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Circular business models and value chains for wind turbine blade end-of-life management: A roadmap for turning waste into value

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ABSTRACT

Circular and sustainable business models (CSBMs) offer promising solutions to address the resource and environmental challenges related to the life cycle management (LCM) of wind turbine blades (WTB). However, most literature and industry practice focus on material and technological innovation, overlooking systemic business model transformation. This paper presents a comprehensive roadmap for implementing and upscaling CSBMs for the efficient end-of-life (EoL) management of WTBs, built upon the definition and characterisation of 15 CSBM typologies and 29 circular innovation patterns. The findings draw on a systematic review of 98 academic and industry sources, 15 expert interviews, and a stakeholder group workshop with 24 participants from 10 organisations. CSBMs are examined across five EoL phases: WTB decommissioning, recycling, material upgrading, end industrial end-use and transversal supporting businesses. For each, the key value creation mechanisms, enablers, and barriers are identified, including sustainability considerations. Subsequently, a three-phase roadmap (2025–2035) is developed to align technological readiness, policy drivers, market conditions, and required resources and competences, supporting the transition from a fragmented, landfill-dependent system to a mature, circular ecosystem. Key opportunities identified include vertical business integration, development of material passports, regional recycling hubs, and advanced recycling methods, such as low-carbon pyrolysis and green solvolysis. Strategic recommendations for industry, policymakers, and researchers to coordinate efforts and unlock circular value at scale, while also offering insights applicable to other composite-intensive sectors undergoing circular transitions, are also provided.

1. Introduction

The rapid expansion of wind energy is central to achieving global decarbonisation targets [1,2], with over 1200 GW installed worldwide by 2024 [3] and capacity projected to exceed 2150 GW by 2030 [4]. By 2050, cumulative capacity is expected to surpass 5000 GW onshore, and 1000 GW offshore [5]. However, this growth intensifies the challenge of managing wind turbine blades at end-of-life (WTB-EoL), with an estimated 43 million tonnes of cumulative waste expected by 2050 [2]. WTBs, predominantly composed of glass and carbon fibre reinforced polymers (GFRP and CFRP: fibers embedded in a resin matrix, most often epoxy- or polyester-based) mixed with other materials (e.g. balsa wood, foams, coatings and metals), present significant recycling challenges due to their composite structure, size, and heterogeneity [6,7]. Consequently, they are often landfilled or incinerated, despite regulatory efforts to restrict these practices in Europe, resulting in the loss of valuable resources that could otherwise be reintegrated into industrial applications [8,9].

The sustainability performance of wind energy systems depends on effective circular WTB-EoL strategies, including recycling [2,10]. However, recycling technologies remain limited in scale, and significant technical, economic, and regulatory challenges persist [11–13]. While mechanical recycling (physical breakdown of composite materials into smaller particles) and thermal recycling (polymer matrix decomposition by applying heat in the absence of oxygen) have achieved high technology readiness levels (TRLs), equivalent to 9 in both cases (actual technology proven through successful deployment in an operational setting), they often lead to downcycled outputs with limited high-value applications in industrial sectors [9,13]. Conversely, chemical recycling (polymers break down by employing chemical agents) remains at lower TRLs (5–6) (engineering pilot scale), facing scalability and economic

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Abbreviations

BAT	Best Available Technologies
CAD	Computer-Aided Design
CFRP	Carbon Fibre Reinforced Polymers
CI	Circular Innovation
CSBM	Circular and Sustainable Business Model
EoL:	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
GFRP	Glass Fibre Reinforced Polymers
IP	Intellectual Property
KPI	Key performance indicators
LCA	Life Cycle Assessment
NISP	National Industrial Symbiosis Programme
OEM	Original Equipment Manufacturers
PCP	Product Circularity Platform
PSS	Product-Service Systems
R&I	Research and Innovation
rCF	Recycled Carbon Fibre
rGF	Recycled Glass Fibre
TRL:	Technology Readiness Level
WT	Wind Turbine
WTB	Wind Turbine Blade

viability barriers [9,11].

The lack of mature secondary markets and the high recycling cost further undermine the economic viability of WTB-EoL management systems and constraint private investment [14]. Sommer and Walther [15] highlight a circular dilemma where the lack of recycling infrastructure limits the supply of recycled materials, while the absence of market demand discourages infrastructure investment. Moreover, limited collaboration among wind industry stakeholders, combined with a lack of empirical data on environmental, social, and operational impacts, constrains the development of innovative solutions, with sustainable value chains still at an early stage [7,16]. On the legislative front, underdeveloped regulatory frameworks, absence of recycling quotas, and insufficient policy incentives further delay progress [17,18].

Addressing these challenges requires urgent advancement in technological, logistical, regulatory, and market solutions for decommissioning, recycling, upgrading, and reintegrating reclaimed materials to foster closed-loop systems [19,20]. This urgency is underscored by major manufacturers' commitments to achieve 100 % recyclable turbines by 2040–2050 (e.g. Nordex [21], Siemens Gamesa [22]).

Circular and sustainable business models (CSBMs) are recognised as key enablers to overcome these challenges [6]. CSBMs entail rethinking a firm's value creation, delivery, and capture mechanisms to support the transition towards resource-efficient and low-impact systems while generating economic, social, and environmental value through stakeholder engagement and long-term objectives [23–25]. In the wind industry, CSBMs can facilitate the reintegration of EoL materials into the economy, reducing dependence on virgin resources and mitigating environmental impact [26].

Various CSBM strategies can directly respond to abovementioned challenges. For instance, CSBMs based on product-service systems (PSS) can extend WTB lifespan by integrating maintenance, refurbishment, and repurposing services, thereby reducing waste and supporting closed-loop material cycles [23]. Take-back schemes combined with extended producer responsibility (EPR) mechanisms, where manufacturers retain ownership of WTBs and oversee recycling, can address regulatory gaps, ensure consistent waste flows in a given timeframe, and incentivise recycling infrastructure development [19,27]. Recycling CSBM that upcycle reclaimed GFRP and CFRP into high-value applications can strengthen secondary markets and enhance recycling profitability.

WTB recyclates can be used in the construction industry (e.g. cement production), the chemical industry (e.g. bulk moulding compounds), the oil industry (e.g. hydrocarbon-based products) [20] and the automotive industry, where recycled GFRP and CFRP can be used to reinforce vehicle components such as pedal brackets and clamps, replacing virgin fibres and enhancing lightweight structures [28,29]. This aligns with forthcoming EU regulations mandating 25 % recycled plastic in automotive applications [30]. Moreover, CSBMs incorporating WTB materials into public infrastructure not only advance sustainable practices but also encourages community participation and raise awareness [2].

Collaborative CSBM that coordinate Original Equipment Manufacturers (OEMs), recyclers, policymakers, and end users can address stakeholder fragmentation, facilitating joint investments and knowledge sharing [31]. Additionally, locally oriented dismantling, recycling and upgrading CSBM networks, can further reduce transport emissions, promote regional value loops and foster job creation and local economic development [16,32,33].

Despite their potential, both research and deployment of CSBM for WTB-EoL management remain at an early stage [see [16,26,34]] and there are notable gaps in the holistic analysis of WTB value chains for successful CSBM scaling up, including [16–18,20,26,41,42].

- Limited focus on the complete life cycle of the assets considering industry practices and empirical data from real WTB-EoL management projects.
- Fragmented and narrowed WTB-EoL management roadmaps, being often theoretical and lacking the comprehensive integration of business model, supply chain, market, and policy aspects.
- Insufficient assessment of sustainability impacts, as most studies focus on analysing technical or environmental aspects of CSBM for WTB-EoL management, rarely analysing the social and economic benefits and/or trade-offs as well.

Stakeholders require guidance, practical experience, and robust evidence to initiate and scale CSBM experimentation [35]. Successful adoption depends on approaches demonstrating the technical feasibility, economic viability, and socio-environmental benefits of alternative CSBM strategies [31,36–38]. Leveraging industry-specific CSBM typologies [31,39] and showcasing related circular innovations (CI) [40] can play a crucial role in building stakeholder capacity to address WTB-EoL challenges through CSBM innovation [20,26]. Access to such knowledge, alongside practical guidance on CSBM implementation, is crucial to support informed decision-making and foster systemic innovation in the WTB-EoL [43].

Furthermore, a structured roadmap is needed to align CSBM development for WTB-EoL management with policy frameworks, market priorities, and emerging technologies, ensuring scalability and long-term viability. This is particularly pressing in the context of the European Green Deal [44] and the 2030 Agenda for Sustainable Development [45], which prioritise circular strategies across sectors, including renewable energy, over the next decade. Existing roadmaps remain predominantly technology-focused and lack integration of CSBM typologies, market drivers, and key barriers [see [10,14,18,46]]. Addressing this gap requires combining technological pathways with business model (BM) innovation to advance circular WTB-EoL strategies.

Based on findings from the EoLO-HUBs project (Section 2), this article characterises CSBMs (Section 3.1) and CIs (Section 3.2) along the WTB-EoL value chain and presents a roadmap (see Section 3.3) to support CSBM deployment from 2025 to 2035.

2. Methodology

A three-step methodology (Fig. 1) was applied to the research, integrating well-established approaches to define and characterise CSBM typologies [e.g. 20,26,47,48], CI patterns [e.g. 23,27,31,40,49] and develop an innovation roadmaps [e.g. 50–52] for circular and sustainable WTB-EoL management, combining insights from both the literature and industry practices.

2.1. Systematic literature review on CSBM, CI, and roadmaps for WTB-EoL

Three literature reviews were conducted to analyse the state-of-the-art related to WTB-EoL management. The first review examined commonly used CSBM canvases to develop a tailored framework for data collection and analysis (Section 2.1.1). The second review synthesised insights from academic and grey literature to identify and characterise CSBM typologies and CIs, highlighting best practices for enhancing circularity and sustainability performance (Section 2.1.2). The third review focused on analysing wind industry roadmaps to align findings with industry standards, based on key priorities, technological advancements, and policy frameworks shaping sustainable business strategies for WTB-EoL management (Section 2.1.3).

2.1.1. CSBM canvas development for data collection and analysis

A tailored CSBM canvas was developed to standardise data collection and analysis across literature (section 2.1.2) and stakeholder engagement activities (section 2.2.1); an approach widely recognised in the literature [20,26]. Based on available CSBM frameworks [e.g. 53–56], the canvas integrated.

i Value management mechanisms: value proposition, value creation, value delivery, and value capture
ii Sustainability impact: environmental and social benefits and trade-offs
iii Circularity innovations: conceptualised as problem-solution patterns addressing ecological, social, and economic challenges in WTB-EoL managament systems, and serving as replicable guidelines for product, CSBM and value chain innovation [40,57]; commonly applied in CSBM research to identify and document best practices [31,57,58].

