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End-of-life management of advanced composite materials: A review focused on wind turbine blade waste and cement co-processing

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ABSTRACT

The widespread adoption of fibre-reinforced polymer (FRP) composites in the wind energy sector has been instrumental in the global renewable energy transition. However, this success created a formidable environmental challenge: the end-of-life (EoL) management of wind turbine blades (WTBs). Methodologically, this study adopts a critical systematic review approach, integrating and synthesising evidence from peer-reviewed academic literature and industrial reports to comparatively assess EoL strategies against the criteria of Technology Readiness Level (TRL) and economic feasibility. Unlike reviews focusing on mechanical downcycling or emerging chemical methods, this paper prioritises industrial scalability, addressing cumulative waste projected to exceed 6.5 million tons by 2049. A critical analysis of EoL management strategies highlights the fundamental trade-off between scalability and value recovery. Amid these options, cement co-processing is distinguished not merely as a disposal route but as a dual-recovery mechanism distinct from passive filler applications. It emerges as the most mature and pragmatic solution for the predominant glass fibre reinforced polymer (GFRP) waste stream. This process recovers energy while leveraging the inorganic fraction for clinker mineralisation, significantly reducing greenhouse gas emissions compared to traditional disposal. We conclude that while an integrated ecosystem is the ultimate goal, cement co-processing provides the essential, immediately deployable pathway to manage the legacy WTB fleet, ensuring the continued sustainability of wind energy.

1. Introduction

The global transition to renewable energy is crucial for mitigating climate change, with wind energy emerging as a cornerstone of this effort. In 2022, the worldwide installed capacity for wind power reached nearly 900 GW (see Fig. 1), and it is projected to surpass fossil fuels as a primary source of electricity by 2040 (EIA, 2023; Zhao, 2025). This remarkable growth, driven by technological advancements and major policy support (European Commission, 2021), has led to the deployment of larger (see Fig. 2) and more efficient wind turbines (IRENA, 2018; Firoozi et al., 2024). However, the very success and maturation of the wind industry have given rise to a significant and widely publicised environmental bottleneck: the end-of-life (EoL) management of wind turbine blades (WTBs) (Beauson et al., 2022; Majewski et al., 2022; Delaney, 2022).

This situation creates a “sustainability paradox” (Echer, 2022; Morini et al., 2021). Although wind turbines are a symbol of sustainable energy, their blades are predominantly fabricated from glass fibre reinforced polymer (GFRP) composites, often with carbon fibre reinforced polymer (CFRP) reinforcements. These materials, prized for their high strength-to-weight ratio and durability, feature a cross-linked thermoset[1] matrix that makes them inherently difficult to recycle (Fraile and Walsh, 2020). Although approximately 85%–90% of a turbine’s total mass (including its steel tower, copper wiring, and concrete foundation) can be readily recycled through established pathways, the blades represent the most problematic waste stream. It is crucial to note that the impending “first wave” of EoL waste is dominated by GFRP designs, making high-value recovery methods often economically unviable compared to cheaper virgin glass fibres.

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[1] Although thermoplastic and recyclable-epoxy solutions are presently under development, the widespread implementation of these alternatives remains distant from achieving large-scale commercial viability.

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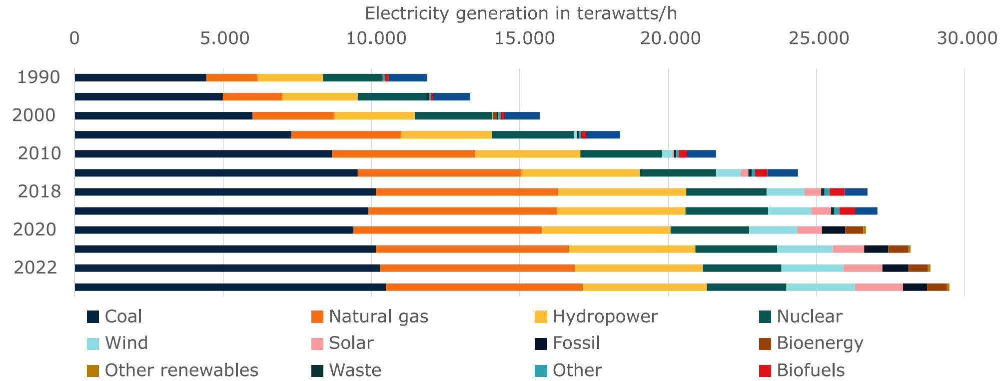

Fig. 1. Different energy sources for electricity generation, worldwide.
Source: Data retrieved from EIA (2023), EMBER (2024).

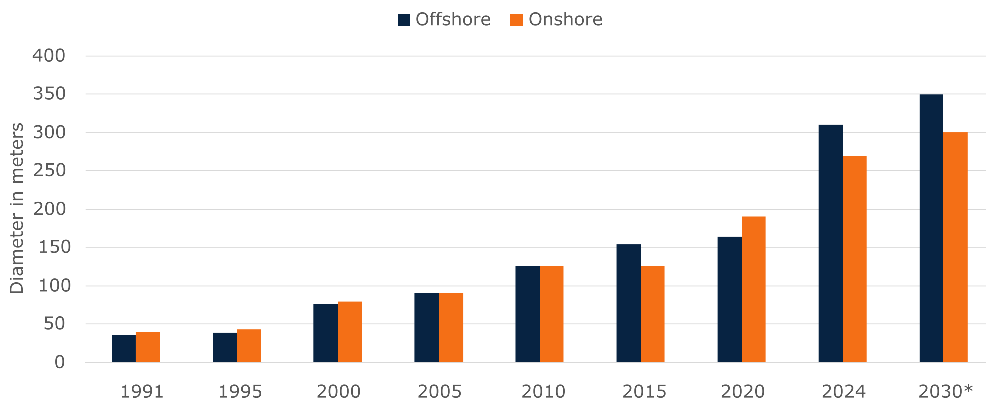

Fig. 2. Evolution of average rotor diameter of wind turbines.
Source: Data retrieved from Zhao (2025).

Projections indicate that the cumulative global waste from WTBs could exceed 6.5 million metric tonnes by 2049, with a sharp increase anticipated after 2025 as this first generation of large-scale wind farms reaches the end of its typical 20–25 year operational lifespan (Delaney, 2022; Majewski et al., 2022).

The challenge of WTBs waste transcends mere technical disposal; it directly impacts the social licence to operate for the entire industry. The issue has garnered significant media attention, with numerous reports highlighting "graveyards" of discarded blades, creating a powerful and negative visual narrative that can undermine public and political support (Holger and Petroni, 2022; Aaen, 2011; Martin, 2020; Neslen, 2021). This scrutiny of the industry's "green" credentials is especially critical for a sector that heavily relies on governmental incentives, public subsidies, and streamlined environmental licensing. Failure to implement large-scale sustainable EoL solutions can fuel public mistrust and provide ammunition for disinformation campaigns, potentially stalling future developments (Caporale et al., 2020). As argued by scholars, social acceptance is not merely public opinion, but a complex process involving institutional performance and governance (Wolsink, 2018). Therefore, addressing the problem of WTB waste is not only an environmental imperative but also a strategic necessity to safeguard the future of wind energy.

