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End-of-Life wind turbine blades: review on recycling strategies

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Abstract

The review focuses on End-of-Life (EoL) strategies, with a primary emphasis on recycling techniques, to manage fiber reinforced thermoset polymer waste from decommissioned wind turbine blades. Wind energy has recently become one of the most important sources of electricity. Over the next few years, further growth is expected, leading to increasing amounts of EoL waste, and especially composite waste, which is difficult to recycle. Glass fiber reinforced polymer (GFRP) is the predominant composite material used in blades. However, the increasing size of next-generation wind turbine blades is also driving the adoption of carbon fiber reinforced polymer (CFRP). GFRP is often recycled through cement kiln process or mechanically due to its low-cost. Thus, research is needed on cost-effective methods that can recover valuable glass fibers. On the other hand, CFRP is a high-value material, justifying the use of high-cost recycling approaches compared to virgin fiber production.

Keywords: Wind turbine blades, A. Recycling, A. Glass fibres, A. Carbon fibre

1. Introduction

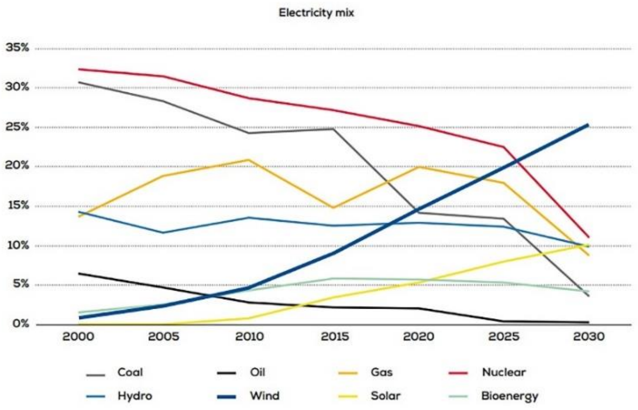
The goal of net-zero greenhouse gas emissions by year 2050 underlies the European Green Deal [1]. A successful shift to a climate-neutral society is urgently needed to address climate change. By the year 2030, Europe has scheduled a 55% reduction in greenhouse gas emissions compared to those of 1990 [2]. For achieving deep decarbonization, the growth of renewable energy is crucial.

Fig. 1a illustrates the electricity mix in EU-27. In recent years, wind power has become one of the most important sources of electricity due to its environmentally friendly nature and numerous wind energy resources. In 2020, wind power accounted for 15 % (382 TWh) of total energy production, exceeding for the first time the quantity of electricity produced by burning coal. Wind power is projected by the European Commission to be the primary source of electricity by 2030, accounting for 25 % of Europe's electricity mix. Additionally, it is forecasted that by 2050, wind farms will cover 50 % of Europe's electricity requirements [2].

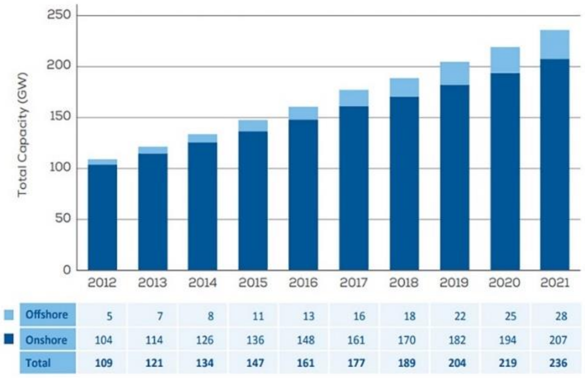
In year 2021, the total installed wind power capacity in Europe (EU-27 and UK) amounted to 236 GW (Fig. 1b). There is a predominance of onshore wind, accounting for 88 % of wind power plants. Europe's new wind installations reached 17.4 GW in 2021. WindEurope foresees the addition of 116 GW of new wind energy installations in the timeframe 2022-2026, translating to an average installation of 23 GW per year [3].

It is clear that such an expansion of the wind industry involves the management of an increasing amount of waste from End-of-Life (EoL) wind turbines. Wind turbine is almost completely recyclable. Blades, however, are composed of composite materials, specifically fiber reinforced thermoset polymers, making them difficult to recycle [4], [5].