A review of CSBM canvases is presented in Table S1, while the tailored canvas employed in this study, along with its analytical blocks, is detailed in Table S2 of the Supplementary File (SF).

2.1.2. Systematic literature review on CSBM and CI for WTB-EoL

To identify CSBMs and CIs for WTB-EoL management, a systematic literature review (SLR) was conducted in October 2023. The academic search applied three structured keyword combinations in Scopus, filtering English-language articles by title, abstract, and keywords, with no additional filters. The first stream targeted WTB recycling initiatives, the second focused on business models (BM) and EoL strategies, and the third addressed specific recycling technologies. A detailed breakdown of the search criteria is provided in Table S3 of the SF.

Of the 99 articles identified, 18 focused on WTB recycling technologies, with only 4 documenting specific projects or business cases. Articles on general renewable energy trends [e.g. 35,59,60], non-recycling circular economy strategies, such as repurposing or reusing blades [e.g. 13,61] and other renewable technologies, such as solar cells [e.g. 62] were excluded from the analysis.

The academic review was complemented by an industrial literature search by using Google, considering reports from key organisations targeting WTB life cycle management (e.g., Wind Europe, IEA Wind TCP Task 45, Spanish Wind Energy Association, NREL), and relying on the CORDIS projects database [63]. This grey literature review led to the identification of 67 additional sources, including 36 company websites (covering businesses, universities, technology institutes, and wind marketplaces), 26 EU-funded projects and 5 renewable energy and wind technology blogs/magazines. Detailed information on all consulted sources is provided in Table S4 of the SF.

To support the classification of CIs, the reviewed sources were cross-referenced with established CI patterns from the literature [23,27,31,40,57,64]. In total, 91 documents were analysed—including 23 academic articles and 68 grey literature sources—to define the CSBM typologies and CI patterns explored in this study.

2.1.3. Literature review on wind industry roadmaps for WTB-EoL management and recycling

The review on wind industry roadmaps was conducted in March 2024 using Google search, prioritising industry reports, white papers, government documents, policy briefs, and thesis studies over academic papers to capture industry-driven perspectives. Relevant keywords combinations and phrases used included “drivers and barriers for WTB

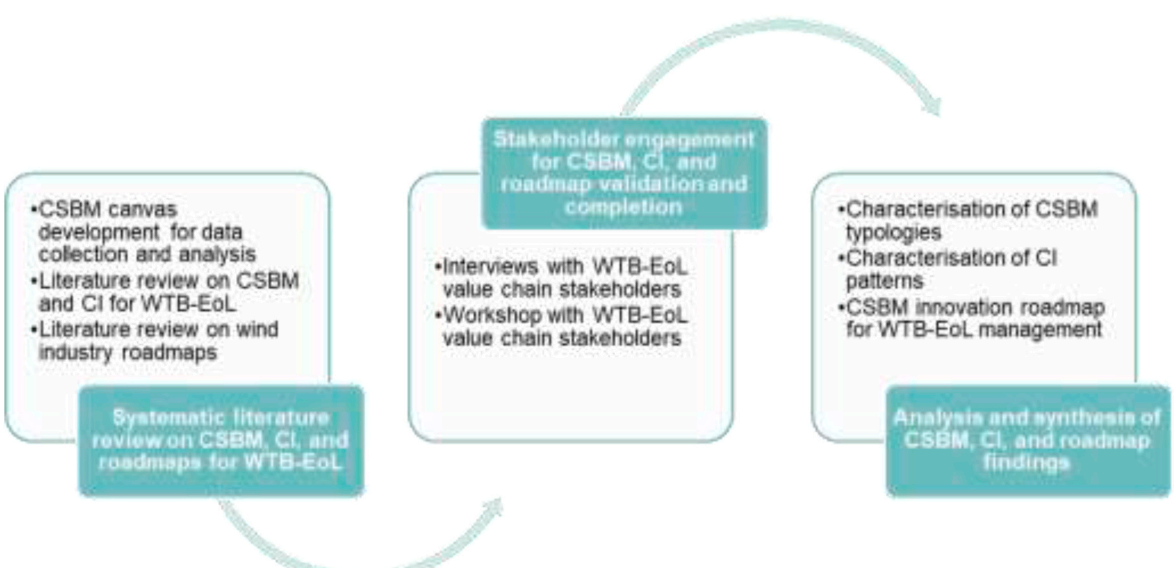

Fig. 1. Research methodology. Acronyms: CSBM: Circular and Sustainable Business Models, CI: Circular Innovations, WTB-EoL: Wind Turbine Blades' End-of-Life.

recycling", "business opportunities for WTB recycling", "resources and competencies needed for WTB recycling", "wind industry roadmap", and "roadmap for the end-of-life management of WTBs". This approach ensured the inclusion of practical insights from industry and policy frameworks. Inclusion criteria focused on reports from the past five years that addressed WTB-EoL management strategies, technological advancements, or sector-specific roadmaps within wind energy. A total of 7 key documents [i.e. 19,65–70] were selected, offering technical, policy, and industry perspectives. A detailed description of these documents is provided in Table S5 of the SF.

In total, 98 documents were analysed across the literature review (91 for CSBMs and CIs, and 7 for roadmaps), building the empirical basis for the development of the CSBM typologies, CI patterns, and the WTB-EoL roadmap presented in this study.

2.2. Stakeholder engagement for CSBM, CI, and roadmap validation and completion

2.2.1. Interviews with WTB-EoL value chain stakeholders

To complement the literature-based analysis, 15 online interviews (1.5–2 h each) were conducted between February and March 2024 with the partners of the EoLO-HUBs project [71], grouping key stakeholders in the WTB-EoL value chain. The EoLO-HUBs project is focused on the development of technological solutions for WTB decommissioning, fibre recovery (via pyrolysis and solvolysis), and upgrading of reclaimed GFRP and CFRP, while co-creating CSBMs and value chains for WTB recycling.

The interviews provided critical insights into CSBMs across decommissioning and pre-treatment, recycling, material upgrading, industrial end-use and cross-cutting knowledge provision. As technologies, such as solvolysis and biological recycling, are still emerging with undefined BMs [6,72], interviews helped bridge knowledge gaps [48,73], particularly around economic viability and sustainability impact. The full interview schedule is available in Section S4 of the SF.

To guide discussions, preparatory work included reviewing EoLO-HUBs' Grant Agreement (GA 101096425), project deliverables, partners' presentations and technical documents. This informed interview themes on technologies, processes, and stakeholder perceptions. Data collection followed a CSBM canvas consistent with the literature review framework (Table S2 of section S2 in the SF). Each session began with a CSBM introduction using a PowerPoint and interactive MIRO board (https://miro.com/), enabling participants to validate and enrich CSBMs, the EoLO-HUBs value chain, and related industrial challenges (Fig. S6 of the SF).

2.2.2. Group workshop with WTB-EoL value chain stakeholders

Workshops are widely recognised for CSBM/CI characterisation [48, 74] and sustainable value roadmapping [75,76], enabling stakeholder engagement, structured dialogue, real-time validation, and alignment with industry needs, while strengthening process mapping and consensus-building [48,74,77].

A group workshop was conducted on June 26, 2024 during an EoLO-HUBs Consortium Meeting and lasted 150 min, bringing together 24 participants from 10 institutions. Facilitated by the authors, it was structured around the WTB-EoL value chain—decommissioning, recycling, upgrading, end use and knowledge provision—dividing participants into five expert groups (Table S7 of the SF). Four interactive activities were designed to foster discussion and collaborative exploration.

i. Validation and refinement of CSBM identified from the literature (section 2.1.1) and stakeholder interviews (section 2.2.1).
ii. CI validation and prioritisation using a 5-point Likert scale (Willits et al., 2016) in Wooclap (https://app.wooclap.com/).
iii. Roadmap co-creation for CSBM innovation, complementing insights from the literature review outcomes (Section 2.1.3).
iv. Plenary discussion on conditions for successful deployment of CSBMs and WTB-EoL value chains.

A PowerPoint introduced core concepts, while MIRO and Wooclap enabled real-time interaction and feedback. Background materials CSBM, CI, and value chains were shared in advance to ensure informed participation. Discussions were recorded, transcribed, and analysed together with MIRO outputs, informing final CSBM categorisation (Section 3.1) and CSBM innovation roadmap (Section 3.3). The workshop was coordinated and driven by the three authors of this paper, who took notes, facilitated discussion and recorded the entire event. Workshop design and materials are available in Section S5 of the SF.

2.3. Analysis and synthesis of CSBM, CI, and roadmap findings

2.3.1. Characterisation of CSBM typologies

Findings from Sections 2.1–2.2 were analysed to characterise CSBM typologies for the WTB-EoL value chain. Using the CSBM canvas (Table S2 and SF), each typology was defined by its value proposition, creation, delivery, and capture mechanisms, alongside environmental and social benefits and trade-offs. Typologies were linked to empirical cases and positioned within the WTB-EoL value chain to define their role in decommissioning and pre-treatment, recycling, upgrading, end use and knowledge provision (see Section 3.1).

2.3.2. Characterisation of CI patterns

The research outcomes (Sections 2.1–2.3) were used to define CI patterns that address industrial challenges at four levels i) product, ii) BM (downstream), iii) BM (upstream) and value chain. CIs were associated with different CSBM typologies, linked to empirical cases, and positioned within the WTB-EoL value chain (see Section 3.2).

2.3.3. CSBM innovation roadmap for WTB-EoL management

Roadmaps serve as strategic planning tools that support long-term vision development, resource allocation and decision-making [78]. By identifying trends, challenges, and key resources, they align CSBM development with industry needs, fostering innovation, and ensuring the scalability of innovative solutions [75].

Developed from sections 2.1–2.2 and following guidelines for sustainable value roadmapping [75,76,78], the roadmap provides a structured framework for CSBM development across short, medium, and long-term time horizons. It is organised into three layers.

i Drivers and barriers: Trends and challenges shaping recyclable WTBs and efficient recycling systems.
ii Business Opportunities: BMs, innovations and value creation responding to those drivers and barriers.
iii Resources and Competences: Knowledge, technologies, funding, skills, and partnerships needed for implementation.