Current EoL strategies for WTBs encompass a spectrum of approaches, ranging from landfilling, which remains prevalent in regions with less stringent regulations, to sophisticated techniques like pyrolysis and solvolysis. Recent comprehensive reviews have extensively covered these technologies (Spini and Bettini, 2024; S. Bulińska and Pyzalski, 2024), while others have focused heavily on mechanical recycling of blades for use as aggregates or fillers in cementitious composites (D. Jasińska, 2025; Rucka and Kurpińska, 2025). However, these alternatives often face significant barriers related to scalability and market absorption. For example, using shredded blades as concrete aggregate is technically feasible but limited by strict construction standards and concerns about durability and alkali-silica reactions. Against this complex backdrop, cement co-processing emerges not merely as another disposal option, but as a distinct industrial pathway capable of handling the massive volumes of the GFRP legacy fleet. Unlike passive incorporation into concrete, this process actively utilises the energy content of the polymer matrix as an alternative fuel and leverages the inorganic glass fibres as a substitute raw material (SRM) for the mineralisation of clinker (Fraile and Walsh, 2020; Beauson et al., 2022). This distinction between physical filling and chemical clinkerization (where the waste elements are structurally integrated into the mineralogy of the binder (Chatterjee, 2011)) is critical to understanding the true scalability of EoL solutions.

1.1. Motivation and objectives

With first-generation wind farms now reaching the end of their operational lifespan, the volume of decommissioned blades is expected to increase exponentially. Forecasts based on existing installations indicate a rapid increase in the coming years, as illustrated in Fig. 3, which shows the expected flow of EoL material from key global markets. This surge presents not only logistical and environmental risks, but also a critical opportunity to establish a circular economy. However, a discrepancy persists between the theoretical potential of advanced recycling methods and the industrial reality required to absorb this mass.

This paper is motivated not merely by the need for another general review, but by the necessity to rigorously evaluate EoL solutions against

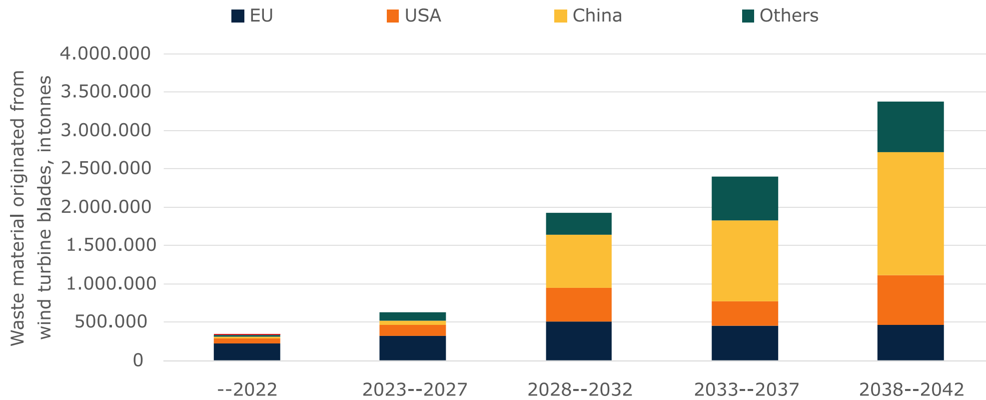

Fig. 3. Projection of total waste material originated from WTBs.
Source: Data retrieved from Delaney et al. (2023).

the constraints of **industrial scalability**. Although recent literature has extensively explored mechanical recycling for concrete applications (D. Jasińska, 2025; Rucka and Kurpińska, 2025), critical questions remain about the long-term market capacity to absorb such fillers without compromising infrastructure durability. Consequently, our primary objectives are threefold:

1. To synthesise the current state-of-the-art regarding the scale of the WTB waste problem, distinguishing between the recycling economics of the legacy fleet (GFRP-dominated) and future designs (increasingly rich in CFRP).
2. To critically benchmark available EoL strategies based on a "Scalability vs. Value Recovery" trade-off, identifying why mechanical and thermal methods currently struggle to handle the gross tonnage of the first decommissioning wave.
3. To provide a focused, technical analysis of **cement co-processing**, differentiating it from passive use in concrete by detailing the chemical mineralisation process (clinkerization) and establishing it as the most immediately viable route for mass-scale decarbonisation.

This review is aimed primarily at stakeholders in the built environment, cement industry professionals, and policy makers seeking scalable cross-sector waste management solutions. By bridging the gap between materials science and industrial logistics, it aims to support decision-making for the sustainable decommissioning of renewable energy infrastructure. Therefore, our aim is to provide a clear and evidence-based resource for researchers and industry stakeholders who must navigate the trade-off between ideal circularity and the immediate pragmatic necessity of diverting waste from landfills.

1.2. Scope and limitations

This review concentrates on the end-of-life management of thermoset composite materials, with a primary focus on the specific challenges posed by the wind energy sector. Although aerospace and automotive applications share similar material classes, the detailed analysis focuses on WTBs because of the unique logistical constraints and the sheer volume of the legacy waste stream.

The boundaries of this review are defined as follows:

- **Material focus:** The primary material considered is GFRP, which constitutes the vast majority of the current and near-future decommissioned fleet. Although CFRP is acknowledged as a critical material for modern, longer blades, it represents a distinct economic case for high-value recycling (e.g., pyrolysis) and is therefore treated as a secondary focus compared to the massive influx of low-value GFRP.
- **Technology focus:** Unlike general reviews that provide the same weight to all EoL routes, this work places a special emphasis on cement co-processing. Other pathways (landfilling, mechanical, thermal, and chemical) are reviewed primarily to establish a comparative baseline for scalability and economic viability. Crucially, this review distinguishes co-processing (clinker production) from the use of recyclates as aggregates in concrete, offering a complementary perspective to recent studies focused on construction materials.
- **Methodological approach:** This research synthesises and critically analyses existing published results to generate a new perspective on industrial scalability. It does not present new experimental data or a Life Cycle Assessment (LCA), but rather provides a techno-economic argumentation based on the synthesis of current industrial capabilities and chemical process constraints.

2. Methodology of the review

This review is based on a systematic analysis of scientific literature and industrial reports, structured to bridge the gap between materials science research and industrial waste management realities. A comprehensive search was conducted using scholarly databases, including Scopus, Web of Science, and Google Scholar. To ensure that the analysis addresses the specific constraints of the legacy fleet, the search strategy combined general terms (e.g., "wind turbine blade waste", "composite recycling", "circular economy") with specific process-oriented keywords such as "cement co-processing", "clinkerization", "industrial scalability", and "supply chain logistics".

The scope includes peer-reviewed articles, conference proceedings, and crucially technical reports from major industry associations (e.g., WindEurope, EuCIA, JEC Group) and governmental bodies, which often provide the most current data on waste volumes and regulatory shifts. The reviewed literature spans primarily from 2010 to early 2025, with a particular emphasis on the surge of publications from 2023 to 2025 to position this work within the context of the most recent academic discussions.

The selection criteria were refined to prioritise studies that provided:

- Quantitative data on waste streams specific to the legacy fleet dominated by GFRP;
- Detailed process descriptions relevant to industrial upscaling (e.g., throughput capacity, energy balance);
- LCAs and chemical analyses focused on the compatibility of recyclates with cement manufacturing (e.g., trace element limits), distinguishing them from studies focused solely on the mechanical properties of concrete composites.

3. The growing challenge of composite waste

3.1. The advanced composites market and production trends

The increasing challenge associated with composite waste arises as a direct result of the material's successful deployment and widespread utilisation across various industrial sectors. The global composites market has exhibited substantial long-term expansion, attaining an estimated volume of 12.7 million metric tonnes (Mt) in 2022, which corresponds to a market valuation of approximately $41 billion (JEC, 2023a). Asia emerges as the predominant market by volume, contributing 47% of the global total, followed by the Americas with 29% and the EMEA region (Europe, Middle East & Africa) at 24% (Gang, 2023). This growth trajectory is expected to persist at a rate of 3%–4% annually until 2027.