The purpose of this review is to present the different EoL strategies for wind turbine blades, focusing on recycling methods available for thermoset composite materials. The second section, after describing the materials used for wind turbines, explores the composite structure of blades and the forecasted quantities that will be decommissioned. Additionally, this section highlights the increasing use of carbon fiber as reinforcing material, especially for longer blades. In the context of wind turbine blade recycling, the focus has traditionally been on glass fiber composites. Nevertheless, it is crucial to recognize the growing utilization of carbon fiber reinforced composites within the wind energy sector, challenging the conventional association of wind turbine blade recycling with glass fiber composites. The third section presents different End-of-Life strategies for wind turbine blades, while the fourth is devoted to describing recycling methods for thermoset composites. Finally, the fifth section provides conclusions drawn from the analysis of EoL strategies and outlines future prospects for wind turbine blade waste management.



(a)



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Offshore	5	7	8	11	13	16	18	22	25	28
Onshore	104	114	126	136	148	161	170	182	194	207
Total	**109**	**121**	**134**	**147**	**161**	**177**	**189**	**204**	**219**	**236**

(b)

2. Materials for wind turbines

The description of materials that constitute a wind turbine is critical for analysing different management options, once the end of their service life is reached. Nowadays, the majority of wind turbine's components are recyclable, with a recyclability rate that equals 85-90%. Tower steel can be processed as a raw material for steel fabrication, while concrete from foundations is used for building materials, road construction or even recycled to build new wind turbines, encouraging the circularity of concrete within the same sector [5], [6], [7] . In some cases foundations cannot be completely removed due to environmental impact concerns or at the discretion of the landowner. On the other hand, wind turbine blades pose a challenge for recycling due to the nature of the materials involved in their composition [5].

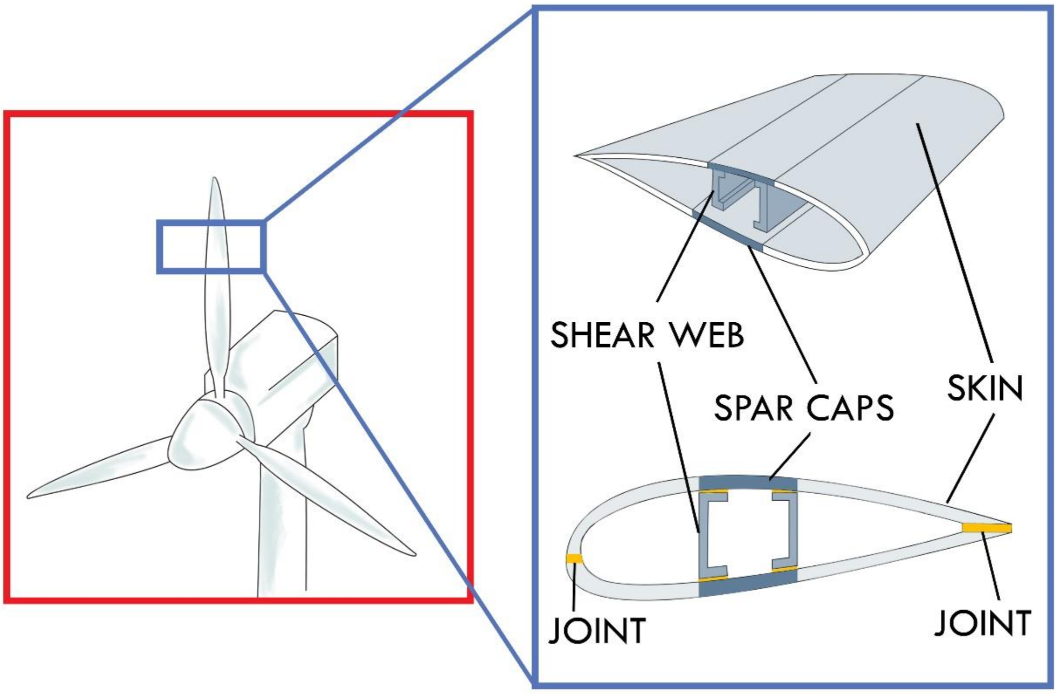
The primary material used for blade manufacturing is glass fiber reinforced polymer (GFRP) composite, with approximately 60-70 % reinforcing fibers and 30-40 % polymer matrix by weight. Carbon fiber reinforced polymer (CFRP) composite is also used in the wind industry, but to a lesser extent [8].

Composites can offer high strength-to-weight ratio to fulfil mechanical and aerodynamic requirements. Furthermore, their design and manufacturing flexibility enable the achievement of high turbine efficiency through the optimization of aerodynamic shape of blades. Other advantages include resistance to fatigue and corrosion [5]. Nevertheless, thermoset composites commonly used in the wind industry are challenging to recycle as after the curing process, polymers become crosslinked [8]. A study of sustainable technological solutions to manage EoL wind turbine blades is therefore necessary to maximize environmental benefits of wind power.

