

Review

End-of-Life Strategies for Wind Turbines: Blade Recycling, Second-Life Applications, and Circular Economy Integration

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Abstract

Wind power is integral to the transformation of energy systems towards sustainability. However, the increasing number of wind turbines approaching the end of their service life presents significant challenges in terms of waste management and environmental sustainability. Rotor blades, typically composed of thermoset polymer composites reinforced with glass or carbon fibres, are particularly problematic due to their low recyclability and complex material structure. The aim of this article is to provide a system-level review of current end-of-life strategies for wind turbine components, with particular emphasis on blade recycling and decision-oriented comparison, and its integration into circular economy frameworks. The paper explores three main pathways: operational life extension through predictive maintenance and design optimisation; upcycling and second-life applications; and advanced recycling techniques, including mechanical, thermal, and chemical methods, and reports qualitative/quantitative indicators together with an indicative Technology Readiness Level (TRL). Recent innovations, such as solvolysis, microwave-assisted pyrolysis, and supercritical fluid treatment, offer promising recovery rates but face technological and economic as well as environmental compliance limitations. In parallel, the review considers deployment maturity and economics, including an indicative mapping of cost and deployment status to support decision-making. Simultaneously, reuse applications in the construction and infrastructure sectors—such as concrete additives or repurposed structural elements—demonstrate viable low-energy alternatives to full material recovery, although regulatory barriers remain. The study also highlights the importance of systemic approaches, including Extended Producer Responsibility (EPR), Digital Product Passports and EU-aligned policy/finance instruments, and cross-sectoral collaboration. These instruments are essential for enhancing material traceability and fostering industrial symbiosis. In conclusion, there is no universal solution for wind turbine blade recycling. Effective integration of circular principles will require tailored strategies, interdisciplinary research, and bankable policy support. Addressing these challenges is crucial for minimising the environmental footprint of the wind energy sector.

Keywords: wind turbine; waste processing; blade recycling; component durability; end-of-life management; circular economy



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1. Introduction

To mitigate global environmental degradation and reduce dependency on fossil fuels, the development of renewable energy sources continues to accelerate. Among them, wind power remains one of the most rapidly expanding sectors, with a global installed capacity of 907 GW recorded in 2022 which is expected to reach over 2000 GW by 2030 [1]. According to the International Energy Agency (IEA), global wind energy production in 2022 reached 2100 TWh, which is 265 TWh more than in 2021 [2]. Wind turbines can operate under a wide range of wind conditions and are continuously evolving in design, size, and material complexity. Modern wind farms often integrate advanced monitoring and control systems to optimise performance. However, these technological improvements do not eliminate the eventual need for end-of-life management of ageing turbines.

Development trends vary between onshore and offshore sectors. Onshore wind energy, as a mature and economically accessible technology, dominates current installations, while offshore wind farms are gaining traction due to their larger scale and higher energy yields. Despite these benefits, the decommissioning of wind farms introduces environmental and logistical challenges. When turbines are decommissioned, the disposal of composite materials—particularly wind turbine blades (WTBs)—presents a significant obstacle in achieving sustainable energy goals [3]. Blades are primarily composed of glass fibre-reinforced polymer (GFRP), thermosetting resins, and fillers, which form complex, durable structures that are resistant to degradation. This durability, though essential during operation, becomes problematic during waste treatment and recycling processes.

Not all components of the blades contain the same type of polymer matrix. The specific selection of materials depends on the location and function of the blade section, with options including polyester, epoxy, vinyl ester, and epoxy modified with polyurethane acrylates [4,5]. In general, glass fibre is the predominant reinforcement material in commercial blades, consisting of silica, alumina, calcium oxides, and other additives in varied proportions [6]. These material combinations increase strength but hinder recyclability. Compared to metals such as steel and copper—readily recyclable with established technologies—composite materials remain a significant technical barrier [7]. According to some estimates, 80–90% of wind turbine mass is currently recyclable, particularly in older models such as the Vestas V52 [8]. However, complete blade recycling remains difficult and is not yet widely practised.

Estimates indicate that between 325 and 495 kilotonnes of wind turbine waste could be generated globally by 2050, primarily from composite blade materials [9]. Currently, a significant proportion of decommissioned blades are sent to landfills, due to limited viable alternatives for material recovery. This trend highlights the urgency of developing efficient and scalable recycling methods. In line with European Union (EU) policy objectives, the circular economy model prioritises the recovery and reuse of materials, thereby minimising landfill disposal [10]. It also aligns with the targets outlined in the European Green Deal and the United Nations Sustainable Development Goals. Addressing end-of-life management of turbine components is, therefore, essential in reducing the environmental footprint of wind energy systems.

Traditional municipal recycling techniques are poorly suited to the treatment of reinforced polymer composites. These limitations have prompted researchers to explore alternative recycling routes, such as thermal, chemical, and mechanical methods. Some approaches aim to extract fibre or resin fractions, while others focus on repurposing whole blade segments into structural or infrastructural elements [11–13]. The development of new, easily degradable biocomposites is also under investigation, with the goal of facilitating future recyclability [14]. In parallel, efforts are being made to extend the operational life of turbines, for example, by reducing component failure through improved reliability assess-

ments. Managing long-term mechanical stress, including heat accumulation in generators, is another key factor in prolonging service life and delaying decommissioning [15].

Figure 1 presents a system-level view of the wind turbine lifecycle, integrating material recovery strategies—including reuse, remanufacturing, and recycling—within a structured, lifecycle-oriented framework.

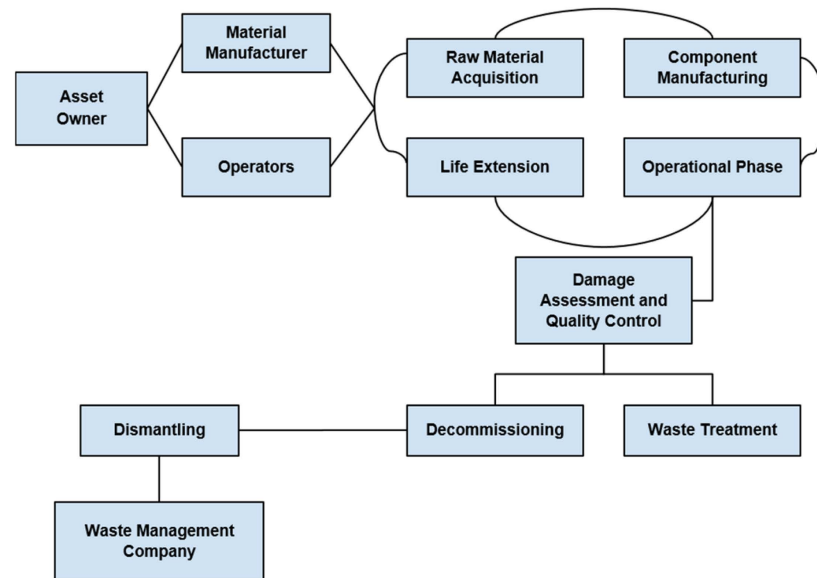


Figure 1. Life cycle of a wind turbine with integrated material management strategies for reuse, remanufacturing, and recycling; author’s own elaboration, based on [16].

This diagram synthesises the turbine lifecycle from a systems engineering perspective, mapping sequential stages—material extraction, manufacturing, installation, operation, and decommissioning—alongside potential intervention points for circular economy strategies. It highlights how early design and operational decisions influence the technical and economic feasibility of end-of-life recovery pathways. The figure reinforces the article’s premise that effective circularity in wind energy requires coordinated lifecycle planning, involving both technological solutions and stakeholder integration, rather than isolated end-of-life measures. Recent studies have demonstrated that recycled wind turbine blades (RWTBs) can serve as additives in concrete mixes [17]. For example, a portion of ground GFRP powder can be used to replace fly ash or other components in cementitious composites, with minimal reduction in mechanical performance. Although complete substitution is not yet feasible, partial incorporation of blade waste has shown promise in increasing density and reducing porosity. Other research avenues include incorporating blade materials into asphalt mixtures, cement, or prefabricated construction elements. These solutions demonstrate the potential for partial recovery, though their widespread adoption remains limited by technical and regulatory barriers.

However, significant innovation has occurred in the wind energy sector; projections suggest that current efforts may fall short of achieving long-term climate neutrality [18]. To meet future energy and environmental goals, end-of-life strategies for wind turbines must prioritise material recovery, waste minimisation, and circularity.

This review aims to provide a comprehensive overview of current approaches to the end-of-life management of wind turbine components. It is distinguished by a systems-level approach that integrates technological, economic, and regulatory perspectives, clarifying interdependencies and conditions for implementation. Its novelty lies in coupling the appraisal of technical options with bankability conditions and public policy levers, thereby identifying pathways scalable under real market regulatory constraints. The review also

structures the field by specifying when solutions can be credibly implemented and scaled within the prevailing context. In addition, it provides a comparative qualitative and quantitative assessment of methods for processing waste from wind turbine blades—covering functional characteristics and limitations, key technical and performance indicators, and economic metrics alongside financing considerations.