In the context of a complex market, the wind energy sector constitutes a particularly significant demand driver. Composites serve as a critical enabler technology, comprising approximately 73% (by volume) of the required materials for the structural components of a turbine (Gang, 2023). However, the material composition has evolved significantly over the decades. The legacy fleet (turbines installed in the 1990s and early 2000s currently reaching EoL, see Fig. 3) relies overwhelmingly on GFRP with polyester or epoxy matrices (JEC, 2023a; Schubel and Crossley, 2012). In contrast, modern multi-megawatt rotors increasingly incorporate CFRP to achieve the necessary stiffness-to-weight ratio (Tyurkay et al., 2024; F.P.G. Márquez, 2020).

This material heterogeneity creates a complex recycling landscape: while high-value recovery methods (e.g., solvolysis) might become economically justifiable for the modern CFRP-rich fleet, they present an unfeasible economic balance for the massive influx of low-value GFRP from the legacy fleet. Consequently, the industry requires a stratified approach in which the EoL solutions are matched to the specific material generation of the blade (Fraile and Walsh, 2020).

3.2. The end-of-life scenario for wind turbine blades

The rapid expansion of wind energy since the early 2000's means that a significant and exponentially growing fleet of turbines is now approaching its designed operational lifespan of 20–25 years, as depicted in Fig. 4. This maturation of the market has created an imminent EoL wave of WTB waste. It is estimated that around 14 000 blades were decommissioned in Europe alone by 2023, equivalent to approximately 40 000 t to 60 000 t of composite waste (Fraile and Walsh, 2020; Beauson et al., 2022). On a global scale, projections indicate a cumulative waste volume that could reach 43.4 Mt by 2050 if a circular economy for blades is not established (Liu and Barlow, 2017). This impending surge presents a formidable logistical, environmental, and socio-political challenge that requires proactive solutions capable of handling industrial tonnages.

A detailed examination of this projection indicates a distinct step-like growth pattern, characterised by plateaus followed by sharp escalations. The initial plateau is indicative of the decommissioning of early, smaller-scale turbines. The first significant surge, anticipated around 2020–2025, aligns directly with the end of the typical 20–25 year operational lifespan for the massive fleet of GFRP-based turbines installed during the major wind energy expansion of the early 2000s. Subsequently, the second and even more pronounced increase projected towards 2030 corresponds to the EoL of the larger, multi-megawatt turbines deployed from the mid-2000s onwards. Although this latter generation achieved notable efficiency through strategic incorporation of CFRP (see Fig. 2), the bulk of the immediate waste stream remains glass-fibre dominant. Consequently, Fig. 4 illustrates a critical implication: the very technological advancements that drove the exponential growth of wind power (Fig. 1) have engendered successive waves of composite waste that demand scalable EoL solutions, different from niche laboratory methods.

However, these forecasts are subject to significant uncertainties that complicate precise planning. The key variables influencing the volume and timing of WTB waste include:

- **Operational lifespan and repowering:** The standard 20-year lifespan is often a conservative assumption. Lifetime extension programmes can push the operation to 30 years, delaying waste generation (Delaney et al., 2023). In contrast, "repowering" projects can accelerate decommissioning (Beauson et al., 2022). Furthermore, the complexities behind the detection of damage (Du et al., 2020; F.P.G. Márquez, 2020) and in-situ repair of WTBs, associated with the susceptibility of composites to environmental degradation (Katsaprakakis et al., 2021), result in a probabilistic waste stream in which blades can be decommissioned long before their designed EoL. This unpredictability favours robust disposal routes capable of handling fluctuating volumes in continuous chemical processing plants.
- **Mass-to-capacity ratios:** Early estimates often used a fixed mass-to-capacity ratio (e.g., 10 t/MW) to forecast waste volumes (Andersen et al., 2016). However, research indicates that this ratio varies significantly with turbine model and size, ranging from 8.4 t/MW to 13.4 t/MW, adding a layer of complexity to material flow analysis (Liu and Barlow, 2017; Arias, 2016).
- **Geographical and regulatory differences:** The EoL landscape is highly fragmented. Although landfilling remains a low-cost option in the US, bans in European countries (e.g. Germany, the Netherlands) force the industry towards recycling (Fraile and Walsh, 2020; Beauson et al., 2022). This regulatory heterogeneity creates a need for solutions that are locally available and comply with strict environmental leaching standards, a requirement that unprocessed landfilling does not meet.

Beyond the volume of material, the physical process of decommissioning presents its own logistical hurdles. The immense size of modern blades necessitates on-site segmentation: cutting blades into smaller pieces to facilitate transport. This process must be carefully managed to avoid environmental contamination (J. et al., 2020; Brussa et al., 2023). Crucially, the resulting segmented material is often rough, of variable geometry, and potentially contaminated with soil or cutting fluids. This state of the feedstock poses a significant challenge for sensitive chemical recycling processes but presents fewer barriers for robust industrial kilns, highlighting the importance of matching the recycling technology to the logistical reality of waste (Delaney, 2022; Delaney et al., 2023).

4. Overview of end-of-life management strategies

The management of wind turbine blade waste encompasses a range of technologies and strategies, each characterised by specific technical challenges, economic feasibilities, and environmental impacts. These alternatives are optimally assessed through the lens of the waste hierarchy, which prioritises prevention, followed sequentially by reuse, recycling, energy recovery, and, as a final measure, disposal (Beauson et al., 2022; European Commission, 2008, 2018), as depicted in Fig. 5. Ideally, strategies should focus on the highest tiers: extending the operational lifetime of blades or enabling their direct reuse. However, for the legacy fleet currently facing decommissioning, these options are constrained by the material reality of 20 years of cumulative fatigue and surface degradation.

Presently, the widespread industrial adoption of lifetime extension remains a significant challenge. This is mainly due to the inherent complexity of distinguishing genuine fault signatures from anomalies caused by environmental conditions (Du et al., 2020). The challenge is exacerbated by the brittle failure nature of composite materials. Although promising techniques such as Acoustic Emission (AE) are sensitive to crack formation (Carpinteri et al., 2007), their application

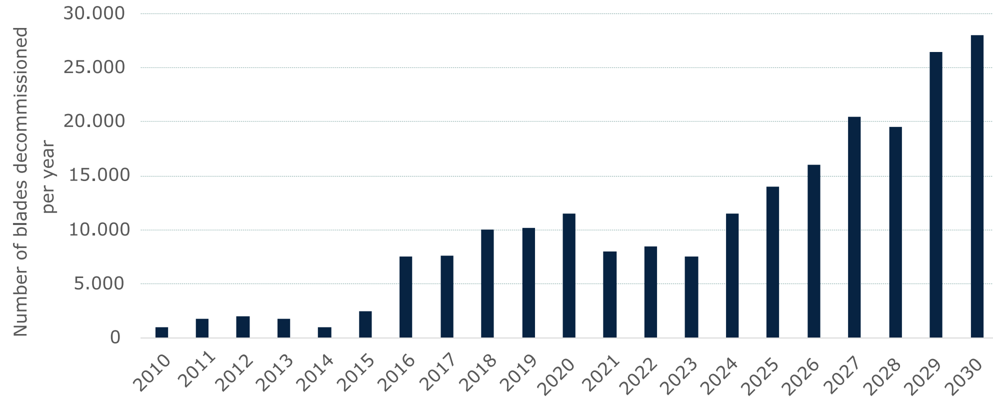

Fig. 4. Projection of the yearly total number of decommissioned wind-turbine blades.
Source: Data retrieved from BNEF (2020).