2.1 Wind turbine blade structure

Resin infusion (under vacuum or pressure), whereby resin is introduced into a sealed mold, is the main technology used for blade manufacturing. As an alternative to resin infusion, the pre-impregnation process (prepreg) is also employed [9].

The composition of the blade depends on the manufacturer. However, the general structure of the cross-section of a wind turbine blade is illustrated in Fig. 2. Two aerodynamic shells (one on the suction or downwind side and one on the pressure or upwind side) are joined together with one or more structural shear webs or a box girder [10].



Spar caps are subjected to high loads associated with flapwise bending. In particular, the pressure-side spar cap is exposed to cyclic tension-tension loads, whereas there are cyclic compression-compression loads on the suction-side spar cap [9]. For this reason, spar caps are made of unidirectional (UD) composite material in the span direction [11], usually GFRP with epoxy as polymer matrix. Alternatively, polyester matrix can be combined with glass fibers, as in LM Wind Power blades [12]. In addition, several manufacturers use CFRP composites in this structural part to produce longer blades, thereby taking advantage of the greater stiffness and lower density of carbon fibers compared to glass ones. The thickness of the laminate is greatest near the root and decreases in the radial direction toward the tip, in accordance with the aerodynamic bending moment distribution [11].

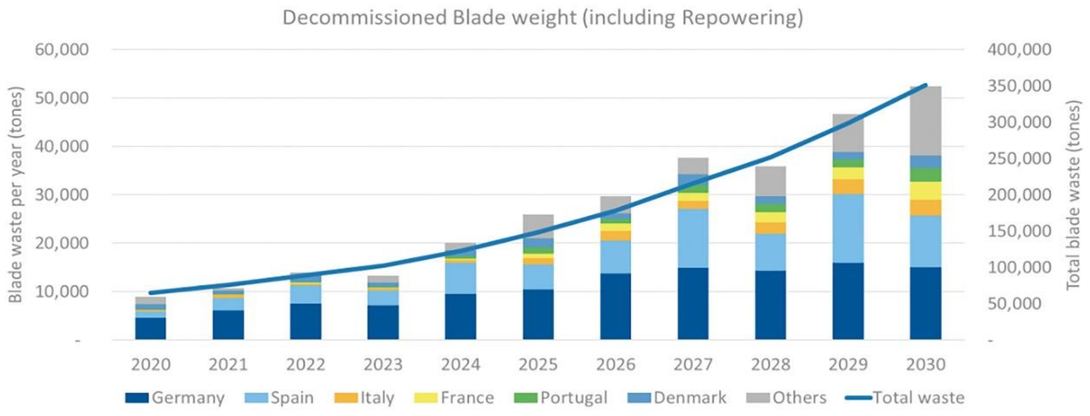
Trailing edge and leading edge are likewise made of UD composite materials [10]. Laminates in these areas are exposed to tension-compression loads related to edgewise bending [9]. Sandwich structures constitute shear webs (flat laminate) and aerodynamic shells (curved laminate), with ±45 °or 0/±45 ° layers as skin. Cores can be made of different materials, such as balsa wood, polyvinyl chloride (PVC), honeycomb structures, or foams [11].

Moreover, surface coatings are applied to protect the blade from ultraviolet degradation and water penetration, as well as to safeguard the leading edge. Examples of other materials that may be present in a blade include metal wiring (for the lightning protection system), bolts, and structural adhesives (for leading/trailing edge and webs bonding) [5], [11].

2.2 Waste from decommissioned wind turbine blades

Wind turbines have variable decommissioning times. The lifespan of a wind turbine is approximately 20-25 years, but it may even be possible to extend it if the turbine is still functioning properly. Nevertheless, sometimes wind turbines have to be dismantled prematurely due to premature damage (e.g., impacts, adverse weather conditions, etc.). Additionally, in other cases, old wind turbines are repowered with newer models that can provide efficient power generation [5], [10].

An overview of the weight of decommissioned blades (including repowering) in Europe is depicted in Fig. 3. WindEurope predicts a total of 350,000 tons of blade waste from the onshore industry by 2030. Starting with 9,000 tons per year, this is expected to rise to 52,000 tons per year by 2030. Germany, Spain, and Denmark are forecasted to be the first countries that will need to dismantle a large number of turbines. Italy, France, and Portugal are also expected to generate a significant amount of waste from EoL blades by 2030 [13]. Furthermore, these numbers represent only portion of the total waste derived from wind industry. In fact, wastes resulting from blade manufacturing process (e.g., dry reinforcement scrap, prepreg cuttings, expired prepreg) must also be considered[14].