The roadmap is presented in section 3.3 and serves as a practical guide for wind energy professionals, providing a clear framework for implementing circular business strategies in WTB-EoL management.

3. CSBM typologies and CI patterns for the WTB-EoL management

Fig. 2 summarises the resulting 15 CSBM typologies within the WTB-EoL value chain (section 2.3.1): 13 CSBM typologies emerged from literature review (Section 2.1.1) and stakeholder interviews (Section 2.2.1), with two additional types (storage solutions and logistics provider) identified during the group workshop (Section 2.2.2).

Fig. 2 also links CSBMs to associated CIs (marked with asterisks), selected from 29 identified CI patterns. As described in Section 2.3.2, CIs are classified into four levels: Product (P), BM–Downstream (BMD), BM–Upstream (BMU), and Value Chain (VC). Section 3.2 presents the

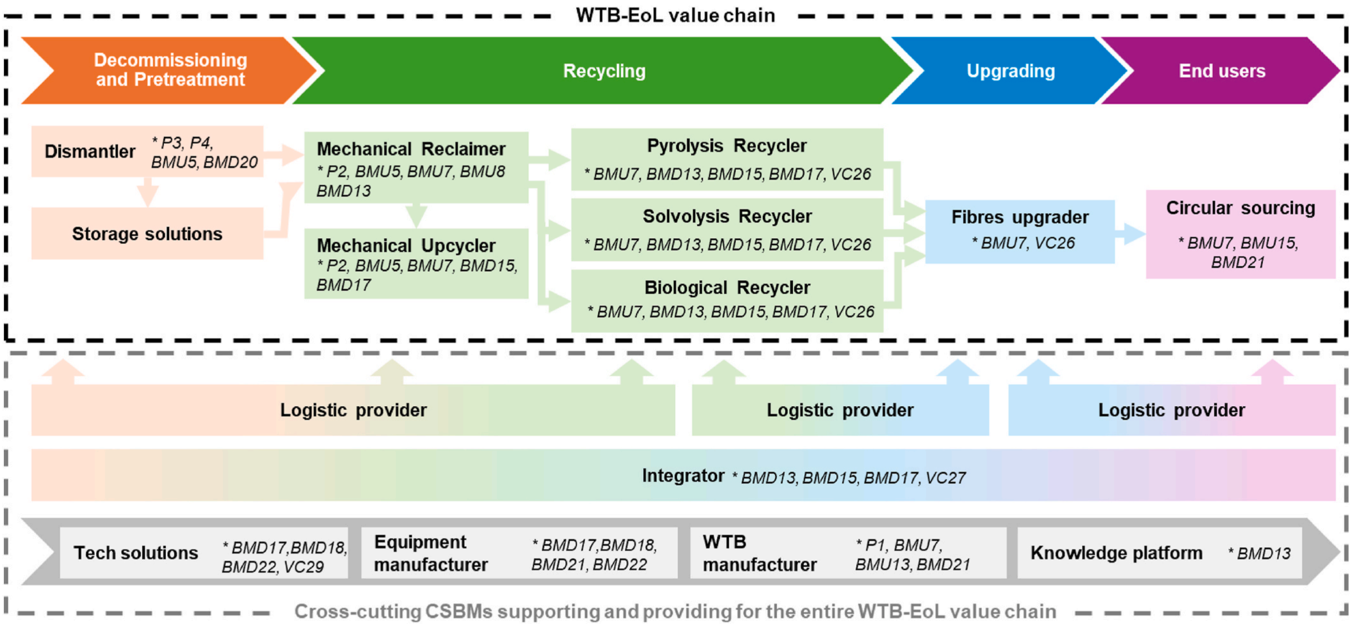

Fig. 2. CSBM typologies across the WTB-EoL value chain. Acronyms: WTB – Wind Turbine Blade, P – Product level circular innovation, BMD – Business Model (Downstream) level circular innovation, BMU – Business Model (Upstream) level circular innovation, VC – Value Chain level circular innovation.

CIs, followed by the CSBM roadmap (3.3) outlining drivers, barriers, and opportunities for a sustainable WTB-EoL value chain.

3.1. CSBM typologies for the WTB-EoL management

Table 1 describes the 15 CSBM typologies and related business cases articulated around the WTB-EoL value chain (Fig. 2), which are discussed in the subsections below (Sections 3.1.1-3.1.5), including sustainability aspects (Section 3.1.6). Section S6 of the SF provides detailed descriptions of each CSBM typology, including their recurrence across literature and stakeholder data (Table S21 and SF).

3.1.1. Decommissioning and pretreatment

This stage includes dismantling, cutting, and transporting WTBs, either separately or with the turbine [71], requiring careful planning for subsequent EoL steps [16]. The **Dismantler** initiates material flow, while **Storage Solutions** buffer materials until viable recycling routes emerge, adapting to market and regulatory changes (Personal communication with EoLO-HUBs partners, 2024; hereafter referred to as Pers. Com., 2024). Similar strategies in scrap metal recycling demonstrate notable revenue potential [79].

3.1.2. Recycling

After dismantling (and storage, if applicable), WTB materials are typically sent to **Mechanical Reclaimer** facilities, where crushing, shredding, milling, and grinding and sorting reduce material size for recovery [6,72]. Shredding yields materials from a few mm to cm, while grinding produces powders (hundreds of μm to mm) [11], and sorting separates sizes or extract specific materials like metals [80]. **Mechanical Reclaimers** recover powder, granular or fibre-rich fractions, which are either used directly or processed into pellets and 3D fillers for product manufacturing [10,17,81]. This function links to **Mechanical Upcyclers,** who use this materials to produce new end-products such as rackets, snowboards, paddles [82], grapevine trellises [83] and highway noise barriers [84]. Mechanical Reclaimers can also serve as a pre-processing step for **pyrolysis, solvolysis, and biological recycling**, optimising material properties for downstream processes [16].

Pyrolysis recyclers apply thermal degradation (300–1000 °C) in oxygen-free conditions to break down polymer matrices, producing gases, pyrolytic oils, and char, while recovering GFRP and CFRP for reuse [6,10,72,81]. Recovered fibres can be reintegrated into new composite applications, although their mechanical properties may degrade due to high temperatures [17]. Oils serve as chemical feedstocks, and gases can fuel the process itself, enhancing sustainability [11,16]. Microwave and fluidised bed techniques improve heat distribution and reduce char formation [72].

Solvolysis recyclers use solvents, heat, and sometimes pressure to break down the polymer matrix of composites, recovering fibres and liquid depolymerised resin [10,11,16]. Depending on temperature (above or below 200 °C) and solvent type, the process can be high-temperature (operating under supercritical conditions, where the solvent behaves as both a liquid and a gas enabling rapid mass transfer and improved solubility) or low-temperature (dissolution, where the solvent acts both as a reaction medium and as a reagent, facilitating chemical bond cleavage in polymer substrates, making it energetically less intense) [14]. Reactive solvents like water, alcohols, glycol, acids, or ammonia (often near or below 100 °C), yield clean fibres free of residual resin [72,81]. Solvolysis enables monomer recovery for repolymerisation, supporting chemical circularity [14]. Efficiency can be improved via vapor [85], microwave-assisted [86] or super critical fluid techniques [17].

Biological recycles use microorganisms (e.g. bacteria, fungi, or enzymes) in slurry form to degrade polymeric materials from WTB and other composites [72]. The process recovers high-quality GFRP and CFRP with minimal length reduction, which could be used as raw materials in sectors like aerospace [87]. While biomaterials enhance circularity, this approach remains at an early stage and requires further validation (Pers. Com., 2024).

3.1.3. Upgrading

Fibres Upgraders bridge the gap between fibre recovery and market-ready products by improving the quality of secondary materials from pyrolysis and solvolysis [16] using techniques such as wet-laid forming and thermoplastic extrusion to produce advanced nonwoven and long fibre thermoplastics [71]. This CSBM, absent from existing literature, was developed based on insights from the EoLO-HUBs project [71].

Table 1
Description of the CSBM typologies, case examples and their environmental and social impacts. Acronyms: WTB – Wind Turbine Blade, GFRP – Glass Fibre Reinforced Polymers, rGF – recycled Glass Fibre, PLA – Polylactic Acid, GHG – greenhouse gas.