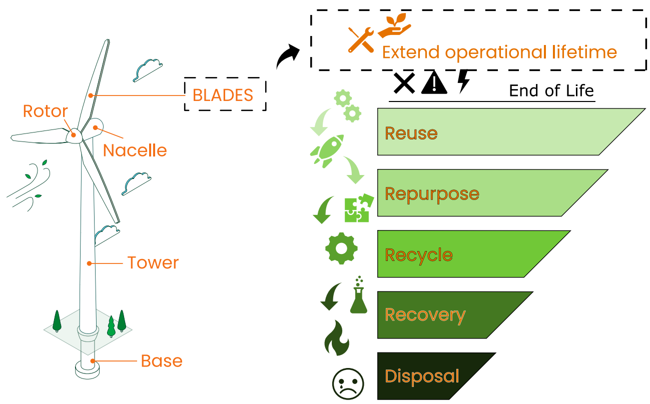

Fig. 5. Hierarchy of EoL approaches for WTBs.

on a mass scale is hampered by signal attenuation over large surfaces and the difficulty in filtering operational noise (Friedrich et al., 2021; Du et al., 2020). More critically, from a logistic perspective, even perfect detection would not solve the obsolescence issue: older blades are often aerodynamically incompatible with newer, more efficient turbine models required for repowering projects.

Consequently, while NDT (Non-Destructive Technique) and SHM (Structural Health Monitoring) methodologies show promise for future fleets, they are not a scalable solution for the current wave of waste. Most inspections still require downtime (Katsaprakakis et al., 2021; OSNDT, 2024; 3WIS, 2025), and the lack of a specialised workforce for in-situ repair creates a bottleneck. Thus, a technological and economic gap persists, meaning that lifetime extension and direct reuse cannot divert the bulk of the decommissioned tonnage. This reality forces the industry to move down the waste hierarchy. This section therefore offers a critical examination of the primary EoL pathways (from landfilling to recovery), benchmarking them not just on technological elegance but also on their immediate capacity to handle the GFRP waste stream.

4.1. Landfilling: The current baseline

Traditionally, landfilling has constituted the default EoL destination for WTBs due to its low operational complexity and immediate capacity to absorb large volumes. In regions with permissive regulatory environments and substantial land availability, such as the United States, it remains the economic baseline against which all recycling technologies must compete (Delaney et al., 2023; Martin, 2020). The procedure typically entails rough segmentation of blades into transportable sections before interment. However, beyond the obvious spatial inefficiency and visual impact, landfilling represents a critical thermodynamic inefficiency: it permanently sequesters the moderate calorific value contained within the polymer matrix energy that could otherwise displace fossil fuels in industrial processes (Fraile and Walsh, 2020). Furthermore, recent studies highlight that landfilled composite waste acts as a persistent source of secondary microplastics due to environmental degradation, posing long-term ecological risks to soil and groundwater ecosystems (Tayebi et al., 2024).

The regulatory framework creates a stark bifurcation in the global EoL landscape. Within the European Union (EU), the push towards a circular economy has led to the ban on the landfill of composite waste in key markets such as Germany, Austria, Finland, and the Netherlands (Fraile and Walsh, 2020; Beauson et al., 2022). This legislative pressure effectively renders landfilling an unviable option in these jurisdictions, driving the search for industrial-scale alternatives. In contrast, in the United States, low tipping fees and the lack of federal bans stifle the economic case for recycling infrastructures, creating a “market failure” where sustainable technologies cannot compete on cost alone (Sproul et al., 2023). Nevertheless, as global sustainability targets harden and the concept of “Extended Producer Responsibility” gains traction, landfilling is increasingly viewed not as a valid management strategy, but as a liability. Consequently, the industry is forced to seek solutions that are not only environmentally superior but also economically resilient enough to function in the absence of landfill options.

A similar transition is observed globally. China, which accounts for the largest wind power capacity globally (≈37% of the total (Zhao, 2025)), is facing a rapidly growing decommissioning wave. While historical data on blade disposal is less transparent, recent regulatory shifts such as the “China Solid Waste Law” (Kurniawan et al., 2022) aim to implement recycling methods ranging from cement kiln co-processing to chemical recycling, moving away from landfilling (Tyurkay et al., 2024). However, regional disparities in waste management infrastructure remain a challenge, mirroring the fragmented landscape seen in the West.

4.2. Reuse and repurposing

Situated high on the waste hierarchy, reuse (of the entire turbine in a new location) and repurposing (using blade sections for new applications) aim to extend the material’s service life, preserving its embedded value. Repurposing, in particular, has captured public imagination and academic interest, effectively transforming decommissioned blades into architectural and civil engineering structures. High-profile examples include pedestrian bridges, playgrounds, bicycle shelters, and noise barriers (Delaney, 2022; André et al., 2020; Devic et al., 2018). Theoretically, this approach offers the highest value retention by taking advantage of the remaining mechanical strength of the composite rather than reducing it to raw materials.

However, a critical assessment reveals a fundamental disconnect between the symbolic success of these demonstrators and the industrial reality of the waste stream. The primary barrier is not merely logistical but structural unpredictability. EoL blades carry a history of cumulative fatigue damage that is difficult to quantify without expensive, case-by-case NDT. This variability conflicts with civil engineering standards that require certified, homogeneous material properties, turning every repurposing project into a bespoke engineering challenge rather than a reproducible industrial process. Consequently, while valuable for raising awareness, repurposing lacks the scalability to absorb the massive influx of waste depicted in Figs. 3 and 4 (Shen et al., 2023). The logistical costs of transporting intact blades for architectural conversion often exceed the value of the structure itself, relegating this strategy to a niche role rather than a systemic solution for the legacy fleet (Beauson et al., 2022).

4.3. Mechanical recycling

Mechanical recycling involves the comminution of WTB material through shredding, crushing and grinding to produce a heterogeneous mixture of short fibres, powdered polymer and fillers, commonly termed “regrind” or “recycle” (Mamanpush et al., 2018; Shen et al., 2023). Although technically mature, the process faces immediate challenges with respect to the complex material architecture of modern blades. The increasing integration of GFRP with stiffening elements such as CFRP or aramid fibres creates a multi-material stream that is difficult to segregate mechanically. Consequently, the output is often a mixed-fraction product with inconsistent properties, limiting its re-introduction into high-performance applications.

The primary outlet proposed for this recyclate is as a filler or aggregate substitute in construction materials. A significant body of recent research, including extensive experimental campaigns reviewed by D. Jasińska (2025) and Rucka and Kurpińska (2025), has demonstrated the technical feasibility of incorporating mechanically recycled GFRP into cementitious composites (mortar and concrete). However, from an industrial scalability perspective, this route represents a classic case of “downcycling” with diminishing returns. The grinding process obliterates the long, aligned fibre architecture responsible for the original composite’s strength, reducing the material to a passive inclusion. Furthermore, replacing natural aggregates with shredded composites often introduces technical drawbacks, such as increased water demand, reduced workability, and potential problems with the alkali-silica reaction (ASR) if the glass chemistry is not compatible (Rucka and Kurpińska, 2025). Economically, this recyclate must compete with virgin aggregates (sand and gravel) or fillers (calcium carbonate), which are among the cheapest commodities on Earth (Sproul et al., 2023). Thus, while mechanical recycling into concrete can divert waste, it does not recover the embodied energy of the polymer or the chemical value of the glass, trapping the material in a low-value loop.

Beyond Portland cement concrete, research has also explored the use of mechanically recycled blade waste in alternative binders, such as geopolymers. It was demonstrated (Figiela et al., 2022) that wind turbine waste can be used as a filler in coal gangue-based geopolymers, achieving compressive strengths suitable for construction products (≈4 MPa), though with a decrease in performance compared to reference samples.

However, whether in ordinary Portland cement or geopolymers, the incorporation of mechanically shredded composite waste presents non-trivial chemical challenges. Recent mechanistic studies (Liu et al., 2025b,a) revealed that the organic resin fraction is not merely an inert filler; in alkaline environments (pore solution), polyester and epoxy resins can undergo hydrolysis. This reaction consumes hydroxide ions (OH^-), potentially reducing the pH of the pore solution and delaying hydration kinetics. Furthermore, the leaching of organic compounds can interfere with the formation of the Calcium-Silicate-Hydrate (C–S–H) gel network, affecting the interfacial transition zone (ITZ) and long-term durability. These findings underscore that mechanical recycling into construction materials is technically constrained by chemical compatibility, reinforcing the need for solutions that fully mineralise the organic fraction, such as co-processing.