2.3 Larger blades: increasing use of carbon fiber in the wind industry

In recent years, the size of wind turbine blades has been continuously increasing. Nowadays, blades can exceed 100 m in length, as is the case of the Haliade-X, the most powerful offshore wind turbine in operation (14 MW) [15]. The increasing in dimensions is related to the necessity of producing more powerful wind turbines since wind power is proportional to the area swept by the rotor, as shown in Eq.1[16]:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{1}$$

where ρ is air density, A is the swept area (area of blades), and v is the wind velocity.

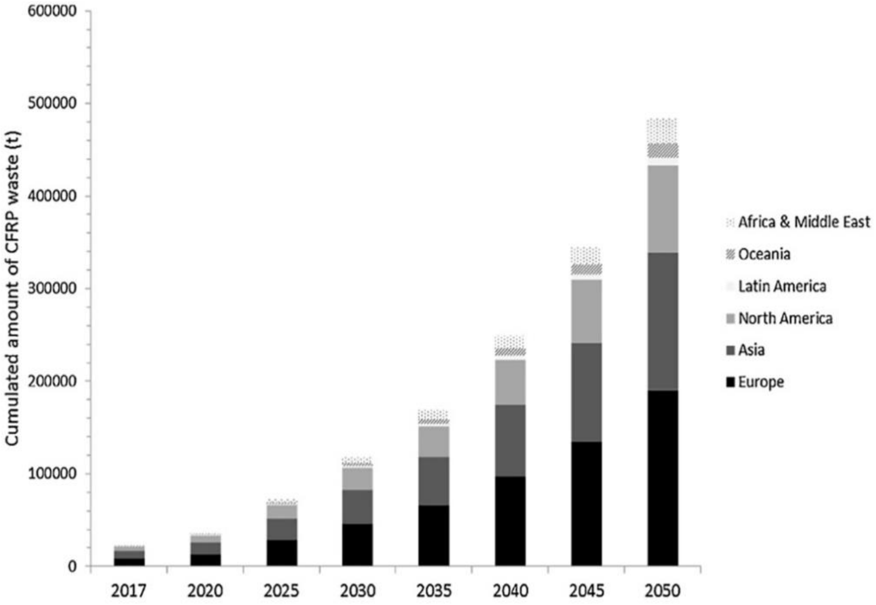
A wind turbine transforms wind energy by turning it into mechanical power. However, mechanical power is affected by a power coefficient, Cp, which defines the amount of wind power that can be derived from an air stream. The maximum value is the Betz limit, which is equal to 59.3 %. Typically, wind turbines possess a Cp of up to 50% [16]

On the other hand, a longer blade results in greater weight, as the blade mass increases with the cube of rotor radius. For weight reduction, carbon fibers can be incorporated as reinforcement in specific structural parts for blades longer than 45 meters. Despite the higher cost of carbon fiber compared to glass fiber, the mass-reduction capability will lead to an increasing use of carbon fibers in the wind industry. A trend toward making blades entirely of CFRP composite is foreseen. Fig. 4 estimates the amount of CFRP waste from EoL wind turbines up to 2050. In 2050, a cumulative CFRP waste of 483,000 tons is expected globally. Additionally, Europe will face the highest cumulative amount of waste by 2050, with

190,000 tons. From this forecast, it is evident that the wind industry must be prepared in a few years to handle the first EoL wind turbines containing CFRP composites [17], [18].

