]. Nevertheless, the final price of refurbished units can vary based on WT design, the original date of manufacture, operating conditions, components quality, maintenance history, and supply and demand fluctuations. For comparison, the cost of a remanufactured 2 MW onshore WT can be 50% (≈€987,500) to 70% (≈€1,382,500) of the cost of a new WT (≈€1,975, 000) [137,143]. However, component failure affects the technical and economic viability of remanufacturing activities. If predictive maintenance for WTs is lacking, more system failures are likely to occur over time, degrading WT performance and quality, which can increase remanufacturing costs by over 50% (+€44,000/WT) [144], as described in S6 of the SF. Additionally, the farther the physical location of remanufacturing plants from wind farms, the greater the transport costs, given that WTs are particularly large and heavy products and can require several haulage trips to complete their removal to a point of remanufacture [131].

This analysis demonstrates that commonalities between CBMs must be carefully analysed when designing and implementing CBMs, as the way value is created and delivered to customers affects the cost-efficiency and the overall circularity and sustainability performance of the business models (section 3.3). In this process, it is also important to consider what CBMs are more suitable for implementation according to the stage of the wind farm project. Building upon Fig. 3, Table 1 and Table S4, Table 2 presents the CBM alternatives most suited to implementation at different stages of a wind farm lifecycle, based on the most common technology management scenarios promoted by the wind industry [145].

Before wind energy projects are developed, the dematerialisation of wind farms should be considered from the early stage of project planning in order to minimise resource consumption and negative impacts derived from technology development and management. Likewise, the application of cleaner manufacturing techniques and closed-loop recycling systems through the implementation of effective reverse supply chains and reprocessing systems can contribute to mitigate resource consumption and environmental impacts further.

Once WTs are manufactured, they can be deployed through collaborative consumption models for a more efficient production and consumption of wind energy [74], including component upgrading through WT retrofitting over time for additional improvements in the operational efficiency.

Finally, when WTs approach the end of their operational lifetime, operators can consider three main options: i) lifetime extension), ii) repowering, or iii) decommissioning [46]. Lifetime extension involves extending the operation of WTs beyond their designed service life, normally requiring more repair and maintenance, and possibly use of reused, refurbished, upgraded or remanufactured components (ibid). Repowering can be partial, which involves the replacement of certain components to increase the units' lifespan and/or power output. This too can be supported by the implementation of retrofitting, refurbishment and/or remanufacturing solutions. Full repowering involves full replacement of a WT with a, generally, larger and more productive model, while reusing a part of the infrastructure such as the cables (ibid). Finally, decommissioning involves disconnecting assets from the power transmission, removal of WTs and foundations, and EoL management of all components. Decommissioned components can be i)

Table 2
Suitable CBMs according to the stage of a wind energy project.

CBM types	CBMs	Wind farm management scenarios				
		New wind farms	Full/partial repowering	Lifetime extension	Hybridisation	Decommissioning and waste management
Dematerialise	Demand reduction services	X	X	X		
Circular production & distribution	Cleaner production	X	X	X	X	
	Collection, take back, and reprocessing of used products	X	X			X
Collaborative consumption	Community-owned wind farms	X	X		X	
	Aggregator platforms	X	X		X	
Circular sourcing	WT-PV-Battery hybrid systems	X	X	X	X	
	Power-to-Gas hybrid systems	X	X	X	X	
	Power-to-Liquid hybrid systems	X	X	X	X	
Long life	Retrofitting (upgrading)	X	X	X		
Next life	Reuse	X	X	X		X
	Refurbishment	X	X	X		X
	Remanufacturing	X	X	X		X
	Repurposing		X			X
	Recycling		X			X

directly reused in other wind farms or reused after being refurbished and/or remanufactured, ii) repurposed for use in different applications, or iii) recycled to recover materials. Between all these options, the hybridisation of wind farms can take place to optimise asset management and system operation [146].

3.3. CBMs sustainability benefits

This section provides an overview of the potential sustainability benefits associated with each CBM with application to the wind industry. Detailed information is presented in Table S5 in the SF.