CSBM typology	Description	Business case examples
Dismantler	Value is created by dismantling and downsizing WTBs using mechanically driven technologies (e.g. cranes, jaw cutters, diamond saws and wire cutters, handheld saws, hydraulic cutters and water jet cutters) to facilitate transport and recycling [10,88]. This process reduces blade volume for transporting and processing, with section size depending on blade type, site conditions, transport mode, and downstream requirements [16,81,88]. Value is captured through decommissioning fees and the sale of processed materials to recyclers (Pers. Com., 2024).	Ventos Metodicos [83] and Jansen Recycling Group [79] provide WTB dismantling services.
Mechanical Reclaimer	Value is created through cutting, shredding, milling and grinding WTBs to reduce size and separate resin and fibres for reuse [81]. Value is captured by selling reclaimed fibre-rich fractions, granulates as-is [10] or processed products such as pellets [89] and 3D fillers [80].	Rahimizadeh et al. (2019) [80], developed a three-stage recycling process (grinding, sorting and 3D filament extrusion) to produce PLA filaments with 5 % rGF. Extreme Eco Solutions [90] supplies fillers, replacing virgin materials like chalk and GFRP. Regen Fiber [91] produces %100 recycled fibre additive sourced from decommissioned WTBs and virgin scrap from new blade manufacturing, for concrete and asphalt.
Mechanical Upcycler	Value is created by manufacturing products from mechanically recycled feedstock [82–84,92]. Value is captured through the sale of sustainable end-products to a wide range of industries such as sports, energy, mobility, electronics, construction and furniture [82,83,92]. Recycling by-products, such as powders, fillers, and metals, are sold as feedstock or reused in beams, gardening parts, and construction materials [83].	Fairmat [89] produces recycled CFRP chips for sheets, laminates, plates, panels. MILJØSKÆRM [84] recycles the GFRP from WTB into noise barrier products.
Integrator	Value is created by managing the full WTB-EoL process, from dismantling to manufacturing new products. Value is captured by reducing costs through vertical integration [93].	Continuum Composite Recycling [94]: Oversees the full EoL WTB lifecycle from collection to end-products. Veolia [89] manages WTB dismantling, mechanical recycling, and cement production using GE Renewable Energy WTBs. Ventos Metódicos [83] is specialised in waste management (dismantling, sectioning, WTB transport, WTB repurposing into furniture). The resulting waste is molded with resin or binders and reintegrated into applications (e.g. beams, gardening components, construction materials).
Storage solutions	Value is created by offering storage for decommissioned or processed WTBs to preserve their recycling potential. Value is captured through storage fees and selling materials when higher-value reuse opportunities arise (Pers. Com., 2024).	Jansen Recycling Group [79] owns a quayside storage facility for decommissioned offshore WTBs and recovered materials, preserving their reuse and recycling potential until higher-value opportunities arise.
Logistic provider	Value is created by transporting decommissioned WTBs and processed materials between stakeholders, optimising logistics for recycling and reuse. Value is captured through specialised transportation fees and contract-based logistics (Pers. Com., 2024).	Lubbers Logistics Group [95] offers specialised transport solutions for decommissioned WTB. Tecnorenova [96] offers Logistics Solution, implementing a Pack and Stack model for transporting WTB.
Pyrolysis Recycler	Value is created by recovering high-quality GFRP, CFRP and energy by-products (e.g. gases and oils from decomposed polymer resins) through controlled heating in a regulated atmosphere [5,10,81]. Value is captured through the sale of reclaimed fibres and recovered chemical products [11]. Pyrolysis gas can also be reused as a heat source within the process, reducing waste and operational costs (Pers. Com., 2024).	Bcircular [97] applies R3FIBER pyrolysis technology and a post-treatment cleaning phase to recover high-quality GFRP and CFRP from WTB, free of resins, along with fuels and syngas for cogeneration. Carbon Rivers [98] recovers 99.9 % pure rGF from WTBs for 3D filaments and composites for next-generation WTB employing pyrolysis. Waste2Fiber [99] will launch a patented low-temperature pyrolysis plant (10,000 t/y) in Navarra by 2026. Gjenkraft [100] tests small-scale pyrolysis to recover fibres and oil and gas fractions from epoxy resins in the REFRESH project (2023–2026).
Solvolysis Recycler	Value is created by chemically breaking WTB composites to recover high-quality GFRP and CFRP, valuable chemicals and resin monomers [10,11,16]. Value is captured by selling reclaimed fibres to composite manufacturing, such as automotive, aerospace, and construction [100–103] and reclaimed chemicals to various industries (Pers. Com., 2024).	CETEC project (2021–2024) [104], breaks down polymer chains into reusable molecular building blocks for high-quality new epoxy production. EuReComp project (2022–2026) [101], develops advanced chemical-assisted and plasma-enhanced solvolysis. EROS project (2022–2023) [103], combines solvolysis and pyrolysis for GFRP and CFRP recovery from WTB and aerospace composites. CIRCE's [100] applies microwave-assisted solvothermal processes to recover GFRP and resin monomers while preserving up to 90 % of the fibres' mechanical properties in the REFRESH project (2023–2026). Note: No commercial solvolysis of WTBs to date [11].
Biological Recycling	Value is created by using microorganisms in slurry (bacteria, fungi, and/or enzymes) to degrade polymeric matrices and recover high-quality GFRP and CFRP with minimal length reduction [72]. Value is captured through the sale of reclaimed fibres to high-value applications [87].	Rebiowind (2023–2024) [87] uses microorganisms to degrade polymer matrices while preserving fibre integrity. Note: No commercial solvolysis of WTBs to date
Fibres Upgrader	Value is created by enhancing the quality of recycled fibers and by-products for industrial use, e.g. improving mechanical properties, maintaining fibre length, purifying gases, oils, and resins, etc. Value is captured by selling upgraded fibres to end users in industries such as automotive and construction (Pers. Com., 2024).	The EoLO-HUBs project (2023–2026) [71], transforms recycled fibres into organosheets and thermoplastic pellets via wet-laid forming and extrusion.
Circular Sourcing	Value is created by procuring reclaimed fibres to replace virgin materials in new composites. Value is captured through improved sustainability credentials, regulatory compliance, and market expansion [105].	The DeremCo project (2022–2024) [105] integrates reclaimed WTB fibres into automotive, construction, and textile products (e.g. lighting frames, WTBs, fences, motorhome shelves, ski binding rails, and technical fabrics).

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Table 1 (*continued*)

CSBM typology	Description	Business case examples
		The EoLO-HUBs project (2023–2026) [70] explores the integration of reclaimed GFRP and CFRP from WTB into automotive and construction sectors.
Tech Solutions	Value is created by developing recycling technologies and equipment for WTB-EoL management. Value is captured through the sale, licensing, and consultancy, training, and technical support services related to these technologies (Pers. Com., 2024).	AITIIP [106], Moses [107], TNO [108], NCC [109], MTC [110] and Fraunhofer [111] develop technologies for non-destructive inspection, cutting, shredding, sorting, green solvolysis, and upgrading within EoLO-HUBs (2023–2026) [71].
Equipment Manufacturers	Value is created by producing technology efficiency WTB material processing and recycling [112]. Value is captured through equipment sales, service contracts, technology licensing, and consultancy services [113–117]. It also secures grants and subsidies for R&D projects, further enhancing their financial sustainability and innovation capacity.	SSI Shredding Systems [114] manufactures shredders for WTB processing. Eco-Wolf Inc [115] produces grinders and fibre integration systems (e.g. ECO-Grinder™ and the ECO-Dispensing Macerator™). ReFiber Aps (2002) [113] commercialises gasification and pyrolysis technologies for insulation. Conenor [117] licenses patented GFRP reinforcement technology for thermoplastics. Makeen Power [116] provides pyrolysis solutions for plastic waste.
Blade Manufacturers	Value is created by producing advanced WTB with enhanced recyclability and performance [21,118–120]. Value is captured through WTBs sales, long-term service contracts, and integration of circular design principles (Pers. Com., 2024).	Nordex [21], LM Wind Power [120], Siemens Gamesa [119], Vestas [118], General Electric [121] and Goldwind [122] adopt circular strategies via recyclable blade design, material reuse, and EoL collaboration.
Knowledge Hub	Value is created through a digital platform that offers information, stakeholder matchmaking, and access to a comprehensive database of recycling technologies and best practices for WTB-EoL management. Value is captured through enhanced market reputation, increased stakeholder engagement, and support for the sustainable transition of the wind energy sector (Pers. Com., 2024).	The EoLO-HUBs Knowledge Hub [71] is a digital platform that provides matchmaking, a recycling tech database, and CSBM support tools.

3.1.4. Industrial end users

Industrial end users advance WTB-EoL circularity by adopting **Circular Sourcing CSBMs**, integrating high-quality reclaimed fibres into their products. This includes WTB manufacturers [123], enabling full loop closure, and sectors like automotive, construction and textiles [105]. Regulatory frameworks support adoption by reducing compliance risks, enabling incentives, and improving market positioning (Pers. Com., 2024).

3.1.5. Cross-cutting (transversal) CSBMs

Several transversal CSBM are required to support the WTB-EoL value chain, including Tech solutions, Equipment manufacturers, WTB manufacturers, Logistic Providers, Integrators, and Knowledge platforms.

Tech Solutions, often led by Technology centres, develop innovations for decommissioning, recycling, and upgrading, typically at medium-to-high TRLs, while **Equipment Manufacturers** commercialise or license these technologies to scale operations. **WTB Manufacturers** increasingly support WTB-EoL research and blade redesign, especially as EPR schemes evolve.

Logistic Providers ensure efficient material flow across the WTB-EoL chain, handling the transport of blades and recovered materials. Due to size and complexity, specialised logistics reduce costs, optimise routes, and ensure regulatory compliance [16] (Pers. Com., 2024).

Integrators optimise the value chain by covering multiple stages—from dismantling to commercialising products from rGF and rCF. In mechanical recycling, companies often combine CSBMs—such as Mechanical Reclaimers and Upcyclers—spanning multiple value chain stages [e.g. 89,93,94].

Finally, an emerging and increasingly relevant CSBM is the **Knowledge Platform**, which supports stakeholders across the value chain by promoting circular practices, enabling knowledge transfer, and fostering collaboration. It provides tools and guidance to align technological, economic, and policy efforts for cohesive WTB-EoL progress.

3.1.6. Sustainability aspects related to the CSBM typologies

The potential sustainability impacts (Table 2) of the identified CSBM typologies along the WTB-EoL value chain highlights a wide range of environmental and social benefits as well as trade-offs. Detailed information is presented in Section S6 and specifically Table S22 of the SF.

From an environmental perspective, many CSBMs contribute to diverting WTBs from landfills, reducing the use of virgin materials, lowering GHG emissions, and promoting circular resource flows [10,65]. This is particularly evident in CSBM such as the Dismantler, Mechanical Reclaimer, Upcycler, Pyrolysis and Solvolysis Recyclers, Fibre Upgrader, and Circular Sourcing, which promote on-site recycling solutions to minimise transport emissions and support material recovery, reuse, and sustainable product development [83,89,105]. In parallel, Logistics Providers, Storage Solutions, and Integrators improve resource efficiency by facilitating material flow, minimising transport emissions, and consolidating materials for optimal recycling (Pers. Com., 2024). Technological enablers, such as Tech Solutions Developers, Equipment Manufacturers, and Blade Manufacturers further enhance the environmental potential by enabling cleaner recycling, material traceability, and design for circularity (Pers. Com., 2024).

Socially, CSBMs such as Biological Recycling, Fibre Upgraders, Solvolysis, and Pyrolysis Recyclers can contribute to job creation, green skills development, and innovation ecosystems. Although the net job creation potential of these CSBMs should be further investigated. Additionally, Knowledge Hubs, Tech Developers, and Circular Sourcing promote SME participation, community engagement, and alignment with policy frameworks [Pers. Com., 2024].

Nevertheless, these CSBMs also present trade-offs. For instance, energy consumption in mechanical, thermal, and upgrading processes is significant [Pers. Com., 2024], and pollutant emissions from pyrolysis (e.g., SO_2, NO_x, hydrogen halides) remain a concern [124]. Hazardous solvents used in chemical recycling require strict safety measures [71], while the environmental footprint of manufacturing recycling technologies and associated occupational health risks must also be addressed (Pers. Com., 2024). Other social trade-offs include market resistance to recycled materials, limited infrastructure access for smaller recyclers, and complexity in managing fully integrated value chains. Finally, digital enablers such as the Knowledge Hub introduce risks related to energy use, e-waste, and data security, along with social inequalities tied to the digital divide (Pers. Com., 2024).