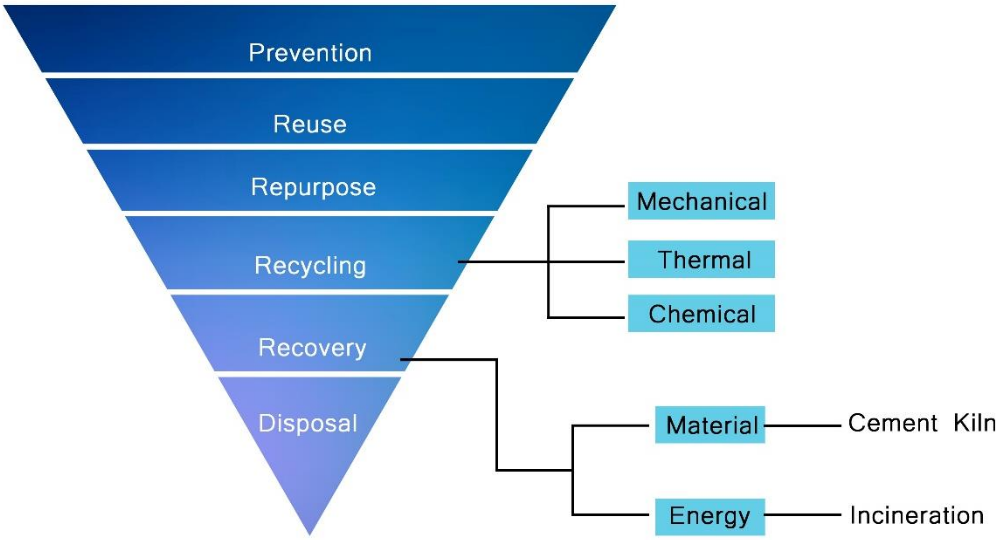
Some authors [8], [19] omit the analysis EoL solutions, and in particular recycling methods, for CFRP wastes generated from wind turbine blades. The objective of Section 2.3 is, therefore, to demonstrate that although the main composite material for blade manufacturing is currently GFRP, CFRP is increasingly being used. For this reason, the evaluation of the best EoL solutions should not be limited to GFRP exclusively.

Moreover, virgin carbon fiber production is an energy-intensive (198-595 MJ/kg) and polluting process, compared to carbon fiber recovery. The recycling cost for carbon fiber could be about $5/kg, which is about 15 % of the price of virgin fiber [20]. As a consequence, recycling high value carbon fiber incorporated into blades could be very advantageous, as also argued by Lefeuvre *et al.* [18].



3. End of Life (EoL) strategies for wind turbine blades

The European Waste Framework Directive (2008/98/EC) [21] defines the waste management hierarchy and ranks the different options based on their desirability. While the most desirable option is at the top of the diagram (Fig. 5), the least preferable one is located at the bottom of the hierarchy[22], [23]. Section 3 is thus devoted to the description of different strategies for EoL wind turbine blades management.



3.1 Prevention

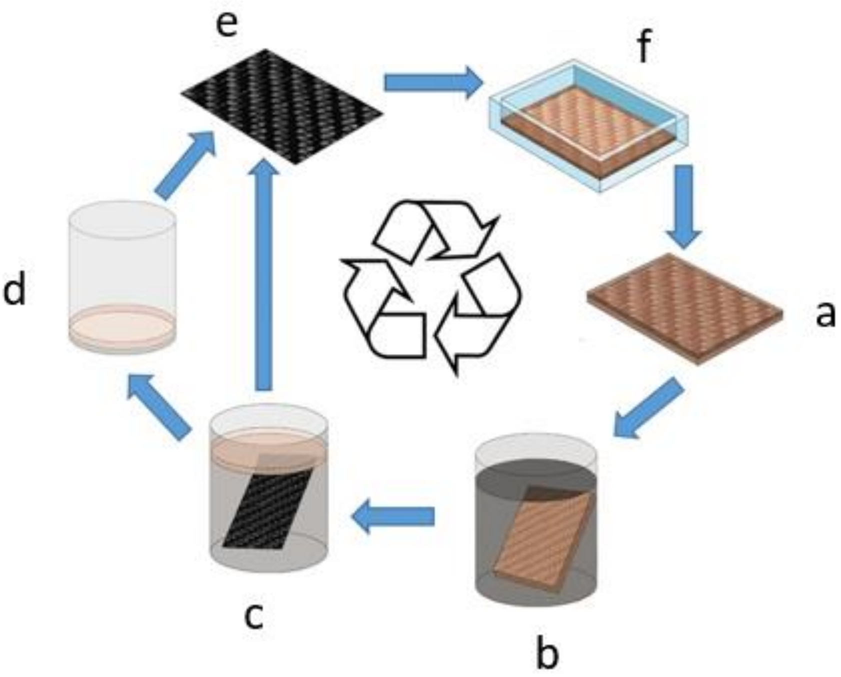
Preventing waste is first in the hierarchy. Based on this approach, blades are designed to have an extended lifespan, to facilitate future recycling, or to reduce the amount of the material usage [23]. The Zero wastE Blade ReseArch (ZEBRA) project is an exemplary effort to design and produce 100 % recyclable blades [24]. The sustainable blade development consortium reunites industrial companies, such as Arkema, CANOE, ENGIE, LM Wind Power, Owens Corning and Suez [25].