4.4. Thermal and chemical treatments

In contrast to mechanical recycling, thermal and chemical treatments aim to break down the polymer matrix to recover the reinforcing fibres. Detailed technical descriptions of these processes, including reactor types and chemical kinetics, have been covered in detail in recent reviews such as Spini and Bettini (2024) and S. Bulińska and Pyzalski (2024). Therefore, this section focusses primarily on the economic and logistic applicability of these technologies to the specific composition of the wind turbine waste stream.

4.4.1. Solvolysis

Solvolysis represents the theoretical ideal of chemical recycling: using solvents, heat, and pressure to depolymerise the resin into monomers for re-synthesis, thereby achieving a genuine “closing of the loop” (Shen et al., 2023). As detailed extensively in reviews such as Spini and Bettini (2024) and S. Bulińska and Pyzalski (2024), this method surpasses thermal routes in preserving the tensile strength of the fibre by operating at lower temperatures.

However, when viewed through the lens of industrial scalability for the legacy fleet, solvolysis faces a prohibitive readiness gap. The process is currently characterised by high operational expenditures (OPEX) related to solvent management and recovery. Crucially, the economic logic of using expensive chemical reagents to recover low-value E-glass fibres from the dominant GFRP waste stream is fundamentally flawed. Although promising for high-value CFRP or future recyclable resin systems (thermoplastics), the technology currently operates at a Technology Readiness Level (TRL 4–6) insufficient to handle the megaton-scale volumes of waste projected for the coming decade (Beauson et al., 2022). Consequently, solvolysis remains a niche research avenue for high-value recovery rather than a systemic answer to the immediate mass disposal crisis.

4.4.2. Pyrolysis and gasification

While solvolysis remains immature, thermal treatments like pyrolysis are often presented as the most viable alternative. Pyrolysis and gasification are thermochemical treatments that break down the composite’s polymer matrix to enable the recovery of reinforcing fibres. Pyrolysis, the more extensively studied of the two for this application, decomposes the material in an oxygen-free or oxygen-starved environment at elevated temperatures (typically 450 °C to 700 °C). This process yields three primary product streams:

(1) a solid char containing the reinforcing fibres (glass or carbon) (Barnes and Walter, 2022),
(2) a liquid oil (py-oil), and
(3) a synthesis gas (syngas) (Xu et al., 2025).

Both the pyrolysis oil (py-oil) and syngas fractions exhibit significant calorific values and can be harnessed for energy production, thus contributing to a partial compensation of the energy consumption inherent in the process. Gasification, a related technological process, employs a carefully regulated quantity of an oxidising agent to predominantly convert the organic components into syngas. Although both py-oil and syngas demonstrate substantial potential for energy recovery, the primary economic impetus for employing pyrolysis technology is the recuperation of high-value fibrous materials.

This creates a technological bifurcation. For Carbon Fibre (CF), projected to face supply deficits driven by the electric vehicle market

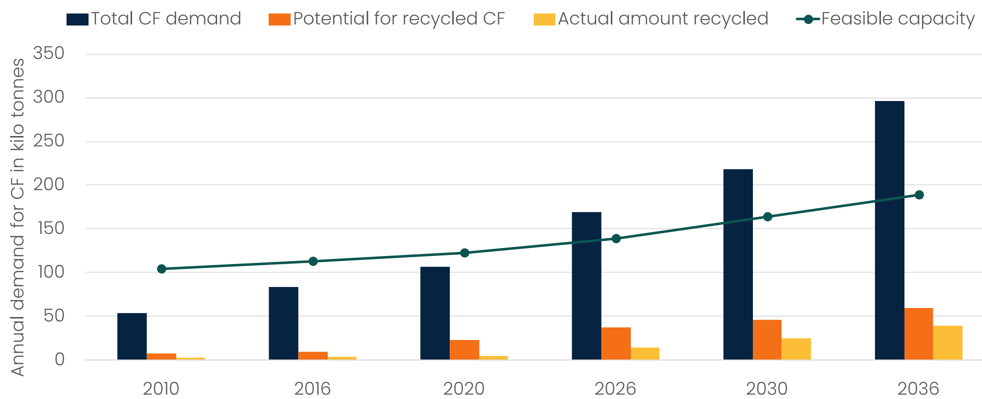

Fig. 6. CF market demand projection, highlighting the economic incentive for rCF.
Source: Data retrieved from Barnes and Walter (2022).

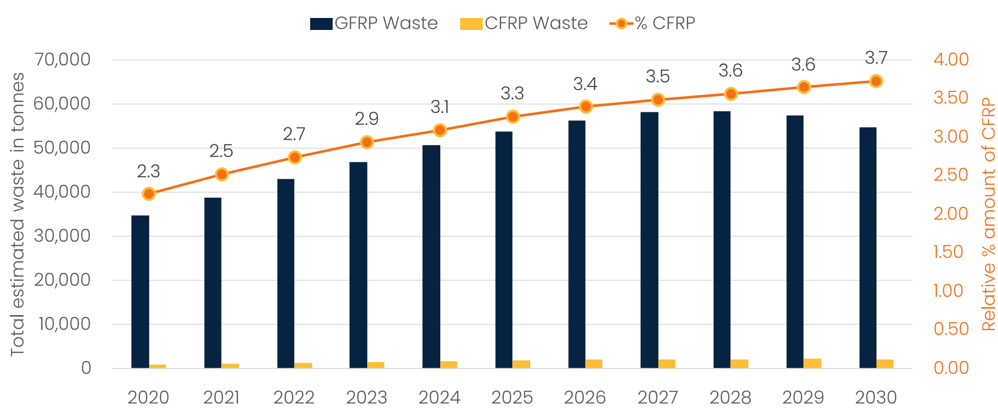

Fig. 7. Estimative of total amount of GFRP and CFRP waste exclusively from WTBs within EU.
Source: Data retrieved from Sommer and J. Stockschläder (2020).

(see Fig. 6), pyrolysis represents a vital circular pathway. The high intrinsic value of virgin CF (often > \$20/kg) justifies the energy-intensive recycling process to obtain Recycled Carbon Fibre (rCF) (Barnes and Walter, 2022).

However, applying this "Carbon-logic" to the "Glass-reality" of the current wind sector presents fundamental contradictions:

- **Fibre quality degradation:** Glass fibres are significantly more sensitive to thermal history than carbon. Process temperatures often degrade the mechanical strength of recovered glass fibres (rGF) by 50% or more, rendering them unsuitable for closed-loop recycling into new blades without expensive resizing or remelting (Shen et al., 2023; Sproul et al., 2023).
- **The legacy fleet composition:** A critical disconnect exists between the technology's focus and the waste's reality. As shown in Fig. 7, the legacy fleet currently entering the EoL phase is overwhelmingly GFRP (Sommer and J. Stockschläder, 2020). While CFRP is crucial for future ultra-large rotors (Riley et al., 2025), it constitutes a minor fraction of the immediate waste tonnage. Investing in pyrolysis capacity now to handle a GFRP-dominant stream leads to a mismatch between processing cost and output value.
- **Economic viability for GFRP:** This is the fatal flaw for pyrolysis of legacy blades. Virgin glass fibre is a low-cost commodity (≈\$2/kg). The cost of collecting, shredding, pyrolysing, and post-treating GFRP to remove char often exceeds the market price of virgin fibre. Unlike CFRP, where the recyclate has a high market value, rGF competes with cheap virgin materials, making pyrolysis economically uncompetitive without massive subsidies.