2. Search and Selection Strategy

The literature base was compiled through a multi-database search (Scopus, Web of Science Core Collection, ScienceDirect, and Google Scholar), complemented by targeted hand-searching of key journals and institutional sources. The time window spanned 2012–2025, with a final search update on 20 September 2025; earlier, field-defining studies were retained where relevant. Within this window, records are predominantly from 2023 to 2025, with a smaller share from 2012 to 2022.

Search strings combined the object of study with end-of-life pathways and policy and economic terms. Representative Boolean queries were

- (“wind turbine” OR “wind-turbine” OR WTB) AND (blade* OR composite*) AND (recycl* OR “end-of-life” OR EoL OR repurpos* OR “life extension” OR pyrolys* OR solvolys* OR “mechanical recycling” OR supercritical OR “fluidis* bed”)
- (circular* OR “circular economy” OR EPR OR “extended producer responsibility” OR “Digital Product Passport*” OR “green public procurement” OR “end-of-waste”)

Spelling and hyphenation variants (e.g., ‘fluidised/fluidized’, ‘wind-turbine/wind turbine’) were included. Backward (reference-list) and forward (citation) snowballing was applied from key publications.

Inclusion criteria. (i) Peer-reviewed articles, conference papers, or authoritative institutional/standards reports addressing end-of-life management of wind turbine components (with emphasis on blade composites); (ii) a substantive contribution to at least one of the following: processing technologies, technical/performance indicators, economic/market aspects or regulatory/policy context; (iii) publications in English; (iv) publication year 2012–2025.

Exclusion criteria. (i) Studies not specific to turbine blade composites; (ii) opinion-only pieces without method or data; (iii) duplicates; (iv) unavailable full text.

Screening proceeded in two stages. Title/abstract screening removed clearly irrelevant records. Full-text screening then applied the inclusion/exclusion rules and extracted variables aligned with the review’s comparative lenses: (1) qualitative characteristics and limitations of each route; (2) quantitative technical/performance indicators (e.g., fibre yield, process energy, indicative material quality); (3) economic metrics and financing/policy instruments. Duplicates were identified and removed using the Mendeley reference manager, and records were maintained consistently across databases to avoid double counting. To mitigate selection bias, multiple databases were queried with explicit Boolean strings, snowballing was applied consistently, and inclusion/exclusion rules were standardised prior to full-text screening. As a result, the evidence base is weighted towards the most recent years, reflecting the acceleration of blade-recycling pilots and the evolution of EU policy instruments over 2012–2025.

To capture the economic and financing dimensions, a complementary search was conducted under the same protocol, targeting finance- and policy-related terminology (e.g., “cost per tonne” OR CPT, gate fee, offtake, “recycled content certificate”, “green public procurement”, eco-modulation, EPR, “project finance”, “scale-up finance”, “carbon contracts for difference”, “industrial decarbonisation fund(s)”). Results from this complementary search were integrated up to 20 September 2025.

These procedures provide a transparent and reproducible foundation for the synthesis presented in this review. They enhance comparability across heterogeneous studies and reduce selection bias, thereby increasing the robustness of the findings. For transparency, the full Boolean strings and screening rules are available on request.

3. Strategies and Methods for Managing End-of-Life Wind Turbine Components

In response to the growing challenge of managing end-of-life wind turbine components, the literature offers a range of strategies aimed at extending the service life of turbines, repurposing decommissioned parts, and developing efficient material processing methods. This section presents a structured overview of the most significant approaches. First, it discusses strategies focused on prolonging the operational lifespan of wind turbine components through design optimisation, maintenance practices, and technological upgrades. Subsequently, the concept of upcycling and second-life applications is explored as a means of reusing components without energy-intensive processing. Finally, various mechanical, thermal, and chemical processing methods are reviewed with respect to their effectiveness in material recovery and alignment with circular economy principles.

3.1. *Methods for Extending the Service Life*

It should be noted that each of the recycling methods discussed is associated with certain limitations. Therefore, extending the service life of large-scale wind turbines (DDWTs—Direct-Drive Wind Turbines with permanent magnets (PMs)) is considered the most beneficial and environmentally sound alternative for managing end-of-life turbines [18].

The operational efficiency of wind turbines can be enhanced, *inter alia*, through the appropriate modelling of blades to ensure their optimal adjustment to local wind conditions. Research aimed at improving performance is conducted for both horizontal-axis and vertical-axis wind turbines [19]. One such example includes experimental investigations on the use of Savonius turbines in urban environments, which demonstrated that higher outlet velocities improve energy conversion by increasing torque. Furthermore, changes in the blade and end-plate geometry were found to significantly affect overall efficiency [20].

In an effort to predict the degradation of key turbine components, Yu et al. (2025) employed deep learning models to develop a system capable of forecasting component wear based on operational data [21]. Meanwhile, Tartt et al. (2024) analysed turbine bearing temperatures and demonstrated that the expected service life can be estimated using data obtained from SCADA (Supervisory Control and Data Acquisition) systems [22]. Key parameters include power output, rotor speed, nacelle temperature, and the temperatures of selected components. Long-term data collected from a wind farm allow for the comparison of predicted and measured component temperatures, thereby enabling the identification of elements most susceptible to failure. The findings indicated that the generator's rear bearing exhibited the greatest vulnerability, which was evidenced by the largest discrepancy between predicted and actual temperatures. This underscores the importance of accounting for uncertainty in service life forecasting [22].

Bearings, as key tribological components, are designed to reduce friction between interacting surfaces and to permit relative motion between them. In wind turbines, rolling-element bearings are predominant. These comprise an inner and outer raceway, rolling elements (balls or rollers), and a cage [23]. Gbashi et al. (2024) emphasised the importance of academic research on optimising bearing geometry and pointed out that spherical roller bearings have long been the dominant type of main shaft bearing in wind turbines [19]. Nevertheless, they are not without reliability issues. The authors noted that although the causes of their premature failure have been identified to some extent, they remain

insufficiently understood or difficult to eliminate [19]. Alternative solutions may include journal bearings or tapered roller bearings.

Besides optimising individual components, extending the working life of a turbine also requires a comprehensive assessment of its remaining useful life (RUL). Industry guidance observes that a wind turbine consists of many parts with differing statistical lifespans; although machines are normally designed for a 20-year service life, site-specific wind conditions and operational practices often permit safe operation beyond this [24]. Determining the RUL calls for a combination of wind resource data, knowledge of operating practices and maintenance history, and the original design parameters, in order to quantify accumulated fatigue and verify structural integrity. Load simulations and probabilistic assessments of structural health, supported by inspections of the blades, tower and nacelle, as well as SCADA data, help to identify components that require repair or replacement. The International Energy Agency emphasises that life-extension programmes must demonstrate safe feasibility, estimate the cost of potential damage, and lay out an appropriate maintenance plan if profitability is to be maintained. New standards such as DNV-ST-0262 and IEC 61400-28 offer methodologies for fatigue assessment, yet experts note that these can be overly conservative because manufacturers seldom disclose detailed strength margins [25]. To unlock longer lifetimes, recent practice, therefore, includes per-turbine load assessments, full turbulence modelling and smart adaptive control strategies that reduce loads and mitigate unnecessary conservatism.

Overall, extending the service life of wind turbines through blade optimisation and predictive maintenance based on SCADA data is a key strategy for reducing waste, lowering costs, and improving the sustainability of wind energy technologies.

3.2. Upcycling and Second Life

A prevailing issue in the management of end-of-life wind turbine components is the lack of detailed knowledge regarding the planning of a value chain map that encompasses all available technologies and processes, some of which remain at the laboratory stage [26]. The reuse of turbine structures constitutes an innovative recycling strategy for repurposing worn-out rotor blades [27]. Second-life practices often involve the resale of components to other countries. Germany and Denmark account for approximately 50% and 60% of such resales, respectively. Unsold components are stored as spare parts (2.5–4%), with the remainder redirected to alternative waste processing pathways. This approach contributes to the reduction in primary material consumption [27]. However, such practices can provoke negative public perception in recipient countries, such as Poland, occasionally triggering strong opposition to wind energy development.

Empirical evaluations of recycling technologies should consider various scales of industrial application and assess

- anticipated investment and operational costs;
- potential revenues from recycled materials;
- environmental impacts [28].

Although the majority of wind turbine components can be effectively recycled, WTBs are still largely disposed of in landfills. Blades present a particular challenge due to the composite materials used in their production. These composites are extremely difficult to recycle, and the existing technologies are considerably less developed than those used for other materials [29]. Nevertheless, blade segments may be reused in infrastructure, provided that relevant legal criteria are met. Composite materials can be recovered by segmenting the blades using a range of mechanical methods, including cutting with tools or water jetting. In many cases, temporary solutions involve converting blade segments into

urban furniture [30], pedestrian bridges, public installations, or playground components, frequently by means of water jet cutting [31].