The CBM potential benefits are analysed in terms of economic sustainability (profit), environmental sustainability (planet) and social sustainability (people) (Table S5). Notably, however, most of the revised journal papers provide only cursory qualitative information regarding the sustainability potential of CE strategies driven by CBMs. Quantitative data was mostly identified for long life (retrofitting) and next life (particularly reuse, refurbishment and remanufacturing) CBMs. Moreover, almost all the revised papers concentrate on analysing just one or two sustainability dimensions, which usually relate to economic and/or environmental performance.

3.3.1. Economic benefits of CBMs with application to the wind industry

There is an agreement in the revised literature that CBMs can help reducing costs and/or increasing revenues (both for suppliers and customers) through four main pathways (Table S5):

i) Optimising manufacturing processes and reducing the dependence on virgin and critical materials [97,147]. For instance, the implementation of optimised NdFeB magnet recovery logistics in the US can generate \$441 M of economic benefits in 10 years [103].
ii) Extending WTs lifetime and reliability, while increasing wind farm energy production [136,148]. For instance, the combination of retrofitting and life-extension techniques can increase WT energy production by up to 46% [118], with the corresponding additional profits.
iii) Reducing the expenditure in the purchase, operation and maintenance of WTs [144]. For instance, refurbished and remanufactured WTs can have 20%–50% of the price of a new unit with considerably higher internal return rates [121,149]. Likewise, WT refurbishment can reduce manufacturing costs by 60% [150].
iv) Optimising the whole system performance through active stakeholder engagement and use of cloud-based solutions (collaborative consumption CBMs) [151], and/or the integration of other renewable energy sources and storage systems to minimise wind power curtailment to operate the grid more efficiently and use surplus wind energy to deliver multiple energy products to the market (circular sourcing CBMs) [113,114,116,132,152]. For instance, the Hepburn community-owned wind park [69] contributes €26 K/year to fund local sustainability initiatives and projects and returns a dividend to their members, which has a positive impact on the local economy.

These CE strategies and CBMs can help reduce the capital expenditure (CAPEX) and OPEX, hence decreasing the levelized cost of electricity (LCOE), making wind energy more competitive in the market. CBMs can also help diversifying the product and service portfolio to satisfy the needs of mature markets demanding circular solutions [17,153] and open new markets in developing countries [94,131,138,154].

3.3.2. Environmental benefits of CBMs with application to the wind industry

CBMs can contribute to achieving significant environmental savings by narrowing, slowing and closing resource loops [155], making it a cleaner energy source, which can help further decarbonise the electricity grid mix of countries (Table S5).

While cleaner production CBMs can support the resource efficient (e.g. lower energy consumption) manufacture of WTs with fewer materials and components per kWh produced [156,157], demand reduction CBMs can ensure greater and more consistent WT electricity production, while reducing energy (e.g. use of fossil fuel-powered vehicles) and material (e.g. parts replacement) consumption in maintenance operations thanks to digital solutions [130] (Table S5). Thus, cleaner production and demand reduction CBMs can facilitate narrowing resource loops.

Focusing on slowing resource loops, long life CBMs (retrofitting) can increase the WT annual energy production from 5% [158] up to 46% [118] thanks to component upgrading plus life-extension. Likewise, between 70 and 75% of the components and materials in a WT can be reused through refurbishment and remanufacturing [149,159] reducing by up to 70% (- 5000 GJ) the primary energy consumption in manufacture, while mitigating GHG emissions by 45%, on average [159]. This can account for over 860 tonnes of avoided CO_2 eq. emissions per WT compared to manufacturing new assets [149].

At the country-level, the reuse of WTs and components can reduce waste generation from up to 110 kt and mitigate GHG emissions by up to 180 t CO_2 eq. from 2030 to 2040 in the UK alone [17]. Likewise, some authors highlight that if only 5% of the Netherlands' yearly production of urban furniture was supported by WT blades repurposing, the total annual blade waste generation could be removed from the waste stream

[13].

Finally, when WTs and components inevitably become waste, material recycling brings additional environmental savings. For instance, steel recycling can reduce the global warming potential and fossil resource depletion potential of wind power generation by 1–6% [160]. Likewise, closing resource loops through the implementation of optimised PM (NdFeB) recovery systems in the US (take back and reprocessing CBMs) could reduce GHG emissions by 113 Mt CO_2 eq. compared to landfilling and using virgin materials [103].