In essence, while pyrolysis is very promising in the future for CFRP, it is an economic dead-end for the millions of tonnes of GFRP currently requiring disposal. This necessitates a solution that recovers value from the glass fraction not as a fibre, but as a mineral resource, pointing directly towards cement co-processing.

4.5. *Cement co-processing: A scalable solution for GFRP waste*

Given the economic constraint establishing that recovered glass fibres often cost more than their virgin counterparts, the industry requires a solution that valorises the chemical rather than structural potential of the material. In this context, cement co-processing emerges as the unique contender capable of managing the vast tonnage of the GFRP legacy fleet. Unlike emerging recycling technologies that require the construction of dedicated facilities with unproven economics, co-processing leverages existing high-capacity industrial infrastructure. It represents a technologically mature form of industrial symbiosis that offers a pragmatic route for diverting waste from landfills (Fraile and Walsh, 2020; Beauson et al., 2022). This section provides a detailed examination of the co-processing principle, shifting the focus from waste disposal to resource efficiency, and analyses the specific chemical synergies that make GFRP an ideal alternative resource for clinker production.

4.5.1. *The principle of co-processing: Dual material and energy recovery*

Co-processing is a distinct industrial concept in which waste materials serve simultaneously as an alternative fuel and as an SRM within the cement kiln system. In the context of WTB waste, the process leverages the composite's heterogeneous nature, utilising both the organic polymer matrix and the inorganic glass reinforcement (JEC, 2023b;

Schindler et al., 2024). The waste blades undergo pre-processing, typically shredding into homogeneous fractions (e.g., <40 mm), to ensure aerodynamic suspension and complete burnout within the kiln's pre-calciner (J. et al., 2020).

Upon introduction into the kiln system, typically at the pre-calciner stage or in the kiln inlet, where temperatures range from 900 °C to 1200 °C, the composite undergoes a bifurcated transformation:

- **Energy recovery (organic fraction):** The polymer matrix (epoxy/polyester), constituting 30%–40% of the mass, combusts exothermically. With a Lower Heating Value (LHV) that generally ranges between 12 MJ kg^{-1} to 15 MJ kg^{-1}, the resin substitutes primary fossil fuels (e.g. coal or petcoke), providing the thermal energy required for the endothermic decarbonation of limestone (Wegman, 2024; Beauson et al., 2022).
- **Material recovery (inorganic fraction):** Crucially distinguishing this process from incineration, the inorganic glass fibres (approx. 60% SiO_2, along with CaO and Al_2O_3) do not become waste ash. Instead, they enter the clinkerization reactions. At temperatures exceeding 1450 °C, the glass silica reacts with calcium oxide to form calcium silicates (Alite C_3S and Belite C_2S), the primary strength-giving phases of Portland clinker. Thus, glass fibre is not only a filler, but becomes chemically mineralised into the binder structure, displacing virgin raw materials such as clay and sand (Schindler et al., 2024; Viczek et al., 2021).

This dual-recovery mechanism positions co-processing uniquely within the EU waste hierarchy (Fig. 5) as a recovery operation (R1) (European Commission, 2008). Unlike simple incineration, where the mineral content ends up as landfilled bottom ash, or mechanical recycling into concrete, where fibres remain chemically inert, co-processing achieves total chemical integration of the waste.

4.5.2. Benefits and environmental performance

The environmental argument for co-processing rests on its unique capability to address the two dominant sources of cement manufacturing emissions simultaneously: thermal energy demand and process emissions. A recent LCA commissioned by European industry associations demonstrated that for every 1000 kg of composite waste treated, cement co-processing saves approximately 830 kg of CO_2 equivalent compared to incineration with energy recovery (Caro et al., 2023). This net benefit derives from specific chemical efficiencies:

- **Emissions avoided from fossil fuels:** Although the composite contains $\approx 60 - 70\%$ inert glass, the organic polymer matrix provides a Lower Heating Value (LHV) typically ranging between 10 MJ kg^{-1} to 14 MJ kg^{-1} (Fraile and Walsh, 2020). Although lower than high-grade petcoke ($\approx$32 MJ kg^{-1}), this moderate calorific value allows the waste to function as a valuable Alternative Fuel (AF), effectively compensating for a significant portion of the primary thermal demand.
- **Emissions avoided from raw material calcination:** This is the critical differentiator. In conventional cement production, $\approx$60% of CO_2 emissions come from the chemical decarbonisation of limestone ($CaCO_3 \rightarrow CaO + CO_2$). The inorganic fraction of GFRP (E-glass) contains significant amounts of calcium oxide (CaO) and silica (SiO_2) in a non-carbonate form. By introducing these oxides directly into the kiln, the co-processing bypasses the decarbonation step required for virgin limestone, thus eliminating the associated process emissions (Schindler et al., 2024).

Crucially, this thermodynamic efficiency highlights the limitations of mechanical recycling in concrete (discussed in Section 4.3). Although using shredded blades as concrete aggregate only offsets the low carbon footprint of mining sand, co-processing actively reduces the high carbon footprint of clinker production. With a material utilisation rate of up to 100% (combining energy and mineral recovery) (Trivyza et al., 2025; Tayebi et al., 2024), co-processing offers a systemic decarbonisation lever that downstream recycling methods cannot match.

Fig. 8, derived from Wegman (2024), visualises this impact. The analysis contrasts the Greenhouse Warming Potential (GWP) of the treatment of 1 t of composite waste. While incineration releases carbon (even with energy recovery), co-processing results in a net negative carbon impact (savings) because of the displacement of carbon-intensive clinker phases.

4.5.3. Technical challenges and process considerations

Despite the clear environmental benefits, the integration of WTB waste into clinker production is constrained by strict chemical and operational limits. Successful co-processing requires navigating three primary technical bottlenecks:

- **Trace element chemistry (Boron):** The most significant chemical limitation arises from the borosilicate nature of E-glass fibres. Boron acts as a strong flux and mineraliser, but in excess concentrations (>0.2% in clinker), it inhibits the formation of Alite (C_3S) and stabilises Belite (C_2S), severely retarding the cement's setting time and the early compressive strength (Schindler et al., 2024). To mitigate this constraint beyond simple volumetric dilution, kiln operators can implement targeted raw mix compensation strategies. This includes increasing the Lime Saturation Factor (LSF) of the raw meal to thermodynamically force the formation of Alite despite the presence of boron. Additionally, the strategic use of compensatory mineralisers (e.g., calcium fluoride) can counteract the inhibitory effects of B_2O_3, while rapid clinker quenching (fast cooling) helps physically lock the highly reactive Alite phase before it can revert to Belite (Chatterjee, 2011; Schindler et al., 2024). These operational adjustments allow for a higher substitution rate of WTB waste without compromising early-age cement performance.
- **Volatile cycles (Chlorine/Alkalis):** Modern blades often contain PVC foam cores. The introduction of chlorine into the alkaline environment of a cement kiln creates volatile alkali-chlorides (e.g., KCl, NaCl). These compounds vaporise in the sintering zone and condense in the cooler preheating towers, causing severe clogging and coating formation that can force unscheduled plant shutdowns (Viczek et al., 2021; Aldrian et al., 2020). This necessitates strict pre-sorting of PVC components or the use of kilns equipped with alkali-bypass systems.
- **Combustion aerodynamics:** Unlike coal, shredded composite particles are light and have varying aerodynamic properties. There is a risk that lighter particles may be entrained by the gas flow into the upper cyclone stages before complete burnout, leading to potential CO spikes or incomplete mineral integration. This underscores the need for precise shredding (typically < 40 mm) and optimisation of the feeding point (direct injection of calciner) to ensure that the residence time satisfies combustion kinetics (J. et al., 2020).