The Zero Waste Blade ReArch (ZEBRA) project is a flagship initiative aimed at designing and manufacturing 100% recyclable blades [32]. However, Haszminezhad et al. (2024) argue that the scope of practical applications promoted within such Zero Waste programmes remains limited [33]. While blade fragments may offer adequate pedestrian load-bearing capacity, attention must be paid to their long-term durability. These innovations emerged in 2019 and have seen only six years of use thus far. Consequently, there is a lack of supplementary performance data, and their longevity has not yet been comprehensively assessed. Seasonal variations, which may induce unforeseen degradation of the plastic materials used in these bridge-like structures, have also not been fully investigated. Moreover, the reuse of blade components in urban infrastructure is often inconsistent with professional technical standards and specifications, which diminishes motivation for their wider adoption. Johst et al. (2025) conducted an experiment comparing two WTB samples to assess structural integrity. If the material composition and constructional condition of a blade are verified during repurposing, it could be monitored based on clearly defined failure criteria [34]. Such assessment and monitoring frameworks could serve as feasible industrial approaches, for instance in the construction sector. Another example of utilising blade components without processing is their application in highway signage. According to a study by Ramaswamy et al. (2025) in the United States, a prototype structure spanning 40 feet (12.19 m) incorporated approximately three tonnes of turbine blades [35]. Compared to conventional signs of the same size, this resulted in savings of 4500 pounds (2041.16 kg) of steel and 10 cubic yards (9.14 m³) of concrete, achieving approximately 73% material savings and reducing CO₂ emissions by 242 tonnes.

Considering the above, while upcycling and second-life applications of wind turbine blades offer promising avenues for reducing environmental burdens and conserving resources, their widespread adoption remains constrained by technical, economic, and regulatory challenges. Further interdisciplinary research, performance verification, and standardisation are required to fully integrate these innovative solutions into circular economy frameworks.

3.3. Component Processing Methods

Due to the varying levels of energy sector development across different countries worldwide, forecasts concerning the volume of wind turbine waste also differ. Over the past two decades, several estimates of future waste production have been proposed in the literature. Research conducted by Liu and Barlow (2017) [36] indicates that by 2050 the distribution of wind turbine waste volumes will be as follows: China—40%, Europe—25%, USA—16%, and the rest of the world—19% [36]. Meanwhile, Turkay et al. (2024) project a 25-fold increase in the total capacity of onshore wind farms decommissioned within 20 years, reaching 188 GW, and approximately a 40-fold increase over 25 years, up to 284 GW, compared to the dismantling capacity estimated at 7 GW in 2027 [16]. Germany, Spain, and France hold the largest shares of onshore turbines being decommissioned in Europe. However, it should be emphasised that obtaining more precise data requires providing more detailed information.

In recent years, numerous solutions enabling the recycling of wind turbine components have been proposed, particularly addressing the problematic blades [37]. Compared with other processes, mechanical recycling requires by far the least energy—about 0.17 to 1.93 MJ per kilogram of material processed—but it results in a deterioration in the mechanical properties of the recovered fibres. Pyrolysis consumes more energy (3–30 MJ kg^{−1}) yet yields higher-quality fibres and produces gas and oil fractions from which energy can be

recovered. Chemical recycling is the most energy-intensive ($61\text{--}93\text{ MJ kg}^{-1}$), but it enables the recovery of fibres and monomers of high purity [35]. In thermal treatments, it is also important to consider the calorific value of the materials: most composite constituents have similar energy content, allowing combustion or pyrolysis to recoup some energy, whereas glass fibres have virtually no calorific value [38].

A qualitative comparison of the principal end-of-life processing routes methods includes process outline, key advantages, key limitations, and the indicative Technology Readiness Level (TRL).

The qualitative synthesis in Table 1 complements the energy intensity patterns outlined above: routes differ not only in specific energy demand but also in deployment maturity and the form of value retained. Mechanical recycling and cement co-processing exhibit the highest readiness (TRL 8–9/9); the former prioritises material circularity with comparatively low energy demand, whereas the latter focuses on energy recovery via fuel and raw meal substitution. Thermal options—including conventional pyrolysis and fluidised bed processes—occupy demonstration to early-industrial readiness; they are scalable but require robust emissions control and yield variable fibre quality (particularly for GFRP), while enabling partial energy recovery through gas and oil fractions. By contrast, solvent-based and electrochemical approaches remain at laboratory to pilot stages, offering clean fibre surfaces and resin valorisation potential but facing scale-up, safety, and cost-of-operation constraints. This maturity gradient should be considered alongside the energy ranges reported above when selecting a route for a given feedstock and target product specification.

Table 1. A qualitative comparison of the principal end-of-life processing routes methods (author’s own elaboration).

Waste Processing Method	Technological Process Outline	Key Advantages	Key Limitations	TRL	References
Mechanical recycling	Mechanical recycling typically entails cutting, crushing, and milling of composite materials, often in combination with separation techniques such as air classification, magnetic, electrostatic, and hydro-gravitational sorting. The process is environmentally benign, cost-effective, and readily scalable for industrial application; however, it typically leads to a deterioration in the mechanical properties of the recovered materials.	Environmentally benign; cost-effective; readily scalable; uses established separation/milling operations; rapid throughput.	Loss of continuous fibres; property downgrading of recyclate (powders/flour); suitability depends on end-use specifications.	8–9	[26,30]
Chemical recycling	This method employs chemical reactions to cleave the chemical bonds present within polymer matrices. It encompasses processes such as solvolysis, electrochemical treatments, and supercritical fluid techniques. These approaches facilitate the degradation of cross-linked polymer structures into linear chains or smaller molecules, enabling material recovery and reuse. Although effective, chemical recycling typically demands significant energy input and precise process control to ensure efficiency and environmental compliance.	Depolymerises cross-linked matrices into smaller molecules; enables fibre recovery with higher quality; potential to valorise resin-derived fractions.	Higher energy/operational intensity; solvent/reagent handling; tighter process control and compliance requirements.	4–6	[15,39,40]

Table 1. Cont.

Waste Processing Method	Technological Process Outline	Key Advantages	Key Limitations	TRL	References
Solvolysis	This process involves the use of solvents, often combined with catalysts or additives, to degrade the resin matrix under controlled temperature and pressure conditions. The treatment breaks down the cross-linked polymer network into linear polymer chains, facilitating the recovery of valuable fibre materials. Solvolysis offers a selective and efficient approach to polymer matrix decomposition, enabling improved recyclability of composite materials while maintaining fibre integrity.	Selective matrix degradation; good fibre surface cleanliness; preserves fibre integrity; potential resin-fraction recovery.	Pressurised solvents/catalysts; corrosion/effluent management; scale-up complexity.	4–6	[29,30,41]
Electrochemical method	This process involves the degradation of waste materials within an electrolyte solution through electrochemically assisted catalysis. Specifically, the waste is suspended in a sodium chloride (NaCl) solution containing a potassium hydroxide (KOH) catalyst. The applied electric current facilitates catalytic reactions that degrade the polymer matrix, promoting depolymerisation and enabling the recovery of valuable components. This method offers a controlled and efficient approach to polymer degradation under relatively mild conditions.	Mild conditions; controllable degradation of matrix; prospect of lower thermal damage to fibres.	Early-stage maturity; electrolyte stability/management; limited multi-tonne demonstrations.	3–5	[42]
Supercritical fluid methods	These techniques involve the dissolution and degradation of polymer waste using supercritical or near-supercritical fluids. Various solvents such as water, propanol, potassium phosphate, and diethylene glycol, often combined with catalysts like sodium hydroxide (NaOH), potassium hydroxide (KOH), sulphuric acid, or benzyl alcohol—sometimes applied without catalysts—have been employed to recover fibres. This approach results in fibres with clean, smooth surfaces, and high tensile strength, making it an effective method for reclaiming valuable composite materials while minimising environmental impact.	Very clean, smooth fibre surfaces; high retained fibre strength; short processing times.	High-pressure equipment/safety; energy demand and CAPEX; solvent make-up/recovery.	4–6	[8,21]
Thermal recycling	Thermal recycling involves the treatment of waste through pyrolysis, combustion, or other advanced thermal methods. These processes enable the separation of composite components by breaking down the polymer matrix and releasing the reinforcing fibres. Additionally, thermal recycling can recover energy in the form of heat generated during combustion or pyrolysis, contributing to resource efficiency and waste valorisation.	Separates fibre/matrix thermally; enables energy recovery; industrial thermal know-how transferable.	Fibre degradation risk (esp. GFRP); off-gas/emissions control needed; residue removal.	6–8	[43–45]

Table 1. Cont.