Considering the wind park as a whole, both collaborative consumption (community-owned wind parks and aggregator platforms) and circular sourcing (wind farm hybridisation) CBMs can also play a key role in maximising overall resource efficiency and environmental performance through system optimisation. For example, off-grid WT-PV-Battery systems can reduce diesel-based power generation from 66% to <1%, resulting in an LCOE of <€0.13/kWh, thanks to the elimination of individual diesel-based power generation engines in locations without access to the main electricity grid, such as remote rural areas or islands [152,161].

3.3.3. Social benefits of CBMs with application to the wind industry

Findings suggest that CBMs can contribute to four major social benefits (Table S5):

i) Job creation through market diversification,
ii) Local community development,
iii) Education and upskilling, and
iv) Satisfying the needs of emerging economies (or less developed energy markets) exploring renewable energy transition pathways.

The potential to create new jobs can be especially relevant for next life CBMs as they entail the development of more labour intensive activities compared to the manufacture of new items [96,153,163].

Likewise, collaborative consumption CBMs (community-owned wind farms are socially driven by definition. They are aimed at recruiting local staff to promote local employment, empowering people through ownership and community engagement and providing greater transparency of the benefits achieved by all stakeholders [74,108]. Besides, a share of the revenues is invested in improving the wellbeing of local communities, through the implementation of community transport infrastructures, household energy efficiency measures and other energy-related solutions [109].

Complementarily, some CE activities, such as refurbishment, remanufacturing, repurposing and collection, take back and reprocessing, can drive the development of educational programs for students, technicians and industry professionals demanding training in highly specialised and skilled jobs [e.g. 104,164,165]. For instance, the hybridisation of wind farms requires new skills for the operation, management and maintenance of multiple energy technologies running in a single location [132].

Finally, as entry level customers from developing countries or less mature markets may not be able or be willing to invest in their own WT manufacturing and management infrastructure, importing cheaper used and/or refurbished or remanufactured WTs represents a suitable choice [131,149,162].

3.4. Industrial challenges and opportunities for the implementation of CBMs

According to the literature review findings, the most relevant challenges for the implementation of sustainable CBMs in the wind industry can be grouped into eight major categories (sections 3.4.1-3.4.8). Additionally, two research challenges (sections 3.4.9 and 3.4.10) are highlighted by the authors of this paper based on the critical analysis of the findings.

3.4.1. Development of servitisation and digitalisation capabilities

Servitisation has the potential to strengthen the competitiveness of manufacturers [166]. However, for OEMs, or O&M contractors, to provide demand reduction services, they must change their relationship with customers from a one-off transactional exchange to a long term invested customer relationship that requires continual nurturing [99].

Likewise, increasing service quality can lead to decreasing product sales, while increasing product quality may cause the customers to procure services less often [166]. Engaging customers in the co-creation of flexible service solutions is therefore crucial. This includes the development of the necessary capabilities for excellence in service design and delivery, such as having smart data gathering, monitoring and management systems in place [41,99].

3.4.2. Accurate balance of costs and benefits

The development of some CE strategies can be costly in the short term (section 3.2.3). For instance, the implementation of cleaner production CBMs may entail high economic investment in new manufacturing technologies (e.g. additive manufacturing) [157,167,168]. Likewise, aggregator platforms require large computational capacity, artificial intelligence, market trading algorithms and predictive models, which are costly to develop [169].

The development of Power-to-X alternatives, through the hybridisation of wind farms also require large economic investments in the implementation of multiple energy production technologies (e.g. energy-intensive water electrolysis to produce hydrogen), storage systems (gas and liquid energy carriers tanks) and distribution and transport networks (e.g. the adaptation of existing gas infrastructure) [81,113,114,132,139], making the cost of green hydrogen, methane and liquid energy carriers higher than fossil-based fuels [170]. Thus, robust economic modelling is essential to determine the long-term viability of CBMs.

3.4.3. Technical constraints for the implementation of circular economy strategies

Although some CE strategies (e.g. retrofitting, refurbishment, remanufacturing) can contribute to extending the WT lifetime and components, they can affect the technology performance in subsequent use cycles, which can lead to lower resource, environmental and cost savings than expected.