Although emissions of NOx and SO_2 must be monitored (as observed in analogous waste streams such as sewage sludge (Yu et al., 2024)) modern cement plants equipped with Selective Non-Catalytic Reduction (SNCR) and scrubbers are generally capable of managing these pollutants. Therefore, the primary barrier remains the stability of the kiln operation and the mineralogical quality of the clinker.

4.5.4. Industrial implementation and regulatory context

Unlike emerging chemical recycling methods that struggle to leave the pilot phase, cement co-processing operates on a full industrial scale (TRL 9). In Europe, pioneering efforts by Holcim (via Geocycle) and Finnsementi have validated the logistical chains required for mass treatment. In particular, a dedicated plant in Bremen, Germany, co-processed 10 kt to 15 kt annually for more than a decade. Although its

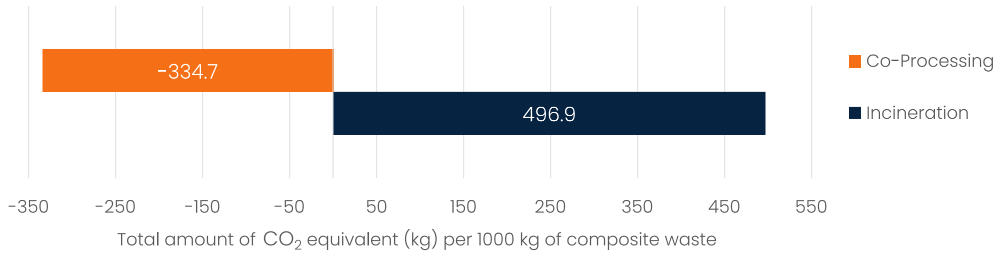

Fig. 8. GWP of treating 1000 kg of composite waste in co-processing versus incineration (Wegman, 2024), showing how co-processing yields net-negative emissions by simultaneously displacing fossil fuels and avoiding the carbon-intensive calcination of virgin limestone.

recent discontinuation driven by volatile energy prices highlights the sensitivity of the process to OPEX, the technology remains proven. Concurrently, the KiMuRa project in Finland (Pietikäinen, 2024) has successfully transitioned into a commercial operation, demonstrating that regional hubs can effectively treat composite waste when integrated with local cement capacity (Nehls, 2024).

In the United States, the trajectory is driven less by legislative bans and more by corporate sustainability mandates. The partnership between Veolia and GE Renewable Energy has processed more than 3000 blades, proving that co-processing is economically viable even in markets where landfilling remains a low-cost competitor (Karidis, 2021; Sproul et al., 2023). The economic feasibility of this model, despite the absence of landfill taxation, can be explained by the interaction of corporate strategic considerations and industrial symbiosis. First, Original Equipment Manufacturers (OEMs) exhibit a willingness to internalise a "green premium" by paying higher gate fees to cement plants than to nearby landfill facilities. This behaviour is driven by the need to comply with stringent Environmental, Social, and Governance (ESG) zero-waste commitments and to preserve the reputation of the corporate brand. In addition, the implementation of long-term, high-volume reverse-logistics contracts enables the realisation of economies of scale that partially mitigate transportation-related cost penalties. From the perspective of cement producers, the intake of WTB waste confers a twofold economic advantage: it secures a predictable stream of gate-fee revenues and simultaneously serves as a financial hedge against the price volatility of primary fossil fuels, thereby fostering a mutually reinforcing and economically resilient industrial ecosystem.

In Europe, large-scale innovative initiatives are validating the logistic chain. For instance, the EU-funded Blades2Build project (a consortium of 14 partners from eight countries) is currently demonstrating the feasibility of "coupled pre- and co-processing" at a pilot scale. By optimising the shredding and chemical adjustment of large blades to serve as ideal feedstock for cement kilns, such projects bridge the critical gap between waste collection and industrial uptake.

A significant step towards mainstream acceptance is the development of international standards. The new ISO standard (ISO/DIS 4349) (ISO, 2024) for the "Determination of the Recycling Index for co-processing" fundamentally changes the regulatory landscape. Its utility lies in providing a standardised methodology to scientifically decouple the "energy recovery" share (derived from resin combustion) from the "material recycling" share (derived from glass mineralisation). Previously, co-processing was often legally categorised purely as energy recovery (lower in the waste hierarchy). This standard allows operators to certify the inorganic fraction as recycled material, enabling national governments and industries to officially count co-processing towards their circular economy material goals (Wegman, 2024).

5. Discussion and future perspectives

The preceding analysis elucidates a fundamental dichotomy in EoL management: the inverse relationship between a technology's capacity to recover high-value materials and its industrial capacity to absorb mass. As summarised in Table 1, each pathway occupies a distinct position on this spectrum. This discussion critically synthesises these findings to identify why, despite the theoretical appeal of closed-loop recycling, the industry is gravitating towards co-processing for the legacy fleet. We further outline the research and policy vectors required to transition from this pragmatic baseline to a truly circular economy.

5.1. The critical trade-off: Scalability versus value recovery

The central challenge in managing WTB waste can be conceptualised as a "Scalability-Value Paradox": methods that retain high material value generally lack the throughput required for the legacy fleet, while scalable methods often degrade material properties. At one end of the spectrum, the repurposing of blades for civil infrastructure offers the highest value retention, preserving the structural integrity of the composite (Delaney, 2022). However, as argued in Section 4.3, this approach represents a "boutique" solution, bespoke and logistically complex. To quantify this disparity: a typical repurposing project (e.g., a pedestrian bridge or architectural installation) absorbs merely 10 t to 50 t of material. This is fundamentally unscalable when contrasted against the impending influx of tens of thousands of decommissioned blades (representing hundreds of thousands of tonnes annually) depicted in Fig. 4 (Beauson et al., 2022). In contrast, chemical recycling methods like solvolysis promise true circularity by recovering monomers and high-quality fibres. However, applying such high-OPEX processes to recover low-value E-glass is economically unjustifiable, restricting their viability to high-value CFRP niche streams (Shen et al., 2023; Sproul et al., 2023).

Between these extremes lie mature industrial technologies. Mechanical recycling, while scalable, reduces high-performance composites to what is effectively "expensive gravel" (a low-value filler competing with abundant natural aggregates (Mamanpush et al., 2018)). Similarly, pyrolysis faces an economic mismatch when applied to GFRP: the energy cost of thermal decomposition often exceeds the market value of the recovered degraded glass fibres (Xu et al., 2025; Sproul et al., 2023). This analysis exposes a critical gap for a solution that decouples processing capacity from the intrinsic value of the recyclate. The industry requires a pathway that is industrially robust enough to handle the volume of mechanical recycling, but chemically sophisticated enough to recover more value than mere landfilling.

5.2. Cement co-processing: A pragmatic and scalable pathway

In the context of the paradox of scalability-value, cement co-processing emerges as the unique solution capable of reconciling the massive volume of the legacy fleet with the economic reality of low-value GFRP. Its status as TRL 9 signifies that this is not a theoretical projection but a proven industrial reality, operationally mature in Europe and gaining traction in the United States (Wegman, 2024; Schindler et al., 2024).

The primary advantage is its logistical absorbency: the global cement industry has a throughput capacity capable of assimilating volumes of shredded waste that far exceed the combined potential of repurposing projects and emerging chemical recycling plants.

Table 1
Comparative analysis of EoL management strategies for WTBs: the trade-off between TRL and value retention.