Biocomposites, whose constituents are based on naturally sourced fibers (e.g., hemp, bamboo) and thermoset matrices, have been investigated as sustainable materials for wind energy sector [26], [27]. Natural fibers, however, have some drawbacks, such as high water absorption [28], low thermal stability, and heterogeneous characteristics, thus limiting the production of high performance composites [29]. Furthermore, when natural fibers are combined with thermoset matrices, reprocessing is unfeasible, so that fibers are not recovered. Combustion of biocomposites for the purpose of energy recovery is therefore considered a viable solution [30].

A further strategy is to study the polymeric matrix to permit EoL composites to be reshaped, melted or dissolved, thus facilitating the separation of fibers and matrix [30]. Thermoplastics can be melted and easily recycled, as they do not undergo the crosslinking associated with thermosets [5]. In-situ reactive thermoplastic resins polymerize at room temperature and can be thermally bonded, avoiding the need for additional bonding agents to join blade skins and shear webs. Additionally, heating can be used to repair the blades. Arkema Inc. developed a thermoplastic resin system (Elium®) [31] for infusion technology that features mechanical properties comparable to epoxy resins [32], [33]. In a recent study, the dissolution of Elium® resin reinforced with glass fibers was analysed. As a result of the process, the matrix and full-length fibers, with unaffected mechanical properties compared to virgin fibers, were recovered [34].

An eco-friendly approach to facilitate future blade recycling is the combination of reinforcing fibers with recyclable thermoset polymers, e.g. vitrimers. Vitrimers present a covalent organic network that can modify the topology exploiting reversible exchange reactions [35], [36]. Recycling of vitrimer composites through the dissolution of the epoxy matrix in a proper chemical medium was achieved by different authors[37], [38], [39], [40]. Reprocessability from powdered material, reshaping, and self-healing functionality are further advantages of this kind of materials [37], [38], [41].

Recent research is also focused on bio-based vitrimers, derived from sustainable resources, such as soybean oil, itaconic acid, and vanillin [42], [43], [44], [45].The development of environmentally friendly, recyclable matrices degradable under mild conditions would enable the recovery of fibers without damaging them. Vitrimer composites (Fig. 6) would permit the reuse of recovered fibers [40], [46] and decomposed polymer chain segments (i.e., future repolymerization)[46], thus closing the loop for future blade production.



3.2 Reuse

Blades can sometimes be reinstalled for new plants after being decommissioned. After checking their damaged state with visual inspections, ultrasound, and natural frequency measurements, blades can be reused at new sites. In this context, countries with well-developed wind power industries (e.g., Germany and Denmark) are able to sell reused blades to territories less experienced in this field that require less powerful turbines [30], [47].

3.3 Repurpose

Repurpose involves the reutilization of wind turbine blade sections for a purpose other than their original one. Blade sections, in fact, have the potential to be used for built environment or for structural purposes. The Wikado playground in Rotterdam (Fig.7a) is a good example of repurposing blades to achieve a new circular economy with applications in architecture [48].

The first bicycle and pedestrian footbridge (Fig.7b) with girders derived from wind turbine blades has been placed on the Szprotawa River by recycling company Anmet and GP Renewables Group [49]. Public seating, bus stop shelters and bicycle sheds are other possible ways to reuse sections of blades for urban installations [50].

(a)

(b)

3.4 Recycling

Recycling represents the next step in the waste hierarchy. A variety of techniques (e.g., mechanical, thermal, chemical) are available to handle composite materials generated by the wind industry. The quality of fibers after recycling, and subsequently future applicability of the recyclate, depends on adopted technology. Recycling processes have different levels of technological readiness (TRL), with relatively few of them being industrialized [5]. The detailed description of the recycling methods for both GFRP and CFRP composites will be presented in Section 4.

3.5 Recovery

Co-processing in cement kilns provides a way to recover materials and energy. The approach is suitable for GFRP regrind since it is an appropriate cement raw material. Its composition is, in fact, compatible with the ratio among the three main oxides that constitute the clinker (i.e., calcium oxide, silica, aluminum oxide). In contrast, the composite polymer phase serves as fuel for the process. The cement kiln route is a cost-effective and scalable solution that can reduce CO_2 emissions during clinker production [51].

A cement kiln route plant can treat 30,000 tons of composite waste per year. Despite the fact that co-processing is currently considered a promising technology for composite waste management, the biggest disadvantage is the loss of the fibers' original physical shape, hindering the manufacturing of new composites [5].