For instance, the retrofitting of WTs sited in complex environments might exacerbate the stress conditions to which those assets are subjected, hence affecting their residual lifetime [171]. Likewise, blade extensions can increase the loads on the rotor and the turbine, which might lead to failure. Consequently, material stress and load mitigation solutions must be implemented to mitigate technical risks upfront [113,172].

Likewise, the greater the damage of a component, the more material and energy must be invested during refurbishment and remanufacturing, increasing technical complexity, costs and environmental impacts. On the other hand, wear and tear are unavoidable consequences of use within an entropic system [173]. Thus, prevention of degradation requires less recyclable materials, which means that greater energetic cost is incurred in recycling activities.

3.4.4. Lack of suitable markets for secondary products and materials

Second-hand markets for refurbished WTs have been largely restricted to major high-value components whose dismantling, management and redistribution expenditure can be easily compensated [174]. Moreover, wind energy technologies continue to evolve at a rate that makes it difficult to install (undersized) reused, refurbished and/or remanufactured components in new or more modern wind farms with larger units [154,175]. Indeed, the steady improvement of the efficiency of new WTs, can limit the demand for older assets in established markets [12].

Similarly, there are a variety of mechanical, thermal and chemical recycling solutions under development for WT blades [135]. However, their viability depend on the price and quality of the recyclates that must match that of the end-markets, including transport, construction, electronics, consumer goods, and other sectors (e.g. biomedical) [12,129]. With variable value and quality of resources entering the recycling process [131], the reduced fibre quality (for blade recycling) compared to virgin materials [135] and the difficulties forecasting the characteristics of materials made with the recyclates [127], the cost-efficient supply and market uptake of WT recyclates is compromised. Innovative design techniques to develop 100% recyclable materials [e.g. 176], including the development of high-efficient recycling technologies, is essential for the upscaling of more sustainable recycling CBMs.

3.4.5. *Complexity of the forward and reverse logistics management*

Structural assessments can enable the development of CBMs by providing insights into the value of components [175]. However, the intrinsic uncertainties and barriers related to the planning and management of forward and reverse supply chains for next life (in particular remanufacturing) and circular production (in particular collection, take back and reprocessing) CBMs, include i) core arrival time, ii) product demand, iii) logistic costs, iv) core condition, v) disassembly requirements, vi) number of defective components, and vii) value of salvaged components [177], being the most critical barriers the reverse logistics and the quality of the products.

The structure of the recovery channel for managing oversized and overweight components must be carefully assessed and configured upfront, which involves defining the actors responsible for the management of reverse supply chains, characterising the transportation logistics for dismantled components, reducing the variability of returned products, and ensuring the quality and end-market of the product outcomes [131].

Likewise, three main strategies can be pursued to ensure a high quality of reused, refurbished and/or remanufactured WTs [149]: i) maintain the product and components traceability, including proper labelling and detailed O&M records, ii) develop standards or certifications to ensure the achievement of the original product performance specifications with extended warranties, and iii) become specialised in handling specific brands through collaborative relationships between OEMs and secondary recovery companies. However, nowadays, there is no industry-wide standard yet that specifies and certifies the work that must be accomplished on a used WT to qualify it as retrofitted, refurbished or remanufactured [175].

3.4.6. *Centralised know-how and industrial capabilities*

OEMs having appropriate resources in place (e.g. R&D, investment capabilities, manufacturing plants and operational expertise) are in a suitable position to support the development of new CBMs, as it is difficult for third party operators to provide integral solutions lacking technical know-how and long-time business expertise. Likewise, OEMs that maintain a substantial part of their oldest WTs can have the appropriate supply chain in place to guarantee the provision of spare parts, at a reasonable price, for a long period of time [178]. Thus, if OEMs do not take direct action towards CE, alongside strategic partnership development, it will be difficult to upscale CBMs in the wind industry.

3.4.7. *Industrial business cases and value chain limitations*

Repurposing solutions for WT blades represent demonstration projects and they do not offer the scalability required for the bulk demand of the future [142]. Besides, finding new applications for repurposed blades is a complex problem, as it is subject to multiple location-dependent (e.g. need for building permits) and design-related (e.g. available size, shape and material composition) constraints [126].