Strategy	TRL	Main Output(s)	Advantages	Disadvantages
Landfilling	9	Waste	Low operational cost (US); immediate capacity.	Permanent loss of energy/material value; legislative bans (EU); long-term liability.
Reuse/Repurposing	6–8	Structural elements (bridges, shelters)	Highest value retention; preserves composite architecture.	**Low Scalability;** structural certification challenges; bespoke engineering required; high logistic costs.
Mechanical Recycling	9	Fillers, regrind for concrete/composites.	Technologically mature; low CAPEX; handles mixed material.	Severe downcycling (inert filler); **limited market absorption** in construction sector due to durability concerns.
Pyrolysis/Gasification	7–9	Recovered fibres (char), py-oil, syngas.	Recovers fibres and energy; ideal for carbon fibre (CFRP).	**Economic mismatch for GFRP;** fibre strength degradation; high energy input; char removal costs.
Cement Co-processing	9	Mineralised Clinker phases + Energy.	Industrially scalable; **Dual Recovery**; mitigates microplastic generation; ISO 4349 compliant recycling.	Loss of fibre structure (downcycling); strict limits on elements as B and Cl; dependent on kiln proximity.
Solvolysis	4–6	High-quality fibres, monomers.	High potential for circularity; preserves fibre strength better than thermal routes.	Prohibitive OPEX for glass fibre recovery; solvent management; low TRL; currently unscalable.

The primary advantage is its logistical absorbency. To contextualise this capacity quantitatively: the projected cumulative global WTB waste of 43.4 Mt by 2050 (Liu and Barlow, 2017) represents approximately 1% of the global cement production in a single year (which currently exceeds 4 billion tonnes annually according to estimative from the United States Geological Survey, USGS (Hatfield, 2025)). Consequently, the global cement industry has a throughput capacity capable of assimilating volumes of shredded waste that far exceed the combined potential of repurposing projects and emerging chemical recycling plants.

Crucially, this review argues for a reframing of the downcycling critique often levelled against co-processing. Although the physical structure of the fibre is destroyed, its chemical value is fully recovered through mineralisation. Therefore, this is a distinct advantage over mechanical recycling in concrete, where the fibre remains a passive, potentially harmful inclusion. By recovering the energy content of the resin (displacing coal or other fuel) and the mineral content of the glass (displacing limestone or other virgin material), co-processing achieves a dual-benefit that aligns with the rigorous definition of recycling under the new ISO 4349 standard. Consequently, it acts not just as a waste management tactic, but as the essential bridging technology. It provides the only immediately deployable pathway to divert the imminent first wave of GFRP waste from landfills (refer to the plateau in Fig. 4), safeguarding the industry's social licence to operate while higher-value circular solutions for future blade generations mature.

5.3. Future perspectives: Towards an integrated EoL ecosystem

As recently emphasised by a landmark forum of European and Chinese academies, achieving sustainability requires not merely technological fixes, but a systemic reimagining of production and waste management systems towards a circular economy (Ambrosio et al., 2025). In line with this vision, a truly sustainable future for composites will likely not rely on a "one-size-fits-all" technology, but rather on a stratified ecosystem where waste streams are routed based on their economic potential. To transition from the current ad-hoc management to a systemic solution, research and policy must converge on the following vectors:

- **Technological bifurcation (GFRP vs. CFRP):** Future developments must recognise the distinct trajectories of fibre types. Although co-processing solidifies its position as the industrial backbone for the massive GFRP legacy fleet, R&D funding for pyrolysis and solvolysis should be aggressively targeted at the growing CFRP stream. For carbon, there is an economic incentive for fibre recovery; the challenge is to reduce the intensity of the energy. For glass, the focus must remain on optimising the clinkerization efficiency.
- **Regulatory harmonisation and standardisation:** The current regulatory fragmentation creates market distortions where landfilling remains artificially cheap. The widespread adoption of landfill bans, as pioneered by Germany, drives innovation but requires EU-wide harmonisation (Fraile and Walsh, 2020). To actively resolve this, policymakers should implement two concrete measures: first, enforcing phased supranational landfill bans on composite waste to eliminate the unsustainable baseline; and second, integrating recycled content mandates into Green Public Procurement (GPP) frameworks for infrastructure projects. This would create a guaranteed market pull for sustainable materials, financially justifying reverse logistics. Crucially, the implementation of the new ISO/DIS 4349 (ISO, 2024) standard is the essential enabler of the industry. Policymakers must adopt this methodology to legally recognise the mineral fraction of co-processed blades as "Recycling" rather than "Recovery", thereby unlocking circular economy credits for operators (Wegman, 2024).
- **Data infrastructure for process safety:** An efficient reverse supply chain requires more than just logistics; it requires chemical transparency. The development of "blade passports" or digital twins is not merely an administrative tool, but a process safety requirement for cement kilns. Accurate data on trace elements (boron, chlorine) and filler composition for specific turbine models allow kiln operators to optimise feed rates and avoid mineralogical defects in the clinker, transforming waste acceptance from a risk to a controlled science (Delaney, 2022).
- **Long-term mineralogical analysis:** Unlike mechanical recycling into concrete, where long-term durability concerns remain a barrier, co-processing alters the chemical structure of the binder. More research is needed to rigorously map the influence of trace elements from blades on the hydration kinetics and long-term durability of the resulting so called Green Cements (Schindler et al., 2024). Comprehensive LCAs that compare these cements with region-specific energy mixes will provide the ultimate validation of environmental trade-offs (Diez-Cañamero and Mendoza, 2023; J. et al., 2020).

In summary, the path to a circular economy is becoming clearer through specialisation. Cement co-processing provides the vital, scalable infrastructure to manage the GFRP legacy fleet today, buying the industry the time necessary for advanced recycling technologies to mature and accommodate the complex, carbon-rich designs of tomorrow.

6. Conclusions

The exponential expansion of the wind energy sector has generated a massive environmental liability: the millions of tonnes of composite waste currently residing in the decommissioning pipeline. As this review has demonstrated, the industry faces a scale-value paradox where the sheer volume of the legacy fleet, predominantly composed of GFRP, overwhelms the capacity of niche recycling technologies.

Based on the critical synthesis of the state-of-the-art, three definitive conclusions emerge:

1. **The economic limits of circularity:** While advanced thermal and chemical treatments, such as pyrolysis and solvolysis, offer the theoretical promise of fibre recovery, they present a fundamental economic mismatch for the legacy WTs fleet. Investing in energy-intensive processes to recover low-value glass fibres is currently economically irrational. These technologies should be strategically reserved for the growing CFRP stream, where the intrinsic value of the material justifies the processing cost.
2. **Limitations of mechanical downcycling:** Although mechanical recycling into cementitious composites is technically feasible, as highlighted in recent literature, it faces significant barriers in terms of market absorption and long-term durability. Treating a ground composite merely as a passive filler or aggregate substitute fails to recover the chemical potential of the material and competes in a saturated market of low-cost natural aggregates.
3. **The primacy of cement co-processing:** Consequently, cement co-processing stands out not merely as a disposal alternative, but as the premier industrial solution for GFRP. It is the only pathway that operates on the required megaton-scale (TRL 9) while achieving a dual-recovery of value: the organic matrix provides essential thermal energy and, crucially, the inorganic glass fraction is chemically mineralised into the clinker phases (C_3S, C_2S). This distinct chemical integration, now validated by the ISO/DIS 4349 standard, positions co-processing superior to landfilling and mechanical recycling in terms of net decarbonisation.

Moving forward, the path to sustainability requires a stratified ecosystem. Cement co-processing provides the vital, immediately deployable bridge to manage the GFRP legacy wave, safeguarding the industry's social licence to operate. Simultaneously, policy and R&D must pivot to prepare for the next generation of waste, ensuring that future recycling technologies match the specific economic realities of the materials they intend to recover.

CRediT authorship contribution statement

Leonel Echer: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Ignacio Iturrioz:** Writing – review & editing, Supervision, Conceptualization. **Giuseppe Lacidogna:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

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

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