Waste Processing Method	Technological Process Outline	Key Advantages	Key Limitations	TRL	References
Pyrolysis	Pyrolysis of wind turbine blade components is typically conducted at temperatures around 600 °C, where thermal decomposition of the resin matrix occurs. This process breaks down the polymeric resin within the composite material, effectively separating the reinforcing fibres while minimising damage to their mechanical properties. Pyrolysis thus enables the recovery of valuable fibres and reduces the volume of composite waste, offering an efficient and sustainable recycling pathway.	Efficient matrix removal; good retention for CFRP fibres; valuable gas/oil co-products.	GFRP fibre property loss; fibre cleaning/post-treatment; tight atmosphere/temperature control.	6–8	[32,46–48]
Fluidised-bed process (thermal pyrolysis variant)	Shredded composite waste is introduced into a fluidised bed of quartz sand and heated to c. 450 °C. Hot air causes thermal decomposition of the polymer matrix. Decomposition products and released fibres are carried by the gas flow and separated in a cyclone; remaining polymer residues are burnt off in an afterburner. The process enables recovery of carbon fibres but is unsuitable for glass fibre composites.	Continuous operation; effective resin removal; suitable for CFRP fibre recovery.	Generally unsuitable for GFRP; media/particle handling; cyclone/afterburner complexity.	5–7	[31,49]
Microwave-assisted pyrolysis	Microwave-assisted pyrolysis operates at lower temperatures compared to conventional pyrolysis, which significantly reduces thermal degradation of fibre-reinforced composite materials. This milder thermal regime better preserves the recovered fibres' mechanical performance, positioning microwave pyrolysis as a promising route for recycling composite waste with improved material quality and efficiency.	Lower bulk temperature; shorter cycles; reduced thermal damage to fibres vs. conventional pyrolysis.	Scale-up and field uniformity; need for susceptors/absorbers; process controllability at scale.	4–6	[15,50]
Combustion	Combustion involves the co-processing of shredded turbine blade materials mixed with other waste streams or co-fired alongside coal in energy recovery facilities. This method enables the recovery of energy content from composite waste, but it typically results in the complete destruction of the composite structure, preventing material reuse. Combustion processes must be carefully managed to control emissions and comply with environmental regulations, ensuring sustainable waste-to-energy conversion.	Highest industrial readiness; full energy recovery; substitution of fuel/raw meal in cement kilns.	No material recovery of fibres; emissions permitting and quality control of clinker feed required.	9	[11,14,16,33]

TRL (EC 1–9): 1–2 concept; 3–4 laboratory/proof-of-concept; 5–6 pilot/demonstrator; 7–8 demonstration/early-commercial; 9 commercial. Note: Key statements summarise the qualitative descriptors in Table 1; quantitative economic figures are intentionally omitted here to avoid duplication with subsequent tables.

To support method selection and process design, Table 2 collates quantitative indicators—fibre yield, energy demand, indicative cost level, and material quality—enabling a like-for-like appraisal of performance trade-offs across routes.

Table 2. Quantitative performance indicators for recycling routes of wind turbine blade composites (authors' own elaboration).

Waste Processing Method	Fibre Yield	Energy Consumption (MJ/kg)	Cost	Material Quality	References
Mechanical recycling	(no continuous fibres; powder product)	0.17–1.93	Low	Low (powder; reduced properties)	[9,31,32,41,50]
Chemical recycling	High (>90%)	61–93	High	Very high (near-virgin fibres; clean surface)	[39–41]
Solvolysis	High (>90%)	NR	High	Very high (clean fibres; monomer recovery possible)	[1,11,41]
Electrochemical method	NR	NR	Medium–high	High (reported case-wise)	[32,41]
Supercritical fluid methods	High (>90%)	NR	High	Very high (smooth, clean fibres)	[8,32,41]
Thermal recycling	Carbon fibre composites: 75.8–77.5%; glass fibre composites: negligible (combustion reported separately)	3–30	Medium–high	Carbon fibre composites: medium–high (properties partly retained); glass fibre composites: low (significant strength loss)	[11,44]
Pyrolysis	75.8–77.5% fibres; gas ≤ 12.9%; oil 8.8–18.7%	3–30	Medium–high	Carbon fibre composites: medium–high; glass fibre composites: low	[43,46,47,51]
Fluidised-bed process (thermal pyrolysis variant)	Carbon fibre composites: fibre recovery feasible; glass fibre composites: unsuitable	NR (operates ~450 °C)	Medium	Carbon fibre composites: medium; glass fibre composites: not applicable	[31,50]
Microwave-assisted pyrolysis	NR (reported comparable to conventional pyrolysis)	NR (trend: lower than conventional)	Medium–high	High (reduced thermal damage)	[15]
Combustion	0% (no fibre recovery)	n/a (net energy recovery)	Low–medium	None (material destroyed)	[11,44]

Across all routes, the principal trade-off concerns energy demand versus the performance and quality of the recovered material. Energy values are reported as $\text{MJ} \cdot \text{kg}^{-1}$ of composite processed (process energy only, where specified); fibre yield is defined as the recovered fibre mass fraction relative to the composite's fibre content; the indicative cost level (relative) reflects an order-of-magnitude view of process economics (CAPEX/OPEX) derived from comparative studies; and material quality is classified as low/medium/high based on the retention of mechanical properties and surface cleanliness (see Table 2). Where datasets are insufficiently harmonised to support a defensible range, entries are marked NR (no robust range reported).

Consistent with these definitions, mechanical recycling exhibits the lowest energy demand ($0.17\text{--}1.93 \text{ MJ} \cdot \text{kg}^{-1}$) and the most favourable relative cost level, while downcycling fibres into powders with limited structural performance. Chemical pathways (including solvolysis and supercritical treatments) deliver near-virgin fibre quality at the expense of higher energy demand and capital intensity, whereas pyrolysis occupies an intermediate position, enabling partial retention of fibre properties alongside oil/gas co-products. Interpretation should be read alongside the indicative TRL reported in Table 1, as maturity and scale-up readiness influence achievable material quality, operational risk, and integration into existing infrastructure. In practice, the preferred option is contingent on fibre type (carbon versus glass), matrix chemistry, plant scale, and the carbon intensity of electricity; moreover, emissions abatement for thermal routes and solvent recovery/effluent treatment for liquid-phase routes can materially shift apparent energy–cost trade-offs. Future studies should report abatement energy and quality benchmarks alongside yield to enable like-for-like comparisons across routes.

It is also important to add, for the sake of a balanced comparison and regulatory compliance, that environmental emissions are intrinsic to non-mechanical routes and must be considered alongside the performance indicators discussed (see Table 2). Specifically, during the processing of blade composites, off-gases and condensable organics are generated, with compositions governed by resin chemistry, fibre type, fillers, and temperature–time profiles. In pyrolysis and related thermochemical treatments, gaseous streams may contain CO/CO₂, light hydrocarbons and volatile/semi-volatile phenolics, and other volatile organic compounds (VOCs); liquid fractions (condensates) are typically phenol-rich oils with dissolved oxygenates, while solid residues comprise recovered fibres and char [44,51]. Combustion/co-processing destroys the polymer matrix but can form regulated pollutants if abatement is inadequate. Accordingly, compliant operation requires integrated air pollution control systems tailored to the route employed [44]. These include primary condensers and knock-out pots for oil recovery; cyclones/filters (including high-efficiency particulate air filtration) for particulate capture; wet or dry scrubbers and catalytic/thermal oxidisers for VOC and acid gas removal; and—where applicable—selective catalytic or non-catalytic reduction for NO_x [44,51]. Energy recovery from hot off-gases and oils should be implemented to reduce net process demand and improve overall environmental performance. In fluidised bed variants, afterburners are typically used to oxidise residual polymer fragments prior to discharge and should be designed together with appropriate particulate and acid-gas control to maintain compliance. In solvolysis, effluent management is required (closed-loop solvent handling and wastewater treatment) to ensure compliance with environmental regulations and to avoid secondary impacts [41]. On this basis, the controls should be regarded as integral process elements—necessary for permitting, influential for lifecycle performance—and reported together with yield, energy, and cost metrics to enable a robust comparison of routes.

Returning to the analysis of available technologies, the literature indicates that variants such as the fluidised bed process and conventional pyrolysis are generally unsuitable for glass fibre composites, whereas carbon fibres exhibit greater recycling potential [50]. Details of the fluidised bed variant of pyrolysis are summarised in Table 1; this method uses a quartz sand bed at around 450 °C to decompose the polymer matrix and recover carbon fibres. Pyrolysis enables the breakdown of cross-linked resin matrices into low-molecular-weight volatile compounds at temperatures of 400–600 °C under anaerobic conditions [51]. Over the years, pyrolysis technology has been extensively studied for optimisation, applications, and environmental impact. Pyrolysis can recover carbon fibres at yields of 75.8–77.5% by mass, depending on temperature, as well as producing gas (up to 12.9% by mass) and phenol-rich oils (8.8–18.7% by mass), which may be utilised for manufacturing new blades. Maximum mass loss occurs at 380 °C, while the optimal process temperature is 550 °C [51]. The study by Xu et al. (2022) highlights that the efficiency of pyrolytic recycling depends on numerous factors, such as material composition, pre-treatment methods, disposal costs and the potential for reusing recovered fibres [52].