Focusing on recycling, there is no current business case for recovering REEs [34] or for the adoption of effective closed-loop recycling solutions for blades [24]. Cement co-processing using glass fibre reinforced polymer (GFRP) blade waste is among the few solutions that is available at industrial scale [18] alongside mechanical recycling. However, cement co-processing has a limited capacity to accommodate the variety of WT blade wastes to be generated over time since it is not suitable for carbon fibre reinforced polymer (CFRP) [180]. Thus, the development of double-sided CBMs for the end of use phase of a WT, in which both the wind operator and end-users (e.g. of recycled composites) are likely to be paying the recovery company, bringing sufficient value together to offer recyclates at no cost or a negative cost to end-users, could offer an intermediary solution.

3.4.8. *Policy development and incentives*

Governance support through new regulatory frameworks, incentives, and technical and safety standards is required for the successful deployment of CBMs [129,181]. This is particularly relevant for the hybridisation of wind farms in the medium to long term [132]. For instance, electricity tax exemptions, substantial start-up subsidies, strict CO_2-certificate prices and CO_2 emission reduction quotas are key for the economic feasibility of PtG and PtL solutions [114]. Implementing regulatory penalties regarding CO_2 emissions by energy and carbon-intensive industries, such as aviation, shipping and chemistry, can also facilitate the market uptake of cleaner energy carriers developed through Power-to-X solutions [114].

Besides, new regulations supporting the standardisation of key WT components, demanding recycled content and reparability ratios, and/or encouraging the implementation of extended product responsibility schemes [129,182] can also facilitate the upscaling of circular production and next life CBMs [140].

3.4.9. *Supply and demand mismatch management*

One of the major limitations for upscaling CBMs in the wind industry is the mismatch between supply and demand for secondary materials, components and products. For example, the total NdFeb magnet supply at the WTs' end of life is 7000–9000 t/year in the US, while just one single dismantler can process up to 5000 t/year [103]. Estimating the volumes and timing of WT resources becoming available for recycling is difficult but crucial for investing in recycling infrastructure [181]. This challenge is most pronounced for the management of WT blade wastes, with notable differences in forecasts [135] and the locations where wastes will emerge [183].

Likewise, waste generation is not necessarily constant over time, as it depends on various factors, including the implementation of life-extension solutions by wind farm owners that can delay waste generation, which may constraint the viability of CBMs relying on damaged components and/or wastes as inputs. Thus, combining WT waste with similar waste streams generated in other industries (such as automobile, shipping and aerospace), through forecasting of real-time waste generation, can be helpful to reach economies of scale and develop cost-effective recycling solutions [183]. In this process, it is also relevant to determine what share of the future wind energy capacity can be satisfied with retrofitted, reused, refurbished and remanufactured WTs to sustainably complement recycling practices with other CE strategies.

3.4.10. *Circular design requirements*

Some WT components (e.g. blades) cannot be remanufactured due to current manufacturing practices (e.g. produced in a single piece), making the commercialisation of 100% remanufactured WTs technically impossible. Likewise, due to the fact that WT technologies are evolving quickly and the physical wearing of components during use [184], WT might be reused, refurbished and/or remanufactured only once. Consequently, these WTs will eventually reach their EoL and they must be properly recycled to avoid material losses and negative impacts. Thus, designing WTs and components for easy disassembly (high standardisation and modularity), life-extension (high durability, upgradability and reparability) and closed-loop recycling (high material recovery) is key to minimise primary resource consumption and facilitate sustainable life cycle management [137,183]. This also involves the use of alternative materials, such as thermoplastics with lower viscosity, cellulosic fibres and bio-resins for manufacturing WT blades [12,135].

3.4.11. Inter-dependencies between CBMs within and beyond the wind energy value chain

CBMs hold the promise to support systems-level sustainability innovation. However, they must be designed with upfront intent to deliver the desirable sustainability outcomes by considering the entire value chain network [185]. Companies interact and co-evolve by relying on other (linear and/or circular) business models to sustain their own business activities [186]. Thus, understanding the inter-dependencies between linear and circular business models within the value chain is essential to identify hotspots and opportunities to implement effective CE innovations leading to higher sustainability performance [185]. The resource and infrastructure requirements between business models (e.g. Table S4) should be carefully analysed to determine how changes in one component of the value chain may induce changes in others, which can in turn influence the business model of the involved companies [44,187]. This business ecosystem view, however, requires more capabilities from companies to be able to analyse and manage system-level data [187], including how to deal with rebound effects and trade-offs to mitigate global impacts [188–190].