3.2. CI patterns for the WTB-EoL management

Table 3 presents 29 CI that embed circular economy principles into WTB-EoL management, improving the sustainability of identified CSBM typologies throughout the value chain. Each CI is defined by a characteristic name, a brief description, and relevant examples of how they are applied in practice, drawn from empirical findings, or adapted from BM pattern literature. Of the 29 CI identified, 17 are industry-specific to the wind energy sector, with 8 derived exclusively from empirical data (literature and interviews) and 9 aligning with both empirical data and existing CSBM patterns in the literature. Additionally, 12 CIs were identified as potential solutions based on pre-existing CI patterns [i.e. 23,27,33,57,64,93,125].

The CI are classified by impact level (Table 3): 4 at the product level (P1–P4), focusing on design improvements and material recovery; 13 downstream BM innovations (BMU5–BMU12), influencing value proposition and delivery; 8 upstream BM innovations (BMD13–BMD25), impacting value creation processes; and 4 at the value chain level (VC26–VC29).

The ranking of the CI conducted during the EoLO-HUBs workshop with partners, along with its statistical analysis, is presented in Table S23 and Table S24 of the SF, respectively, and it provides insights into the perceived impact and feasibility of different CI in the WTB-EoL value chain. The mean score (3.68) and median score (3.7) indicate that most CI were rated as moderately to highly relevant, with a notable spread in scores ranging from 2.7 (lowest score of the bottom quartile) to 4.5 (highest score of the top quartile). The standard deviation (0.43) suggests moderate variation in stakeholder opinions, with strong consensus around the highest-ranked CI.

The top quartile of the CI ranking (≥4.1 out of 5) includes “BMU7. Waste as an Input” (4.5), “BMD13. Ensuring Transparency and Traceability” (4.3), “VC27. Vertical Integration” (4.2), “BMU6. Fostering Collaboration” (4.2), “P1. Blades Ecodesign” (4.1), “P3. Efficient On-Site Recycling Solutions” (4.1), and “BMU8. Reducing Pollution” (4.1), indicating broad agreement among stakeholders on the importance of these innovations.

The highest-rated CI, “BMU7. Waste as an Input”, suggests that value chain actors recognise the importance of using waste as a resource to optimise WTB-EoL circularity. This aligns with key objectives of the EoLO-HUBs project [71], which emphasize recirculating process outputs (e.g. water, abrasive, chemical building blocks, pyrolysis gas) to minimise material consumption and energy use, thereby enhancing sustainability and efficiency (Table 2). “BMD13. Ensuring Transparency and Traceability” (4.3) and “VC27. Vertical Integration” (4.2), also emerged as essential enablers for sustainable WTB-EoL management, reflecting the growing demand for supply chain visibility and process control. Participants stressed the need for data transparency throughout the lifecycle, including the implementation of material passports and digital tools—such as blockchain—to ensure access to key material information (e.g. structural, chemical, environmental) from the manufacturing stage to end-of-life.

The bottom quartile (≤3.4 out of 5) includes “BMD24. Next life sales” (3), “BMU12. On demand” (3) and “BMU10. Asset management” (2,7), likely reflecting scalability and industry adoption constraints (Table S9a). The overall distribution of scores, with a moderate standard deviation and no extreme outliers, reinforces that stakeholders broadly agreed on the most impactful innovations while acknowledging uncertainties in implementation feasibility. These findings underscore the need to prioritise highly ranked innovations while further exploring barriers to adoption for lower-ranked strategies.

4. CSBM innovation roadmap for the wind industry

Fig. 3 outlines the CSBM innovation roadmap across three timeframes: 2025, 2025–2030, and 2030–2035, highlighting drivers and barriers, business opportunities, and required resources and competences for regional deployment.

4.1. 2025: persistent barriers and limited circularity

4.1.1. Drivers and barriers

By 2025, WTB-EoL remains fragmented, with **landfilling** as the default cost-effective option [16,66,70]. Lack of **harmonised EU regulations** facilitates cross-border movement of decommissioned WTBs, as companies seek less restrictive regulatory environments (Pers. Com., 2024). Policy volatility, regional disparities, and low public pressure further hinder coordinated industry action [16,19,66,70].

Technological barriers persist. The **absence of design for recycling** limits recovery efficiency and increases disposal costs and processing complexity (Pers. Com., 2024). **WTB material complexity,** including reinforced fibres, epoxy resigns, balsa wood, foams, coatings and metals, complicates separation and reinforces EU dependency on virgin materials [16,19,66,70]. **Poor WTB traceability and data availability** hamper standardisation, especially with mixed flows of recyclable and legacy blades. Conflicting strategies (recycling, reuse, repurposing) create uncertainty in circular planning (Pers. Com., 2024).

Market constraints are significant. **Inconsistent and unpredictable WTB waste volumes** prevent economies of scale and deter investment in recycling infrastructure [16,66,70]. **Immature supply chains** and **high transportation costs** hinder logistics, while **recycling processes and recyclates remain expensive** and uncompetitive. In the **absence of financial incentives** and mandatory targets, disposal prevails [19]. **Incumbent BMs resist circularity** due to perceived risk and low short-term returns (Pers. Com., 2024).

4.1.2. Business opportunities

Dismantlers and Integrator CSBMs offer **turnkey solutions (VC27)** for dismantling, recycling, and disposal, creating new revenue streams and better logistics (Pers. Com., 2024). **Joint ventures** among operators, recyclers, and decommissioners foster **collaborative BMs (BMU6, BMD16)** and cross-sectoral collaboration.

Early investment in scalable recycling technologies is a strategic priority [19], aligning with offshore wind’s shift toward ecodesign and lifecycle analysis [67,70]. Offering flexible material outputs increases recyclers’ ability to serve diverse sectors like construction and automotive (Pers. Com., 2024). Enabler CI include **blade ecodesign (P1)**, **integrating advanced technologies (P2)**, **efficient on-site recycling solutions (P3)**, **avoiding dust at the wind farm (P4)** and **reducing pollution (BMU8)**.

Harmonised policies and voluntary guidelines begin to shape circular norms. WTB life extension and improved recycling enhance resource use (Pers. Com., 2024). **Certification and standard-setting bodies** emerge to assess sustainability across the supply chain.

4.1.3. Resources and competences

A circular vision requires an **industry roadmap** to define roles and coordinate services (Pers. Com., 2024). Key resources include **Horizon Europe** funding, knowledge platforms—requiring **digital and open-access capabilities and infrastructure** and **specialised expertise** —and **EU-wide stakeholder integration** [19,67].

Developing human capital through continuous professional development (CPD) **training in circular decommissioning, systems thinking, collaboration and sustainability** is key.

Table 2
Potential sustainability aspects (positive and/or negative) related to the CSBM typologies [10,65,71,83,87,89,105,124] (Pers. Com., 2024).

CSBM/ Sustainability aspects			Dismantler	Mechanical Reclaimer	Mechanical Upcycler	Integrator	Storage solutions	Logistic provider	Pyrolysis Recycler	Solvolysis Recycler	Biological Recycling	Fibres Upgrader	Circular Sourcing	Tech Solutions	Equipment Manufacturers	Blade Manufacturers	Knowledge platform
Benefits	Environmental	Reduces landfill waste.	x	x	x		x		x	x	x		x				
		Reduced demand for virgin materials, conserving natural resources.		x					x	x	x	x	x				
		Decreases GHG emissions and overall carbon footprint.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
		Resource efficiency.		x	x	x			x	x	x	x	x			x	
		Enables material recovery, reuse, recycling and sustainable product manufacturing.		x	x		x	x	x	x	x	x	x	x	x		
		Use of biomaterials.									x	x					
	Social	Creates job and business opportunities.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Promotes skills upskilling.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Supports regional economies and SME development		x	x		x	x	x	x	x	x	x	x			
	Both	Drives technological innovation and eco-design.		x	x				x	x	x	x	x	x			
		Promotes circular economy.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Promotes energy transition.												x	x	x	x
		Enhances compliance with evolving environmental regulations.											x	x	x	x	x
		Boosts community engagement, knowledge sharing, and circularity awareness.												x			x
Trade-offs	Environmental	Energy consumption, energy-intensive processes.		x	x				x	x							
		Dust, fine particles, and noise pollution.	x	x	x			x	x								
		Emission of pollutants (e.g., SO_2, NO_x, dioxins).							x								
		Use of hazardous solvents.								x							

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Table 2 (*continued*)

CSBM/ Sustainability aspects		Dismantler	Mechanical Reclaimer	Mechanical Upcycler	Integrator	Storage solutions	Logistic provider	Pyrolysis Recycler	Solvolysis Recycler	Biological Recycling	Fibres Upgrader	Circular Sourcing	Tech Solutions	Equipment Manufacturers	Blade Manufacturers	Knowledge platform
	High environmental footprint from processes.							x	x							
	Transportation related emissions.	x				x										
	Material degradation over time.					x										
	Low recyclability of blades.														x	
Social	Human health and safety concerns (dust, noise, chemical exposure).	x	x					x	x				x	x		
	Requirements for specialised operators.	x					x	x	x	x	x		x	x	x	
	Market acceptance barriers.			x							x	x				
	Organisational complexity.					x	x	x	x	x	x	x				
	High infrastructure and investment demands.				x	x	x	x	x	x	x					
	Economic barriers limiting access for smaller actors.	x	x	x	x	x	x	x	x	x	x	x				
	Public infrastructure strain and traffic congestion.					x	x									
Both	Digitalisation impacts (e-waste, privacy risks, digital divide).												x			x

Accurate forecasting of WTB-EoL volumes supports infrastructure planning and investment alignment, while deploying **specialised equipment and physical infrastructure**—cranes, vessels, scanners, shredders, dust control, and storage space—is critical to scale efficient, safe WTB-EoL operations (Pers. Com., 2024).

Institutional support is also vital. **Policymaking champions and lobbyists** can drive regulatory change, while engaging **investors, industry associations and public influencers** fosters acceptance, reduces innovation risks and support early CSBM adoption.