Incineration to reclaim heat or energy is another way to manage composite wastes. Careful control of the process is essential to avoid harmful emissions. An additional drawback of incineration is that the generated ash must be discarded in landfills[52]. The latter approach is, therefore, not an environmentally feasible solution.

3.6 Disposal

Landfilling or incineration without energy recovery is the lowest level in the waste management hierarchy. Nowadays, landfilling is a common solution for managing EoL composite waste. Germany and other European countries, however, have banned landfilling due to its non-sustainable nature [53]. In addition, in some countries the landfill tax makes this practice not economically viable [54].

4. Recycling methods for thermoset composite materials

As stated in Section 3, recycling is not placed at the top of waste management hierarchy. Despite the fact that prevention is the most desirable solution, alternative materials proposed for production of sustainable blades are currently under investigation. In 2021, Siemen Gamesa produced the RecyclableBlade, a wind turbine blade that can be recycled at the end of its service life through a mild acid solution. Siemens Gamesa's RecyclableBlades were recently installed in RWE's Kaskasi offshore wind project in Germany and are being tested under operational conditions [55].

LM Wind Power produced the first prototype recyclable blade in 2022 using Arkema's Elium® thermoplastic resin. Full-scale structural lifetime testing will be conducted to validate material performance. Following the recycling of this first blade, further analysis will also be carried out to verify the recycling technique [56].

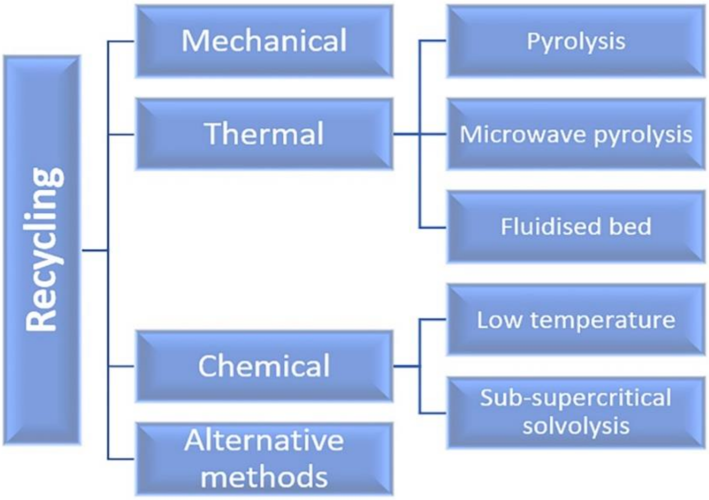
Clearly, prevention is crucial to ensure the recyclability of next-generation wind turbine blades. However, this approach is not a sufficiently effective response to the challenge of managing a large amount of thermoset composite waste from the wind industry. Consequently, a different EoL strategy is required to deal with waste arising from blades made of traditional materials.

Reuse is a viable solution for older generation blades, which are small in size and still perform well. The major disadvantage is that reuse is suitable only in some circumstances. In fact, this approach is unfeasible for damaged blades as well as for longer blades, for which transportation would be problematic and a costly task. Similarly, it is challenging to render repurposing a scalable EoL solution. Elements fabricated from blade sections are required to accommodate different blade geometries, in accordance with wind turbine model. Besides, dismantled blades differ in age and exhibit dissimilar damage states, thus complicating the task of guaranteeing specific material characteristics when material quality is desired [30].

Reuse and repurpose, which are ranked higher than recycling in the waste management hierarchy, are therefore limited to specific applications. Moreover, reused or repurposed blades will still have to be dismantled at the end of their service life. These latter EoL approaches seems only to postpone the problem of waste generation and management.

Recycling, on the contrary, means that recyclates are used for production of new materials which have either the same or a different functional use [5]. As a result, this EoL approach can be seen as the beginning for the establishment of an advanced circular economy [54]. This chapter describes the different recycling methods available for both GFRP and CFRP thermoset composites. Fig. 8 illustrates the recycling technology categories that will be discussed in Section 4.

Several parameters, including process cost, sustainability, and mechanical properties of recycled fibers play an important role in evaluating the advantages and drawbacks of each recycling method. In general, process cost is often the main obstacle preventing the diffusion of some recycling techniques. Recycling must be cost-effective to be an appealing solution for EoL blade waste management. For GFRP, this is particularly challenging since glass fiber reinforcements are low-cost materials. For E-glass, with a density of 2700 kg/m^3 and a Young's modulus of 80 GPa, costs are expected to be 2.5 €/kg. On the other hand, carbon fiber reinforcements are expensive, and their price ranges from 15 to 60 €/kg, depending on the type [14]. For this reason, high-cost recycling methods can be justified in the case of CFRP composites.