New methods for recovering materials from decommissioned wind turbines continue to be developed. Research by Alavi et al. (2025) showed that solvolysis has a favourable environmental profile owing to its fibre recovery potential [1]. The authors also note the significant influence of electricity consumption—especially in solvolysis and pyrolysis—which, despite their benefits, remain among the most energy-intensive routes [37]. Given that fossil fuels are still widely used in energy production and waste disposal, the authors compare the environmental impacts of these processes, measured by carbon footprint, in the context of renewable energy utilisation. Cheng et al. (2024) developed a solvent-free and energy-efficient rapid recycling method converting glass fibre-reinforced plastics into silicon carbide (SiC), which can be used as an anode material in lithium-ion batteries [53].

Meanwhile, research by Luo et al. (2025) resulted in a superhydrophobic coating produced by grinding previously milled blades and synthesising them with appropriately prepared agents [54]. The resulting coating demonstrated broad hydrophobicity and retained its properties after exposure to various mechanical damage and harsh chemical conditions.

Overall, despite numerous studies and developed technologies, recycling wind turbine components remains difficult owing to compositional heterogeneity and substantial process energy requirements. Continued efforts are necessary to optimise processes and to introduce solutions with lower environmental impacts, enabling the effective integration of these methods into a circular economy.

4. Innovative Solutions for Wind Turbine Blade Recycling and Their Implementation Challenges

The increasing number of wind turbines approaching end-of-life necessitates the development of sustainable recycling and repurposing strategies. Among turbine components, rotor blades present the greatest material and technological challenge due to their composite construction and resistance to degradation. This section reviews current advances in blade recycling, novel applications of recovered materials, and the main obstacles hindering large-scale implementation.

4.1. Advanced Materials and Functional Reuse

The structural complexity of wind turbine blades has prompted extensive research into innovative materials and repurposing solutions. Luo et al. (2025) [55] demonstrated the fabrication of a laminated composite for railway applications using blade-derived recycling powder functionalised with silver nanoparticles. The resulting material exhibited high tensile strength and effective electromagnetic shielding, indicating the feasibility of advanced functional reuse. In parallel, ongoing studies aim to develop novel materials to reduce environmental impact at the end-of-life stage [56].

One promising direction is the development of bio-based and biodegradable composites for turbine blades [57]. Biocomposites combine natural fibres (e.g., hemp, flax, bamboo, or wood) with polymer matrices such as vinyl ester, polyester, or epoxy; lignin-derived carbon fibres are another example. Life-cycle assessments indicate that such materials could reduce CO₂ emissions during production by 34–97%, depending on the category considered [58]. However, their mechanical strength remains lower than that of conventional glass or carbon fibre composites, so they are currently unsuitable for primary load-bearing structures. Ongoing research is focused on improving their durability, for example, through the use of hardwood-derived fibres, hybrid laminates or new resin systems. In the long term, these materials may facilitate recycling and lower the environmental footprint of blades, but they do not yet offer advantages in terms of service life extension.

Thermal degradation of polymeric blade materials—via pyrolysis or oxidative treatments—produces valuable gas, oil, and fibre fractions [59]. However, recycled polymers often exhibit reduced mechanical performance. To address this, natural fillers and biodegradable materials are being tested to enhance structural properties and facilitate biological degradation under environmental conditions [60].

Investigations by Oliveira et al. (2025) [56] identified polyethylene terephthalate glycol (PETG) reinforced with glass fibre as a promising candidate for future blade production. Simultaneously, research into wood-based and nacre-inspired composites reinforced with recycled glass fibre-reinforced polymer has demonstrated improvements in mechanical- and durability-related properties [56]. These studies point to growing potential for integrating recycled blade materials into novel composite systems.

Bio-based resins and alternative binders are also being explored to replace petroleum-derived epoxies. Their application could simplify the chemical breakdown of future blades and improve overall sustainability. Nonetheless, their performance under long-term stress and weathering remains under evaluation. Further research into fire resistance and UV degradation of these biocomposites is essential for commercial implementation [58].

Efforts are also underway to integrate design-for-recycling principles from the early stages of material development. This includes limiting the use of mixed resin systems and adhesives, which currently complicate post-use processing [37]. Such considerations are critical in aligning material innovation with practical recovery needs.

4.2. Applications in Cement, Asphalt, and Infrastructure

The reuse of pulverised blade waste in construction materials is one of the most promising circular applications. Liu et al. (2024) [60] showed that thermal treatment of composite powder at 550 °C improves pozzolanic reactivity, enhancing cement hydration in alkaline conditions. Similarly, studies confirm that moderate substitution of traditional fillers with blade-derived materials can improve compressive and tensile strength, provided that particle size, pH, water content, and pressure are carefully controlled [9,60].

Tan et al. (2025) [61] demonstrated enhanced mechanical performance in asphalt mixtures incorporating organic and inorganic fibres from blades, including improved rutting resistance and fatigue life. Additionally, Manso-Morato et al. (2025) [30] reported that adding 2% re-crushed blade waste (RCWTB) optimised mechanical properties, while higher dosages led to diminishing or plateauing effects. These findings underscore the necessity of dosage control and composite optimisation.

Beyond cementitious composites, full blade segments have been reused as infrastructure elements such as bridges, playgrounds, or highway signage [30,31,35]. Despite their environmental benefits, such applications face challenges related to long-term durability, regulatory acceptance, and lack of standardised testing [32,33].

Incorporating shredded composite waste into prefabricated elements offers flexibility for scale-up. Panels, barriers, and noise walls produced from post-consumer blade materials can reduce both cost and embodied carbon. Johst et al. (2025) [34] emphasised the importance of structural reliability in such systems, particularly for load-bearing uses. Integrating recycled composites into public projects also promotes social acceptance of circular design.

The environmental benefits of such reuse pathways are supported by lifecycle assessment data, especially when compared to landfilling or incineration [9]. However, successful implementation depends on consistent quality control and institutional readiness for adopting alternative building materials.

4.3. Chemical Processing and Recycling Techniques

Recent developments in chemical recycling of wind turbine blades offer high-value material recovery but remain limited by technological complexity and operational costs. Solvolysis, particularly with the use of catalysts and controlled thermal conditions, has proven to be effective in decomposing resin matrices while preserving fibre integrity [1]. Supercritical fluid methods—although highly effective—require high temperatures and pressures, which can compromise the mechanical strength of glass fibres [26]. For instance, tensile strength may decrease by up to 90% when fibres are exposed to 650 °C [26].

Zhao et al. (2025) [62] proposed an alternative degradation process involving oxonium ions and ionic liquids, offering a more environmentally benign pathway. Similarly, Cheng et al. (2025) [63] highlighted the risk of fibre structure deterioration at elevated

temperatures during oxidation. Thus, chemical processes must be precisely calibrated to minimise degradation and ensure compliance with chemical and market standards [40].

The reuse of recycled fibre-reinforced polymer composites has also been explored through mechanical testing. Mao et al. (2025) [64] and Liu et al. (2025) [65] observed that incorporating small proportions of FRP or carbon fibres into concrete significantly enhanced flexural and compressive strength. Such outcomes support the integration of recycled composite materials into structural applications, provided that suitable formulations are employed.

Heterogeneous material compositions in blades complicate recovery efficiency and separation processes. As noted by multiple studies [37,53,54], pre-treatment steps—such as shredding, sorting, and thermal conditioning—are critical for effective recycling. Moreover, automated material recognition systems could facilitate more efficient processing in future industrial-scale operations [66].

One of the most limiting factors remains to be the economic feasibility of these methods, particularly when compared with mechanical reuse options [63]. Although chemical processes offer superior material recovery, their deployment requires high capital investment and continuous process optimisation.

Despite substantial progress, blade recycling remains limited by process costs, low material uniformity, and insufficient industrial infrastructure. A technology-specific approach—adapted to blade composition and recovery goals—is needed to support large-scale deployment. The integration of design-for-recycling principles, including modularity and labelling, could enhance downstream processing [26,37]. Cross-sector collaboration and policy incentives will be key to overcoming these limitations. Establishing quality standards for recycled composites and expanding their use in public procurement can strengthen demand. Ultimately, combining innovation in materials science with system-level planning will enable circularity in the wind energy sector.