4.2. 2025–2030: regulatory shifts and emerging circular solutions

4.2.1. Drivers and barriers

Between 2025 and 2030, better policy, regulatory, and financial incentives could accelerate circularity in WTB-EoL [19,68,70]. Stricter **waste management policies** and **Extended Producer Responsibility (EPR)** may hold blade manufacturers responsible for WTB-EoL, driving demand for recyclable designs [69]. EU-wide circularity policies, including **eco-design standards** promoting recyclable resins and modular blades, could reinforce this transition [68]. Harmonised regulations may improve planning and reduce policy uncertainty, though the lack of a dedicated **waste code for WTB-EoL** and composites still hampers classification and compliance (Pers. Com., 2024).

Financial incentives will be key to supporting CSBMs, lowering entry barriers and encouraging private investment in dismantling, recycling, repurposing, and upgrading. **Recycled material standardisation** can strengthen secondary market integration across sectors like construction and automotive (Pers. Com., 2024).

Large-scale demonstration projects can validate innovations and recover high-value materials like GFRP and CFRP [19,68]. **Material passports (MPs), data sharing and digital traceability solutions** can improve tracking, classification and recycling consistency [19,66,69,70].

However, recycling is still costlier than landfill, and the geographical dispersion of actors, coupled with supply chain inefficiencies, limits infrastructure scaling and raises transport emissions [70] (Pers. Com., 2024).

4.2.2. Business opportunities

Opportunities emerge in **commercialising reclaimed fibres and recycled materials** and **scaling advanced recycling infrastructure**. Selling recycled composites to sectors like construction, automotive, and consumer goods opens high-value markets and strengthens sustainability credentials [19,66,69,70]. **Scaling lab-to-industrial recycling processes** is critical. Large demonstration facilities will help validate emerging technologies [19,67,69], with Spain poised to lead EoL services as ~22 GW of renewable capacity nears decommissioning by 2030 [67].

Mechanical recycling, with TRL 7–9, is the most viable, offering energy efficiency and scalability despite reduced fibre quality [6,10,17,65,80]. **Pyrolysis** (TRL 7), allows CFRP and GFRP recovery but needs post-treatment to remove residual char and restore fibre quality [18]. rCF retain mechanical performance, while rGF lose over 50 %, limiting reuse and economic viability [11]. rCF has strong market potential (EUR 50 million in 2022), whereas rGF still faces technical and cost barriers. **Solvolysis** (TRL 3–6), especially for CFRP, offers high recovery with low degradation, but lacks commercial facilities and faces solvent and scaling challenges [11]. **Biological recycling** is emerging but still under validation [87]. A flexible, multi-path strategy, advancing pyrolysis and solvolysis pilots, scaling mechanical recycling, and exploring bio-based alternatives (Pers. Com., 2024), could be supported by **semi-decentralised networks (VC28).**

Reusing (BMD23) and **Repurposing (BMD25)** decommissioned WTB in bridges, buildings, noise barriers offer a low-carbon, resource-efficient alternative [10]. **Storage solutions** enable WTB recycling when infrastructure becomes available but requires timely flow and commercialisation to avoid degradation, while **Supplier diversification (BMU5)** can stabilise input flows and support downstream operations (Pers. Com., 2024).

Digital innovation tools, such as **computer-aided design (CAD)**, **product circularity platforms (PCPs), material passports, and digital twins,** can simulate dismantling, support lifecycle integration, and improve traceability and coordination [70] (Pers. Com., 2024). **Secure data management systems (e.g. BMD13)** enable real-time tracking, predictive analytics, stakeholder alignment, and IP protection.

4.2.3. Resources and competences

Resources and competences shift toward scaling circular capabilities. Priorities include infrastructure, standardisation, and collaboration for WTB-EoL management.

Establishing **Knowledge platforms** is key to centralising efforts among industry, research, recyclers, and policymakers. These hubs foster innovation, support **standardisation of emerging technologies** and promote best practice exchange (Pers. Com., 2024).

Decommissioning services will expand, supported by **reskilling professionals from adjacent industries** (e.g. oil and gas), while regional recycling hubs will require **skilled chemical engineers** to define reactor configurations and operating parameters, particularly for chemical recycling solutions.

Open access to recycling technologies remains vital for smaller actors. **Dedicated storage facilities** for decommissioned WTBs will buffer reuse or delayed recycling. Digital capabilities, like real-time monitoring, predictive analytics, and traceability (Section 3.3.2.2), are essential, requiring **skilled software developers and data professionals** [19,66,69].

Cross-sectoral collaboration will intensify via a European platform linking recycling industries with downstream sectors in energy, construction, and automotive. This could support joint innovation, practice harmonisation, and international alignment [19,69]. Finally, sustained **investment in scaling recycling technologies** is vital to compete with virgin inputs and reinforce the circular business case.

4.3. 2030–2035: market maturity and circular standardisation

4.3.1. Drivers and barriers

Beyond 2030, circular practices are expected to be firmly embedded in the wind energy sector, supported by mature recycling infrastructure, strong policies, and financial incentives such as subsidies and bonuses [70]. Regulatory frameworks like the **European Green Deal and EU sustainability goals** will continue driving resource efficiency, carbon neutrality, and circular WTB-EoL solutions [69] (Pers. Com., 2024). **Full implementation of EPR** schemes will be key, holding blade manufacturers accountable for material recovery and enabling closed-loop systems [69].

Cross-industry standards could enhance market integration, allowing WTB materials to be reused across sectors under aligned regulations (Pers. Com., 2024). Recognising **waste as a new resource** and responding to raw **material scarcity** will further incentivise CSBMs (Pers. Com., 2024).

Market dynamics may favour **early entrants** of advanced recovery technologies, offering competitive advantages and new revenue streams (Pers. Com., 2024). Research and innovation opportunities are likely to grow, though economic viability and investment risk may persist (Pers. Com., 2024). A more **mature WTB-EoL ecosystem**—with stable material flows and quality-controlled recyclates—will be essential to reduce landfill dependency and advance circularity [16,19,69,70].

Transparent data-sharing mechanisms and **standardised evaluation metrics** will improve decision-making, comparability, and trust in recycling options [19,69]. Increased availability of data on blade composition, geometry, and quality will support better evaluation of EoL methods. **Future blade designs** are expected to incorporate features for decommissioning, reprocessing, and monitoring. However,

Table 3
Circular innovations (CI) to enhance the WTB-EoL value chain. Each CI is codified to indicate whether it belongs to the product level (P), business model upstream level (BMU), business model downstream level (BMD) or value chain level (VC). Acronyms: WTB - wind turbine blade, AI - artificial intelligence, EPR - extended producer responsibility, BAT: best available technologies, KPI: key performance indicators, IP: intellectual property, LCA: life cycle analysis.

Circular innovation	Description	Industry-specific examples	Pre-existing patterns
P1. Blades ecodesign	New WTB materials and designs (e.g. thermoplastics, biodegradable) ease recycling and reduce environmental impact.	Vestas [104]: WTB production with recycled content. RecyclableBlade [123] ecodesigns WTBs using new resin via solvolysis.	Product design [57]
P2. Integrating Advanced Technologies	Integrating robotics and AI in recycling boosts efficiency, cuts costs, improves material quality, and enhances worker safety. Advanced shredding and sorting increase purity and value while reducing energy use and on-site risks.	Fairmat [82]: Applies IA/robotics for CFRP cutting and recycling. EoLO-HUBs [71]: Develops a mobile tool with a robot arm for slicing, inspection, water jet cutting and de-coating, operable autonomously.	
P3. Efficient on-site recycling solutions	Mobile cutting/shredding units at wind farms lower transport needs and carbon emissions.	SSI Shredding Systems [114], EcoBlade [126]: offer mobile shredders for on-site WTB processing, reducing transport, emissions, and costs, while recovering scrap value (~€50/ton) [126]. EoLO-HUBs [71]: Automates blade decommissioning with portable cutting and decoating, reducing pre-treatment time by 50 %, dismantling costs by 10 %/MW, WTB-EoL waste by 70 %, cutting time by 40 %, and transport-related GHG emissions by up to 87 %.	
P4. Avoiding dust at the wind farm	Mobile solutions with dust and particulate capture ensure cleaner, more efficient recycling. Air-treatment or truck-mounted systems prevent emissions from WTB cutting, improving environmental and operational performance.	EoLO-HUBs [71]: Truck-mounted WTB cutter with dust containment to prevent site contamination (Factory-in-a-Box). Ventos Metodicos [83]: Sawmill truck with automatic waste suction for reuse. REFRESH [100]: Transportable shredder with integrated air-treatment for dust capture. ANMET [127]: Uses a frame saw with fogging and dust capture to reduce particle dispersion; closed water circuits in plants improve recycling and lower environmental impact.	
BMU5. Suppliers' diversification	Engaging multiple sectors diversifies composite waste feedstock, strengthens supply chains, and cuts dependency.	Vestas [89]: Mechanically recycles WTBs in closed collaboration with wind farm operators and the construction industry construction to use waste as raw material input.	Collaborative value creation [125]
BMU6. Fostering Collaboration	Strengthening value chain partnerships enhances recycling through innovation, streamlined processes, and resource efficiency, building a resilient and adaptable ecosystem.	Decomblades [88] and Life + Brio [128]: Apply cross-sector collaboration (recyclers, government agencies, industrial firms) to develop recycling solutions using rGF.	Collaborative approaches [23], collaborative value creation [125]
BMU7. Waste as an input	Using waste as feedstock reduces virgin material use and environmental impact, capturing value through cost savings, lower disposal fees, and upcycled product revenue.	EoLO-HUBs [71]: Uses waste in several forms including 1) water/abrasive recirculation from waterjet cutting, 2) revalorisation of chemicals from blade decoating, and 3) pyrolysis gas recovery for energy. Carbon Rivers' [98]: Produces ESG pyrolysis crude oil as sustainable fuel or precursor for next-gen polymers, supporting circularity in oil and chemical industries.	Circular supplies [125].
BMU8. Reducing pollution	Reducing pollution through cleaner processes, better waste management, and emission controls ensures regulatory compliance, cost savings and a stronger sustainability reputation.	EoLO-HUBs [69]: Factory-in-a-Box concept.	Cleaner production and eco-efficiency [27].
BMU9. Renewable energy	Integrating renewables into energy infrastructure powers operations sustainably, lowering costs, emissions, and enabling access to incentives and subsidies.	Jansen Recycling Group [79]: Uses self-generated renewable energy to reduce reliance on non-renewables.	Circular supplies [27], substitute with renewables and natural processes [23], prosumer [64].
BMU10. Asset management	Optimising companies' own assets (e.g. ICT, vehicles) through pooling, sharing, reuse, refurbishment, or resale to reduce costs.	ABB Wind Retrofit packages, PowerCone® Retrofit or SG Energy Trust Solution [20]	Asset management [27].
BMU11. Industrial Symbiosis	Uses residual outputs from one process as inputs for another, leveraging proximity to reduce supply costs.	No example found within the industry	Industrial Symbiosis [27]
BMU12. On demand	Producing only after confirmed demand avoids overproduction, reduces waste, and captures cost savings.	Business as Usual practice within the WT manufacturing sector	On demand [27]
BMD13. Ensuring transparency and traceability	Providing stakeholders with material and recycling data via WTB scanning, digital tracking, and material passports enhances accountability, optimises recycling, ensures compliance, and strengthens stakeholder trust.	Veolia's integral digital management system [89]: Ensures end-to-end recycling monitoring, boosting confidence in their methods. EoLO-HUBS [71] and LM Wind Power [120]: Use Material Passports for blade traceability, optimising processes like water jet cutting [71]. TNO's UWiSE software [129]: Provides KPI analysis, enhancing visibility and accountability. Life + Brio [128]: Publishes BATs and recycling guidelines to optimise processes based on blade.	