3.4.12. Need for robust sustainability assessment frameworks, tools and indicators

The current cost-driven focus of the wind industry hinders the transition to a circular industry [179]. Thus, business success should not be measured in monetary terms only (economic profits) but in terms of net positive impacts by putting more back into society, the environment, and the global economy than a business takes out [191]. Consequently, analysing CBMs from a system perspective is essential to implement WT design and technology management practices that could positively impact upon the availability of resources for sustainable re-circulation. This requires the use of holistic frameworks [e.g. 192], standards [e.g. 193,194], tools [e.g. 195], and indicators [e.g. 196] to properly quantify, assess and enhance sustainable value creation, delivery and capture across stakeholder value networks, as it has been recently highlighted by various projects launched by the wind industry [e.g. 34–37,197,179].

4. Conclusions

A comprehensive characterisation of 14 CBMs (section 3.1, Table 1), grouped in six typologies (Fig. 3), has been presented in this paper with the aim of providing guidelines to assist the wind energy industry and stakeholders in the development of sustainable value chains.

This study demonstrates that although each CBM has a specific purpose, they share common requirements, such as the need for stakeholder engagement and collaboration, the implementation of effective forward and reverse logistics and the use of digital solutions to deliver circular products and services to customers (section 3.2, Table S4). Understanding these common requirements can help reduce (economic and technical) efforts to build CBMs and transition from one CBM to another based on the r sustainable resource management needs of the wind industry.

Though the findings of the literature review demonstrated a lack of comprehensive sustainability studies on CBMs within the wind industry, this paper has discussed potential sustainability benefits, as measured by cost, resource and environmental impact savings, profit generation and the social developments that can be achieved through the implementation of CBMs (section 3.3). However, industrial, policy and research action is required to overcome ten major implementation challenges.

In the first instance, the wind industry should consider developing more servitisation capabilities to deliver use- and/or result-oriented solutions to create long-term material custody and generate greater resource and environmental savings than product-based offerings. In tandem with servitisation, the digitalisation and development of data analytic competencies are essential for component performance monitoring. Likewise, they can help with developing CE solutions in the early stages of the technology life cycle aimed at preserving functional and material quality, and reduce negative impacts.

Smart design solutions to mitigate technical operational risks from the implementation of CE strategies are also required. This includes designing WTs and components for easy disassembly, life-extension and closed-loop recycling, including materials labelling. Circular design strategies should be complemented with the configuration of effective forward and reverse logistics for the cost-efficient dismantling, collection, disassembly and recovery of technologies and components at the EoL. Partnership and active collaboration between key stakeholders and OEMs, is also critical to driving CE innovations and developing a shared vision for industry sustainability.

Complementing industrial activity, policy-makers could encourage the development of markets for the supply and reuse of secondary products, components and materials, through the provision of both material reuse incentives and/or the development of regulatory frameworks. Active involvement in the deployment of circular wind energy projects by developing standards and extended producer responsibility schemes, and integrating minimum CE tender and permit criteria, would assist the development and upscaling of CBMs.

Finally, research needs to be undertaken on the potential effects of supply and demand mismatches in terms of volumes, timing and location of resources becoming available from operational WTs to feed CBMs. Related to other research needs, a limitation of the research presented in this paper is that it has been focused on analysing literature resources that explicitly mention the words business or business models to obtain focused results. Although the findings demonstrated that the CBM categorisation system used as baseline was useful to analyse the current situation of the wind industry and the potential improvement opportunities, the presented study could be replicated by expanding the literature review to incorporate wider sustainability focussed studies, which could lead to the identification, categorisation and characterisation of new wind energy CBMs. Critically, further research is also required to demonstrate the full resource decoupling and economic, environmental and social sustainability potential of circular business cases and value chains. This entails a careful analysis of the inter-dependencies and trade-offs between CBMs and linear business models within and beyond the wind industry by applying a business ecosystem approach. To do so, holistic (but practical) sustainability assessment frameworks, tools and indicators addressing the particularities of CE for the wind industry should be developed and applied.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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