4.4. Industrial Deployments and Scalability

Although many recycling routes remain at the pilot scale, several industrial and pre-commercial initiatives have demonstrated practical feasibility and outlined boundary conditions for scale-up. A prominent example concerns thermoplastic, chemically recyclable blades. Within the ZEBRA consortium, LM Wind Power (Kolding, Denmark)—‘LM’ originated from Lunderskov Møbelfabrik (Lunderskov, Denmark), the company’s historical predecessor—and Arkema (Colombes, France) are partners. They have progressed beyond laboratory trials by manufacturing full-scale prototypes (approximately 62 m and 77 m) using Elium[®] resin and by publicly documenting closed-loop processing of blade laminates back into reusable materials [67]. This work suggests a credible circular pathway for thermoplastic systems and clarifies key constraints around laminate architecture, joining methods and downstream re-compounding. In addition, the programme has begun to map manufacturing tolerances and repairability considerations that are critical for certification and field maintenance. These learnings frame realistic timelines for industrial adoption by linking design decisions to verifiable recycling outcomes.

A different line of evidence is provided offshore, where recyclable blades have entered early commercial service. Siemens Gamesa Renewable Energy S.A. (Zamudio, Spain)’s RecyclableBlade was first installed at RWE AG (Essen, Germany)’s Kaskasi wind farm in 2022 and has since been contracted for subsequent projects, such as the Sofia development [68]. While these deployments are still limited in number, they indicate genuine market uptake for blade systems designed for chemical recovery, together with emerging offtake channels for recovered polymers. Notably, the progression from initial demonstration to repeat orders suggests that qualification pathways and warranty considerations can be addressed

within existing project delivery frameworks. Even so, broader roll-out will depend on supply chain readiness and standardised end-of-waste criteria across jurisdictions.

Thermochemical recovery has also reached industrial operation for carbon fibre-containing composites. Carbon Conversions, Inc. (Lake City, SC, USA) operates a dedicated facility processing continuous streams of CFRP scrap and returning reclaimed fibres to market applications [69]. Although detailed capacities and gate-to-gate energy balances are not universally disclosed, the plant-level experience demonstrates that continuous feed logistics, product qualification, and downstream offtake can be organised at scale, provided that fibre quality (strength retention, surface cleanliness, and sizing compatibility) is consistently verified. Evidence from customer applications indicates that reclaimed fibres can meet specified performance windows when appropriate surface treatments and sizing are applied. Future competitiveness will turn on consistent grade definitions and long-term offtake agreements that stabilise pricing.

From the perspective of high-volume outlets, co-processing of GFRP in cement kilns has moved from concept to practice within large cement groups, including Holcim Ltd./Geocycle (Zug, Switzerland) [70]. Shredded blade composites are used as an alternative fuel and raw material under established co-processing frameworks, and recent project communications report the integration of recycled blade fibres into concrete for wind farm foundations. This pathway does not recover continuous fibres, but it offers a near-term, geographically scalable outlet for substantial GFRP volumes, provided that emissions controls and clinker-quality specifications are met. Its attractiveness lies in the ability to absorb heterogeneous feedstocks while delivering both energy and mineral substitution benefits. Nonetheless, lifecycle performance depends on local kiln conditions and regulatory acceptance, which can vary across regions.

By contrast, solvolysis, and supercritical routes—while delivering the highest fibre quality—remain largely at the pilot or demonstration scale, typically in the TRL 4–6 range. The transition to continuous industrial plants will hinge on solvent management (closed-loop recovery and losses), energy integration (heat recovery and pinch matching), and the establishment of robust fibre quality benchmarks linked to downstream performance in composites and cementitious matrices. Progress will also require clear specifications for recovered resin streams and transparent reporting of solvent make-up rates and fugitive emissions. Without these disclosures, comparative techno-economic assessments risk overstating scalability or underestimating operational complexity [66].

The practical cases presented above show that industrial activity is emerging along several pathways. These include thermoplastic design, enabling closed-loop options, thermochemical recovery for CFRP, and cement-kiln co-processing for GFRP. Looking ahead, transparent reporting of plant capacities, product specifications, yield and quality distributions, and gate-to-gate energy balances will be essential for like-for-like techno-economic and environmental appraisals and for turning pilot demonstrations into bankable, replicable solutions [66]. Equally harmonised certification protocols and bankable contracting models will be needed to de-risk investment in new assets. Establishing interoperable quality grades for recovered fibres and polymers would further accelerate adoption across downstream sectors.

5. Wind Turbine End-of-Life in the Circular Economy: Regulation, Markets, and Finance

This chapter situates wind turbine blade recycling within circular economy (CE) frameworks by linking material pathways to the enabling policy and market context. It first distinguishes closed- and open-loop routes, then examines EU regulatory alignment alongside the market-creation and financing instruments that translate policy into bankable

projects. Comparative indicators are presented, including cost per tonne (CPT) bands and deployment status, followed by discussion of design, standardisation, and data infrastructures. A system-level synthesis is provided, and targeted recommendations for policymakers complete the section.

5.1. Circular Economy Frameworks and Regulatory Alignment in the EU

Integrating wind turbine blade recycling into CE frameworks requires a shift from purely technological fixes to comprehensive, system-level strategies. These strategies should address the full material lifecycle, cross-sectoral cooperation, and the regulatory and economic instruments needed to foster circularity [66].

A key distinction in CE models is between closed-loop and open-loop recycling. In a closed-loop system, materials are reused within the same product cycle or industry—e.g., reprocessing blade composites into new blade components [71]. By contrast, open-loop recycling transfers materials to other sectors, such as using shredded composites in construction panels or asphalt mixtures [72]. While open-loop routes reduce overall waste, they may entail gradual declines in material quality and traceability, raising concerns about downcycling [73]. For wind turbine components, most current recycling and repurposing efforts are open loop [74]. This reflects fibre quality degradation during processing and the complexity of reintroducing used composites into the same production cycle. Consequently, the construction sector has emerged as a primary recipient of repurposed materials, benefiting from low-cost and durable inputs [75].

Despite the availability of pilot technologies, several barriers to implementation persist. A major challenge is the lack of harmonised legal frameworks across the European Union. Although the EU Circular Economy Action Plan (CEAP) provides high-level direction, national rules on composite waste classification, cross-border transport, and end-of-waste criteria vary significantly [76], creating legal uncertainty for producers and recyclers [77]. This regulatory fragmentation should be addressed through an EU-wide framework that couples harmonised rules with targeted incentives to scale high-value recovery [11,27,37], specifically via standardised classification and end-of-waste criteria for blade-derived composites adopted under the EU waste acquis—supported by common List of Waste entries, mutual recognition across Member States, and quality grades for recycled fibres and resins. Together, these measures would enable cross-border movements of secondary composites and provide legal certainty for operators [11,37]. In addition, a sector-specific Extended Producer Responsibility scheme for wind turbines—explicitly covering blades—should be mandated. Eco-modulated fees would reward design-for-disassembly, the use of recyclable matrices, and the provision of Digital Product Passports, alongside progressively rising take-back, recovery, and recycling targets and minimum information requirements on composition and dismantling procedures [78].

To translate regulatory clarity into investable projects, market-creation instruments are also required. Priority options include green public-procurement rules specifying minimum recycled-fibre content; recognition of verified recycled composite content via tradable certificates; time-limited investment support (CAPEX grants or soft loans); accelerated depreciation; and reduced electricity levies for certified recycling plants, within State-aid rules [79]. Complementarily, graduated restrictions on landfill and incineration of untreated blades should apply wherever high-value recycling is technically and economically feasible [11], with derogations only in justified cases. Cross-border coordination should be strengthened through an EU-level digital registry of decommissioned blades and end-of-life flows, interoperable with product passports and uniform reporting. Standardisation work (CEN/ISO) should be prioritised to define test methods and quality grades for recycled fibres (e.g., strength retention classes), enabling conformity assessment and mutual recogni-

tion. Taken together, these measures would deliver clearer incentives and more consistent environmental outcomes across the EU.

5.2. Market-Creation Instruments and Financing

Building on the EU regulatory alignment set out in Section 5.1, this subsection introduces the market instruments and financing models that translate circular economy rules into bankable projects. Accordingly, a comparative view of cost per tonne (CPT) bands and deployment status is presented alongside typical revenue streams and policy/financing levers, to make explicit the conditions under each processing routes scale (see Table 3).

Table 3. Indicative economic and deployment indicators by recycling route (authors' own elaboration).