(*continued on next page*)

Table 3 (*continued*)

Circular innovation	Description	Industry-specific examples	Pre-existing patterns
BMD14. Sustainability reporting	Enhancing transparency and accountability by sharing insights on recycling and impact reduction. Identifying cost-saving opportunities through material recovery improves efficiency and reputation. LCA supports compliance and guides sustainable decision-making.	Several cases [84,87,101,105,130] show how LCA helps assess environmental impacts, optimise processes, and enhance transparency by sharing findings, promoting best practices, and supporting WTB-EoL sustainability.	
BMD15. Product diversification	Diversifying offerings from recycling and recyclates enables entry into multiple markets and increases revenue. Maximising material use reduces waste and fosters innovation. Segmented, targeted marketing (e.g. separate websites) supports circular strategies in WTB EoL, including repurposing, recycling, and end-product sales.	Ventos Metodicos [83]: Markets furniture and products under a separate brand from its recycling operations. Tecnorenova [96]: Segments blade collection/recycling and product sales/repurposing, each with a dedicated website for target customers.	
BMD16. Customer engagement	Involving customers early in technology and process development helps identify technical obstacles and meet specifications. Partner visits bridge knowledge gaps, ensuring alignment and effective collaboration.	Deremco [105] and EoLO-HUBs [69]: Actively involve end users in defining specifications and testing recycling systems to ensure alignment and optimise performance.	Collaborative value creation [76].
BMD17. Customisation	Tailoring products and processes to customer requirements and environmental standards promotes flexibility, resource efficiency and waste reduction.	SSI Shredding Systems [114]: Develops tailored shredding systems to enhance productivity and reduce environmental impact. Fairmat [82]: Utilises smart technologies like robotics for bespoke manufacturing solutions. Continuum Composite Recycling [94]: Produces panels with up to 92 % reclaimed materials, offering custom finishing options. MTB [131]: Provides customised recycling solutions based on preliminary on-site studies. Lubbers Logistics Group [95]: Offers customised transport with specialised trailers, route planning, and multi-modal logistics to cut costs and emissions.	Mass customisation [93].
BMD18. Access model	Offering temporary access (e.g. equipment and space rental) instead of ownership enables continuous revenue generation.	SSI Shredding Systems [114]: offers a rental service for their shredding machines.	Access model [27].
BMD19. Performance model	Providing agreed functionality or performance instead of product ownership enables continuous revenue generation.	No example yet found within the WT and WTB industry	Performance or result model [27] (LP).
BMD20. Collection and reprocessing of used products	Cooperation across the value chain helps close material loops, enabling new revenue streams or cost savings.	EoLO-HUBS [71]: Dismantlers and recyclers collaborate across the production value chain to close material loops in WTB recycling. Take-back schemes combined with EPR policies, where manufacturers retain ownership of WTBs and offer recycling services [19].	Collection, take back, and reprocessing of used products [27].
BMD21. Lifetime products	Durable, repairable high-end products and support premium pricing strategies.		Lifetime products [27].
BMD22. Premium products with life extension services	Products paired with life extension services (e.g. repair, upgrades) enable recurring revenues, including full-service offerings with procurement and stock-holding.	Services usually offered by WT manufacturers and/or third parties	Premium products with life extension services [27]
BMD23. Second-hand markets	Second-hand markets for used goods reduce waste and idle assets; reuse may involve repair or be offered free or resold.	Wind turbine global marketplace and used wind turbines for sale [20]	Direct reuse [27].
BMD24. Next life sales	Incentivising returns of used items enables refurbishment and remanufacturing, allowing resale and additional revenue from second users.	Solvento comprehensive restoration of WTs [20]	Next life sales [27].
BMD25. Repurposing	Incentivising returns of used items enables producers to reuse or reprocess parts for new applications, reducing material costs and supporting alternative uses beyond original functions.	Re-Wind Design Atlas to repurpose WTB into multiple products [20]	Repurposing [27].
VC26. Specialist	Companies focusing on a single value-adding step across industries benefit from economies of scale, efficiency, and quality through specialised expertise.	Standard practices already applied in the industry	Layer player [93].
VC27. Vertical integration	Companies managing multiple value-adding steps—from collection and recycling to manufacturing—gain efficiency, economies of scope, lower costs, and greater value creation stability.	Veolia WTB recycling [89]: Manages WTB recycling from dismantling to cement co-processing. MTB [131]: Provides turnkey, "all in one" services from design to production and integration of recycling equipment.	
VC28. Semi-Decentralised Networks	Strategically located facilities for WTB collection, dismantling, recycling, and repurposing reduce transport, improve efficiency, and support local circularity by processing waste near its origin.	The big portal for wind energy [20]	Semi-Decentralised Networks [33].
VC29. WTB-EoL spin-offs	Creating WTB-EoL spin-offs leverages IP and research to build specialised businesses, foster public-private collaboration, commercialise innovations, and expand markets, generating jobs and economic growth from technological advances.	Bcircular [97]: Spin-off from CENIM [132] leveraging IP and expanding markets through public-private collaboration.	

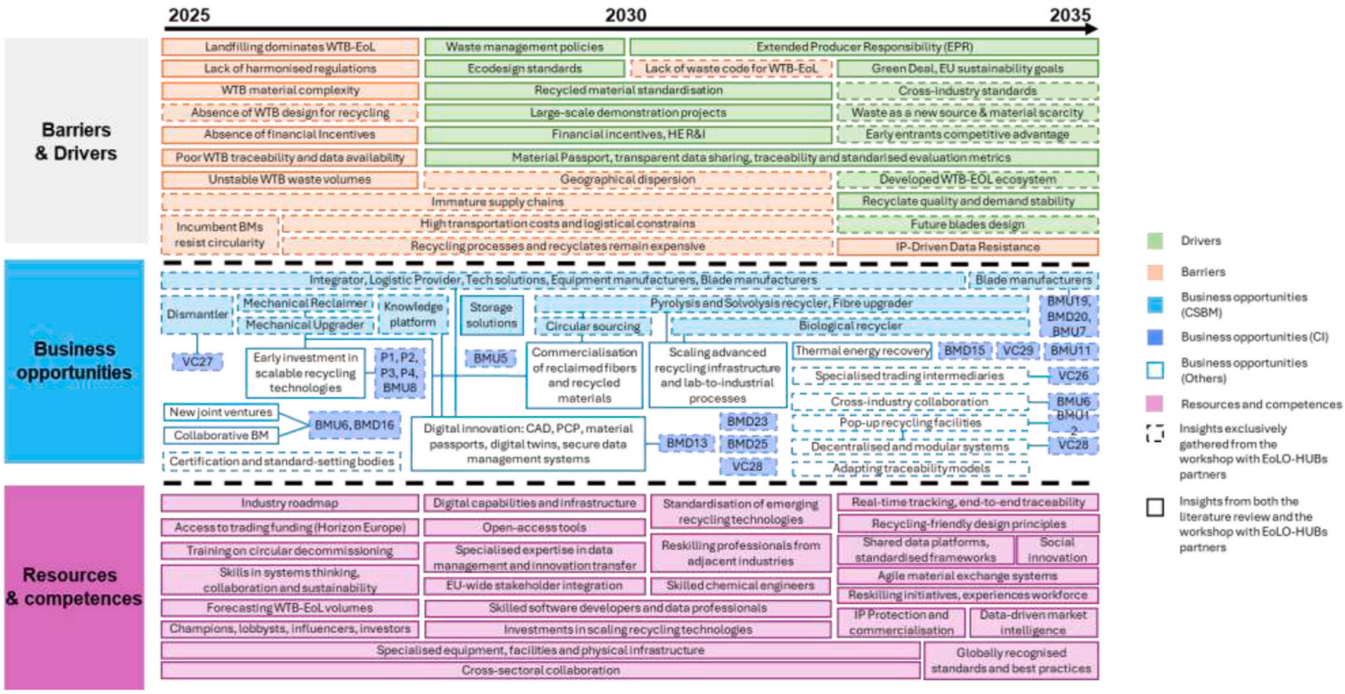

Fig. 3. CSBM innovation roadmap for the wind industry. Acronyms: BM – Business Model, WTB – Wind Turbine Blade, P – Product level circular innovation, BMD – Business Model (Downstream) level circular innovation, BMU – Business Model (Upstream) level circular innovation, VC – Value Chain level circular innovation.

data-sharing resistance may remain due to intellectual property (IP) concerns [70].

4.3.2. Business opportunities

A mature circular ecosystem for WTB EoL is expected, supported by advanced infrastructure, recycling technologies, and established circular value chains [19,66,69]. This maturity will unlock diverse business opportunities integrating innovation, resource efficiency, and cross-sector collaboration.

Thermal energy recovery from polymeric components via controlled incineration can generate energy for industry and reduce waste from non-recyclable materials. As solvolysis and pyrolysis technologies advance, new CSBM may emerge through **product diversification (BMD15)** and **WTB-EoL spin-offs (VC29)**, enabling IP commercialisation and cross-sector technology transfer from, for example, **Tech Solution** providers.

Specialised trading intermediaries (VC26) for niche recycled materials can improve market uptake, inspired by models like the UK's National Industrial Symbiosis Programme (NISP) [133]. These platforms enhance material flow, reduce logistics costs, and support **industrial symbiosis (BMU11)** by connecting producers and users across sectors.