Waste Processing Method	CPT (€/t, Band *)	Deployment Status	Expected Revenue Streams	Financing and Policy Instruments	References
Mechanical recycling	Low (<150)	Industrial	Sale of fillers/powders; gate fees; avoided landfill	EPR take-back fees; green public procurement for recycled content; SME CAPEX grants	[12,30,41,76]
Chemical recycling	High (>400)	Pilot/demo	Near-virgin fibre premia; monomer streams	PPPs for first-of-a-kind plants; innovation funds; tax credits for recycled content	[15,32,33,39]
Solvolysis	High (>400)	Pilot/demo	High-grade fibres; possible resin/intermediates	EPR eco-modulation; soft loans; carbon contracts for difference (where applicable)	[32,71]
Electrochemical method	Med–High (150–400+)	Lab/pilot	Select fibres/oligomers; licencing	R&D grants; pilot-line PPPs	[32,80]
Supercritical fluid methods	High (>400)	Pilot	Premium fibres	First-of-a-kind guarantees; green bonds	[81–84]
Thermal recycling	Med–High (150–400)	Demo/industrial (route-dependent)	Oils/gases; CFRP fibre (part-retained)	Industrial decarbonisation funds; energy recovery incentives	[41,44,51]
Pyrolysis	Med–High (150–400)	Demo/early industrial	CFRP fibre resale; pyro-oil/gas	Project finance with offtake; EPR; reduced electricity levies	[43,47,59],
Fluidised-bed process (thermal pyrolysis variant)	Medium (150–300)	Pilot/demo	CFRP fibres; energy recovery	PPPs; regional waste-to-resources programmes	[83,85,86]
Microwave-assisted pyrolysis	Med–High (150–400+)	Pilot	CFRP fibre resale; condensate oil/gas	Innovation grants; pilot guarantees	[15,87,88]
Combustion	Low/Negative **	Industrial	Gate-fee revenue; energy and mineral substitution	Co-processing guidelines; landfill/incineration restrictions	[70,89]

* CPT (cost per tonne) means the process cost per tonne of composite at the plant gate; it excludes upstream logistics (collection, on-site segmentation/cutting, transport) unless stated otherwise. By default, CPT includes utilities/energy, reagents/consumables, routine labour/maintenance, and environmental compliance costs (dust/air-emissions control, effluent handling). Monetary values are expressed in euros at 2024 price levels (EUR-2024), i.e., historical figures uprated to 2024 using Consumer Price Index (CPI)/Harmonised Index of Consumer Prices (HICP) inflation, and—where non-euro currencies are involved—converted at average 2024 exchange rates. ** Low/Negative" CPT for co-processing denotes cases where a gate fee received by the operator offsets processing costs; the net balance depends on environmental control requirements and transport distances.

Bearing in mind the ranges reported in Table 3, routes that deliver premium fibre quality (solvolysis and related chemical pathways) exhibit higher CPT and earlier deployment status, realising price premia for near-virgin fibres and, where feasible, additional value from resin/monomer streams. Thermochemical options (conventional pyrolysis and fluidised bed variants) fall within an intermediate CPT band with demonstration to early-industrial deployment; their viability is most sensitive to electricity/heat integra-

tion, emissions abatement, and the post-treatment required to meet fibre-performance specifications. By contrast, mechanical recycling and cement-kiln co-processing provide lower-CPT, near-term outlets with broad scalability; however, the former entails down-cycling to powders/fillers, and the latter recovers no fibres, relying instead on gate-fee revenue and energy/mineral substitution.

According to these CPT and deployment status patterns, the cost–quality trade-off is governed by three recurrent factors evident in Table 3: (i) energy and solvent management (notably closed-loop recovery in liquid-phase routes), (ii) the stringency of environmental controls (integral to compliant operation and material to CPT), and (iii) offtake certainty for recovered outputs (fibres, oils/gases, fillers). On this basis, financing and policy instruments that reward verified recycled content, internalise landfill/incineration externalities, and de-risk first-of-a-kind investments are pivotal to advancing higher-value—yet capital- and energy-intensive—routes from pilot to bankable scale, while maintaining lower CPT outlets capable of handling heterogeneous waste streams at volume.

5.3. Circular Design and Digital Traceability

With EU regulatory alignment and market-creation tools set out above, the decisive question is whether incentives reach the design stage. Price signals remain too weak to shift early choices. Extended Producer Responsibility schemes for the wind sector have been proposed but are not yet widespread [90], and without clear obligations or calibrated incentives, manufacturers may not prioritise design-for-disassembly or recyclability [62]. Product-policy levers, therefore, need coupling with green procurement and eco-modulated EPR so that signals from end-markets transmit back to design.

Circular design in wind turbine manufacturing is still at an early phase [91]. Some producers are piloting thermoplastic resins [92] and modular blade architectures, yet these initiatives are neither standardised nor scaled [93]. Mandatory labelling, harmonised resin families, and shared dismantling protocols would make material flows traceable and lift the quality of secondary outputs [36,57,58]. Linking such specifications to Digital Product Passports would secure data continuity across the lifecycle and lower transaction costs for recyclers and offtakers.

Fragmentation among stakeholders—from manufacturers and operators to recyclers, policymakers, and local authorities—continues to impede efficient planning and investment [94]. Without integrated platforms for information-sharing and joint scheduling, infrastructure develops unevenly, with missed opportunities for load-balancing, cross-border optimisation, and aggregation of small waste streams into bankable lots. An EU-level digital registry of decommissioned blades and end-of-life flows, interoperable with Digital Product Passports and uniform reporting, would strengthen coordination and improve offtake certainty.

Properly aligned design incentives, shared specifications, and interoperable data infrastructures transmit market signals upstream and lower transaction costs, establishing the conditions for the next system-level feedback considered.

5.4. System Perspective and Feedback Loops

A system perspective clarifies how design choices, policy instruments, and operational decisions interact across the wind turbine end-of-life chain. Figure 2 presents these linkages in a system-level synthesis. It maps how upstream enablers—product design choices and EU circularity policies—shape downstream end-of-life pathways for wind turbine components: life extension, open-loop and closed-loop recycling, and repurposing. It then highlights the central role of wind farm operators. They implement operational decisions and coordinate with stakeholders, leading to two parallel outcomes: continued wind en-

ergy generation and interaction with regulatory authorities. These interactions operate as feedback loops that inform future policy alignment and market signals. The schematic from design through end-of-life shows that progress depends not only on recovery technologies but equally on early-stage design interventions, information continuity (e.g., Digital Product Passports), coordinated data infrastructures, and governance loops—with regulatory authorities at the bottom of the scheme acting as the governance anchor that reinforces circularity across the lifecycle.

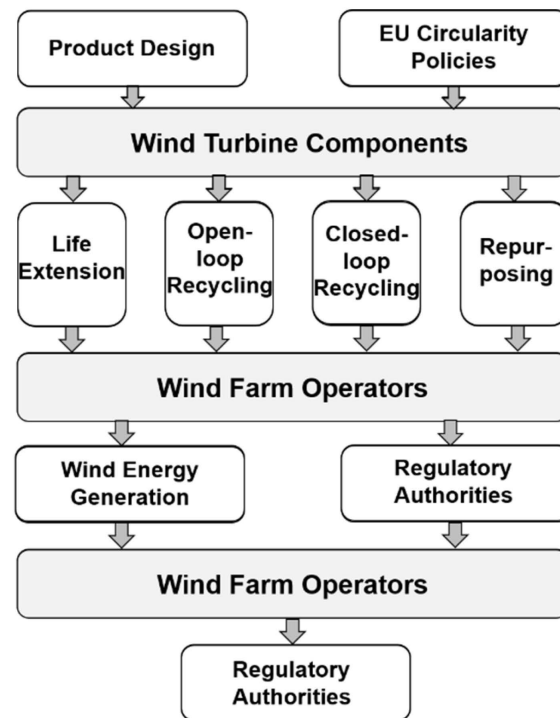


Figure 2. Circular economy pathways for wind turbine components—system-level approach (authors' own elaboration).

In this representation, three practical leverage points become salient: (i) credible offtake arrangements for recovered outputs, (ii) recognised quality grades and conformity assessment for recycled fibres, and (iii) interoperable registries that reduce search and coordination costs. Together, these elements translate regulatory intent into predictable cash flows and investment decisions, strengthening the circularity feedback depicted.

To conclude, embedding wind turbine blade recycling within CE frameworks requires more than just technical innovation. It requires consistent regulation anchored in clear end-of-waste rules, market-creation instruments that make projects bankable, circular product design supported by standards and passports, and coordinated data and governance systems spanning the supply chain [95]. Progressing from experimental solutions to scalable, economically viable systems will be essential to meet EU climate and waste targets while supporting a genuinely circular wind energy sector [96].

6. Summary and Perspectives

The circularity of wind turbine components remains one of the most significant challenges in the renewable energy sector [97]. While metals and electronics can be recycled with existing infrastructure, composite materials—especially those used in rotor blades—pose far greater difficulties. Their complex structure, high durability, and contamination risks hinder traditional recovery routes [98]. Addressing these challenges requires integrated

end-of-life strategies that combine technological innovation, supportive policy frameworks, and market readiness.

In response to growing concern, recent years have seen increasing attention to the environmental impacts of blade disposal, prompting extensive research into viable alternatives [99]. Mechanical reuse, repurposing, and advanced chemical processes offer differentiated opportunities depending on regional conditions, technical feasibility, and cost-effectiveness [100,101]. However, many of these methods remain at the pilot or experimental scale, and their practical implementation is limited by regulatory gaps and lack of commercial incentives.

A clearer overview of current and emerging end-use pathways for wind turbine blade waste is presented in Table 4. This summary focuses on practical material flows and their potential for reintegration into various sectors, including construction, energy, transport, and consumer goods. Applications are categorised according to target sectors and the types of materials derived from blade waste, providing a complementary perspective to previous technological considerations.

Consistent with the environmental controls outlined in Section 3, Section 3.3, the following basic health-and-safety precautions should be observed before implementing the uses catalogued in Table 3. Several of the applications below involve on-site segmentation and finishing; therefore, LEV (local exhaust ventilation) and HEPA (high-efficiency particulate air) controls are referenced where appropriate:

- **Segmentation and cutting.** Preference should be given to low-dust methods (e.g., water jet cutting) and on-site containment to minimise re-handling. Where dry cutting/grinding is unavoidable, use integrated LEV with point-source capture and shrouded tools [102].
- **Dust control.** Apply wet suppression where practicable; provide LEV with appropriate filtration (e.g., HEPA for fine particulates); avoid compressed-air cleaning; maintain housekeeping using vacuum systems fitted with HEPA filtration; enclose cutting bays or use temporary curtains to limit fugitive dust [103,104].
- **Worker exposure and PPE.** Conduct task-specific risk assessment; provide protective clothing, gloves, eye/face protection, and respiratory protective equipment commensurate with measured concentrations; ensure training and fit-testing where respirators are used; institute exposure monitoring/medical surveillance as required by national regulation [105].
- **Odour and nuisance.** Use temporary enclosures and negative-pressure regimes where needed, particularly in urban settings or during indoor preparation of blade segments [102].
- **Waste handling.** Collect dust and offcuts into sealed, labelled containers for appropriate downstream processing; do not mix with municipal waste streams [89].

These health-and-safety measures should be specified in method statements for each application listed in Table 4 below and applied as standard operating practice.

Table 4. Sector-specific applications of wind turbine blade waste and associated materials (author's own elaboration).

Sector	Application	Material Type	References
Construction	Concrete additives, cement clinker substitute, fillers in asphalt mixtures, polymer-based construction panels, sound barriers, bridges, urban furniture	Powdered GFRP (Glass Fibre Reinforced Polymer), crushed blade particles, fibre mats, composite laminates	[12,13,16,30,52,61,64,72,96,106]

Table 4. *Cont.*

Sector	Application	Material Type	References
Energy	Co-firing in cement kilns and industrial furnaces, fuel for pyrolysis-based energy recovery systems	Combustible resin matrix, GFRP fragments, pyrolysed solids and liquids	[8,15,18,39,47,99,107]
Transport	Fillers for road subbase layers, reinforcement elements in railway infrastructure, noise protection panels	Thermally treated composite aggregates, fibre-reinforced particles, GFRP-derived composites	[34,45,54,76,108]
Consumer Goods	Production of urban equipment, sports equipment, furniture, and household items with recycled blade fibres	Composite fibre panels, GFRP powder, reformulated thermoplastics	[16,20,24,90],
Public Infrastructure	Playground structures, outdoor shelters, information signs, pedestrian bridges, bus stops	Cut blade segments, surface-treated GFRP panels, laminated composites	[2,32,55,109]
Agriculture	Fencing, protective panels, livestock enclosures, wind barriers	Mechanical offcuts, reused composite sheets, reinforced laminates	[33,35,110]

The practical examples presented in Table 4 illustrate how composite blade waste can be repurposed into value-added applications across multiple industries. These use cases align with circular economy objectives by extending material lifespans and reducing demand for virgin resources. However, the transition from pilot initiatives to scalable deployment remains limited due to fragmented infrastructure, high variability of composite properties, and regulatory barriers. Despite these constraints, some applications—particularly in the construction sector—have shown promising performance and social acceptance [89,107,110] and may serve as entry points for broader deployment of circular solutions. Their wider adoption will depend on material standardisation, improved design-for-reuse strategies, and institutional support. In parallel, product labelling, quality control, and market stimulation mechanisms (e.g., public procurement or EPR schemes) could help expand the uptake of recycled composites in practice [109].

Looking forward, future strategies should prioritise the improvement in economic feasibility for existing recycling technologies, while simultaneously fostering innovation in material design at the upstream stage [109]. Lifecycle assessments and dynamic system modelling will play a critical role in supporting evidence-based decisions and optimising recovery processes across the value chain. Achieving meaningful progress in this area will require coordinated collaboration between academia, industry, and policymakers to overcome institutional inertia and embed circularity more deeply into wind energy systems.

To strengthen the effectiveness of recovery systems, the design phase of wind turbine components must increasingly take end-of-life considerations into account. The adoption of modular structures, the use of uniform resin types, and the implementation of embedded information labelling can significantly facilitate future disassembly and material recovery. In parallel, public institutions should be encouraged to incorporate recovered composites into procurement policies, thereby stimulating demand for secondary raw materials and supporting market uptake [89].

Emerging strategies should also reflect the social dimension of circularity. Activities focused on reuse and repurposing not only extend material lifespans but also generate local employment and reinforce regional resilience—particularly in areas surrounding decommissioned wind farms. Integrating circular economy objectives into national energy and waste policies could accelerate the adoption of these solutions and foster greater public

acceptance of secondary material use. In this regard, EPR schemes, targeted subsidies, and public–private partnerships may play a decisive role in building stable markets for secondary composites. Simultaneously, transparent communication and stakeholder engagement are essential to address public concerns, ensure social legitimacy, and create equitable value chains across regions.

7. Conclusions

This review has examined the technical, systemic, and policy-related dimensions of wind turbine end-of-life management, with particular attention given to rotor blade recycling. Mapping existing and emerging strategies—ranging from life extension to advanced recycling techniques and second-life applications—offers a critical synthesis of current capabilities and future directions. The findings underscore the need for integrated, circular approaches tailored to the complexity of wind turbine materials and lifecycles. The analysis is framed at the system level, linking processing routes to deployment maturity (indicative TRL) and to qualitative/quantitative indicators that enable like-for-like appraisal.

1. Wind turbine blades, due to their heterogeneous composite structure, remain the most technically challenging component to recycle. Among available options, chemical recycling—particularly solvolysis—demonstrates the highest potential for fibre recovery with minimal degradation, provided that solvent management and heat integration are engineered to industrial standards and environmental compliance requirements are met.
2. Mechanical recycling and second-life applications offer feasible short-term solutions, especially when recovered materials are redirected to the construction sector. Their environmental benefits, however, are often constrained by quality limitations and lack of standardisation. In practice, these routes are most immediately applicable to GFRP, but they entail downcycling; fit-for-purpose standards and product specifications are, therefore, essential to secure predictable performance and market uptake.
3. The adoption of bio-based and biodegradable composites may significantly reduce the environmental burden of future blade production. Nonetheless, further research is required to optimise their mechanical performance and economic viability. Priority gaps include long-term durability, fire/UV resistance, and certification pathways, so that design-for-recycling gains do not compromise service integrity.
4. Upcycling approaches—such as the transformation of blade segments into infrastructure elements or urban furniture—represent a low-energy alternative to full material recovery, though they currently face social, regulatory, and durability-related barriers. These applications should follow engineering qualification and monitoring protocols, with use targeted to noncritical or moderately loaded elements.
5. The integration of circular economy strategies within the wind energy sector necessitates not only technological development but also institutional support. Instruments such as EPR schemes and digital material tracking systems can enhance transparency, accountability, and resource circulation. Equally important are harmonised end-of-waste criteria, recognised quality grades for recovered fibres/polymers, and demand-pull levers (e.g., green public procurement, eco-modulated EPR fees).
6. Advancing interdisciplinary research and establishing industrial symbiosis between the wind energy, construction, and waste management sectors are essential to closing material loops and fostering market acceptance of recycled composites. Near-term priorities include standardised fibre quality classes and test methods, transparent gate-to-gate energy balances that include abatement/solvent-recovery penalties, and bankable offtake arrangements to de-risk first-of-a-kind plants.

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List of Abbreviations

IEA	International Energy Agency
EPR	Extended Producer Responsibility
WTBs	Wind Turbine Blades
GFRP	Glass Fibre Reinforced Polymer
EU	European Union
RWTBs	Recycled Wind Turbine Blades
DDWTs	Direct-Drive Wind Turbine(s)
SCADA	Supervisory Control And Data Acquisition
ZEBRA	Zero waste Blade ReseArch, project designing and manufacturing the first 100% recyclable wind turbine blade.
SiC	Silicon Carbide
PETG	Polyethylene Terephthalate Glycol
RCWTB	Re-Crushed Blade Waste
FRP	Fibre-Reinforced Polymer
CE	Circular Economy
CEAP	Circular Economy Action Plan

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