Cross-industry collaboration (BMU6) (e.g. boating, automotive, and aerospace sectors) offers potential to aggregate material volumes, optimise processes, and develop shared quality standards. **Blade manufacturers** could diversify their CSBM by integrating **product-as-a-service models** such as **performance models (BMD19)** where manufacturers retain ownership of blades throughout their lifecycle and manage EoL logistics directly, and closed-loop material flows, in which high-value recovered fibres are reintegrated into new blade manufacturing, eliminating dependency on landfilling and virgin raw materials through **collection and reprocessing of used products (BMD20)** and using **waste as an input (BMU7).**

On-demand production (BMU12) and **"pop-up" recycling facilities** and **decentralised and modular systems (VC28)** near decommissioning sites can boost responsiveness and cut logistics costs [69]. Lastly, **adapting traceability models** from sectors like organic food could improve composite material tracking, quality assurance, and compliance with circular standards (Pers. Com., 2024).

4.3.3. Resources and competences

Resources and competences evolve to consolidate a mature, efficient, and socially accepted circular ecosystem for WTB-EoL management.

A critical enabler is the widespread adoption of material passports, documenting WTB origin, composition, and recyclability. Combined **real-time tracking and end-to-end traceability** and paired with **recycling-friendly design principles**, they reduce processing costs and improve dismantling outcomes (Pers. Com., 2024).

Continued European collaboration will be vital to harmonize regulations and accelerate innovation. **Shared data platforms and standardised design frameworks** will support cross-country alignment and reinforce Europe's leadership in composite circularity (Pers. Com., 2024).

To process increasing blade volumes, **regional recycling hubs**—equipped with cranes, shredders, vessels, and storage—will become fully operational. **Reskilling initiatives** must transition **into stable systems, integrating** professionals from sectors such as oil and gas to build an **experienced workforce** (Pers. Com., 2024).

Agile material exchange systems, inspired by the UK's NISP [133], will improve resource allocation through **real-time matching** of waste streams and material users, lowering storage and logistics costs.

However, while the roadmap provides robust guidance, any long-term strategy will inevitably encounter unforeseen elements, many being cultural. According to Sovacool and Griffiths' lens on culture and low-carbon energy transitions [134], culture comprises the norms, everyday practices, and material artifacts that can either catalyse or constrain low-carbon transitions. Therefore, beyond technological innovation and CSBM development, fostering a genuine circularity culture is essential for the roadmap's success. This requires a fundamental shift in three main areas.

i) changing norms and values, so that EoL-WTBs are universally viewed as valuable resources, and circular responsibility is fostered over conventional waste management practices,

ii) embedding new practices into the daily business routines of all stakeholders, from engineers incorporating eco-design principles to consumers actively choosing products with recycled content, and
iii) creating new material artifacts that become desirable symbols of this new circular culture.

In this context, the role of social innovation becomes crucial to maintain public support. Humanists, designers, and artists can act as critical facilitators, helping to shape the narratives and aesthetics that connect the technical and economical circularity goals to broader cultural values, making the new practices aspirational and the new artifacts meaningful. Without this deep cultural integration, even the most detailed business roadmap risks failing to inspire the collective action required for the deployment of a truly circular ecosystem.Finally, adopting **globally recognised standards and best practices** will ensure quality, support international collaboration, and encourage consistent uptake of circular solutions. Coupled with **data-driven market intelligence**, these standards can help firms respond to evolving demands and **monetise IP** linked to advanced recycling technologies, such as solvolysis or pyrolysis, as they expand into new markets [19,69].

These results indicate that advancing WTB circularity is not only about material and technology innovation, but also about embedding systemic enablers that align business incentives across the value chain. In line with the broader circular economy literature [23,25], stakeholders acknowledged business models (section 3.1) and innovations (section 3.2) that facilitate resources recirculation through information traceability across the value chain. When potential customers lack information regarding a WTB's origin and service history (e.g., manufacturing batch, material composition, repairs performed, etc) or the quality of recovered fiber (e.g. recyclates), they hesitate to invest. In light of this, traceability through digital product passports coupled with processes standardisation and certification can mitigate this barrier. Thus, the success of WTB-EoL strategies will depend on coupling technical-economical feasibility with mechanisms that foster transparency, trust, and collaboration across industrial ecosystems.

The WTB-EoL management roadmap also resonates with recent debates in the circular economy literature that emphasize the role of business models as transition vehicles rather than add-ons to technology deployment [20,26,35]. By mapping short-, medium-, and long-term pathways, the roadmap moves beyond technology readiness to consider policy, market, and social enablers. For example, using material passports and setting up local or regional recycling hubs shows that digital tools coupled with the need to keeping activities closed together help circular systems to grow. This alignment reinforces that WTB circularity can serve as a testbed for wider CE principles, where multi-level coordination, policy frameworks, cross-sectoral industrial symbiosis, and stakeholder engagement, becomes indispensable for systemic impact.

Taken together, the CBMS and CI ranking results and roadmap suggest three priorities to improve WTB circularity. First, value creation must be retained within the system through eco-design and closed-loop material systems, thereby reducing dependency on virgin resources. Second, enabling infrastructures, such as regional recycling hubs and digital traceability platforms, are required to lower transaction costs and build trust among actors. Third, social and institutional innovations, including EPR and cross-industry collaboration platforms, should complement technological advances to ensure adoption at scale. These insights reinforce broader CE arguments that achieving circularity requires simultaneous progress on technological, business, and governance dimensions [20,24].

5. Conclusions

This paper presented a comprehensive roadmap for developing and upscaling circular and sustainable business models (CSBMs) driven by the implementation of circular innovations (CI) in the wind energy sector, specifically targeting the end-of-life (EoL) management of wind turbine blades (WTBs).

By characterising 15 CSBM typologies and 29 CI patterns across the WTB-EoL value chain, the study offers strategic framework and guidance to support the transition from linear waste production pathways to circular and sustainable value-generating systems. It helps to shift the debate from a traditional and narrowed approach focused on (for example) *"which WTB recycling technology is best?"* to a more strategic and systemic perspective focused on *"How do we build a viable, self-sustaining business ecosystem that can turn blade waste into sustainable value?"*.

As outlined in the 2025 phase of the roadmap, currently, there are a number of barriers available that re-enforce each other, creating a systemic lock-in. For example, the lack of harmonised regulations and clear policy incentives, creates industrial uncertainty, which discourages private investment in advanced WTB-EoL management infrastructure. As a result, supply chains remain immature and logistics are expensive. This, in turn, reinforces landfilling (in some places) or other low-quality solutions (such as mechanical recycling over thermal and/or chemical recycling) as the most economically short-term option, which further suppresses the market signals needed to drive policy change and business investment.

However, whereas the analysed CSBMs offer viable alternatives to the current linear business models, creating new pathways for sustainable value management, the examined CIs provide specific guidance to make these models efficient and competitive. In turn, the roadmap offers a blueprint for coordinated action among a diverse set of stakeholders to sequentially dismantle key barriers.

The findings demonstrate that, there is consensus on the need for a multi-pathway strategy combining technology development, market facilitation, and regulatory alignment. Key innovations such as vertical integration, waste as an input, blade ecodesign and digital tools for transparency and traceability are seen as critical to unlocking circularity at scale.

However, transitioning towards a sustainable WTB-EoL system demands more than just technological innovation. Cross-sectoral collaboration, stakeholder engagement, and institutional support are fundamental enablers. Knowledge platforms, circular training programmes, reskilling from adjacent sectors (e.g., oil and gas), and expanded regional recycling hubs must be prioritised to consolidate infrastructure, talent, and innovation capacity.

Importantly, the roadmap identifies distinct priorities for 2025 (persistent barriers and limited circularity), 2025–2030 (regulatory shifts and emerging circular solutions), and 2030–2035 (market maturity and circular standardisation). This temporal layering helps align industrial strategies with evolving regulatory, market, and technological contexts.

More specifically, a number of additional key recommendations for short-term implementation can be drawn.

- Industry: i) s**ecure WTB waste volume and quality by** signing multi-year offtake agreements and pre-specifying recycled fibre quality for target applications to drive demand for recyclates, ii) c**ut cost at source by** deploying **on-site, dust-controlled and efficient scanning, cutting and shredding** equipment to reduce logistic requirements, iii) encourage business experimentation by **p**iloting **vertical integration** or close partnerships between dismantlers – recyclers – upgraders - end users to reduce risks and ensure the achievement of collaborative business goals.

- Policymakers, and standardisation bodies: i) analyse the possibility implement Extended Producer Responsibility (EPR) schemes across the EU to shift the financial and operational responsibility for EoL management to WTB producers, creating a powerful market pull for design-for-circularity and recycling, ii) normalise circular procurement (e.g. tender criteria) and demand mandatory adoption of digital material passports for WTBs, ensuring transparency and traceability, while providing recyclers with critical data on material composition, iii) harmonize permitting and create targeted financial incentives, such as tax credits, or subsidies, to de-risk private investment in the deployment of regional recycling hubs and advanced recycling facilities.
- Researchers: i) develop detailed techno-economic models and life cycle assessment studies to guide policy development, industrial innovation and investment toward the most sustainable outcomes, ii) develop in-depth, longitudinal empirical case studies to track the evolution, implementation challenges, and performance of CBMS for WTB-EoL management over time to improve the systems performance, iii) Integrate digital twins, artificial intelligence and predictive analytics into WTB-EoL operations to improve efficiency and success.

Regarding the limitations of the research, although a comprehensive literature review was performed, the research was supported with the development of 15 expert interviews and one multi-stakeholder workshop (24 participants). Although experts from different parts of the value chain were involved, the sample can be considered small and not representative of the entire global WTB value chain, including experts from different world regions, company sizes and roles. Also, as experts can share their own views and groups can influence answers, some bias could have influenced the end results. Consequently, the research findings are indicative rather than prescriptive and should be validated with assessments and expert consultations in other geographical regions. To partially address these limitations, a Fuzzy Cognitive Map (FCM) built from these insights could be applied to further explore causal assumptions and enable scenario/sensitivity checks.

Finally, expanding the analysis to other sectors dealing with composite waste streams (e.g. aerospace, automobile, maritime, construction) could foster industrial symbiosis and circular value chain adoption.

CRediT author statement

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI's ChatGPT as a writing assistant to support the refinement of language and structure during the preparation of this manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.116382.

Data availability

No data was used for the research described in the article.

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