4.1 Mechanical recycling

The mechanical recycling process works by gradually decreasing the size of composite waste, with the purpose of achieving variable particle dimensions. The waste is initially comminuted into sizes of about 50-100 mm. At this stage, the removal of metal components, which might be present in the waste, is a key step. Subsequently, high-speed grinding operations for size reduction between 50 μm and 10 mm are used. Cyclones, sieves, and air classifiers are employed for the separation and classification of the ground composite [57][58].

The resin-rich fraction (fine powder) has the potential to be used as filler, whereas fiber-rich products (coarser powders) can serve as reinforcement [14], [19]. Mechanical recycling does not separate reinforcing fibers from the polymer matrix. After processing, it actually results in short fibers with a preserved surface sizing and residual matrix on the surface [59]. Mechanical recycling is a cost-efficient process with a low carbon footprint. Deterioration that occurs in fiber properties, however, prevents shredded material from being usable for high-load structural purposes [60].

Regarding GFRP composites, the resin-rich fraction can be used as filler in sheet molding compounds (SMCs) or bulk molding compounds (BMCs) to replace virgin fillers, such as calcium carbonate. The maximum percentage at which recyclate can be incorporated without greatly impacting mechanical properties is about 10 %. The component weight can be reduced by 5% due to the lower density of the polymer compared to that of virgin fillers. However, the lower cost of virgin fillers does not make this substitution economically competitive [57].

Recycling through SMC and BMC technologies can find application in the automotive industry, where the introduction of Directive 2000/53/EC requires car manufacturers to reuse 85% of the weight of EoL vehicles [19]. The perspective, for sectors such as automotive, is to move toward a circular recycling by organizing their own recycling program. This could clearly limit the use of recycled material from the wind power sector in other sectors.

Considering circularity as a key concept, mechanical recycling cannot be considered as an applicable technology in the wind power sector due to the reduced performance of the resulting recycled material.

Fiber-rich products used as reinforcement indeed have inferior quality compared to virgin reinforcement. Adhesion between shredded material and polymer is also difficult, and larger particles can contribute to increased stresses, leading to the initiation of failure [57]. Beauson *et al.* used shredded glass fiber composites from a wind blade load carrying beam to manufacture novel composites. The recyclate was incorporated as the only reinforcing part, using a special vacuum infusion set-up. However, they observed low failure strength and strain, which may be related to poor adhesion between shredded material and the new polyester matrix [61].

A careful separation of the recyclate, proper reformulation procedure, and manufacturing process, however, are crucial for production of new dough molding compounds (DMCs), according to Palmer *et al.* More specifically, a longer mixing time is critical for improving the interface between recyclates and the new polymer matrix. Researchers demonstrated that the replacement of virgin reinforcing fibers with a recycled fraction has a minimal impact on mechanical performance. Furthermore, large percentages of recyclate can be incorporated without side effects [58].

Researchers investigated different applications for crushed GFRP composites. Rahimizadeh *et al.* suggested the reuse of recycled GFRP from wind turbine blades as a reinforcement for PLA filaments with the aim of enhancing the mechanical performances of 3D printed parts. The elastic modulus and tensile strength of the reinforced filament increased by 16 % and 10 %, respectively, compared with pure PLA filament [62].

Crushed GFRP was added to a particleboard to increase its strength. As a result, thickness could be decreased, facilitating storage and transportation. Tests, however, showed that strength was not enhanced by the introduction of crushed material. The possibility of dispersing GFRP powder in wood coatings was also explored. Improved UV stability of the final product was proved. Nevertheless, a drawback of this application is the requirement for very fine particles (less than 50 µm), which means more machining and extra cost [8]. Mamanpush *et al.* proposed a composite panel realized with mechanically recycled wind turbine blade material and polyurethane adhesive as a binder. The produced panel exhibited better water resistance than wood-based particleboards and would be suitable for use as floor tiles or plastic road barriers [63].

Mechanically recycled GFRP composites can be potentially used as a raw material for building materials and concrete. Ribeiro *et al.* studied polymer mortars filled with GFRP waste, demonstrating their better mechanical properties than unmodified mortars [64]. García *et al.* found that use of mechanically recycled GFRP for microconcrete production can improve flexural and compressive strength at 28 days by 16 % and 22%, respectively [65]. Zhang *et al.* obtained promising results by adding mechanically recycled GFRP scrap into an Fe-rich silicate slag for the purpose of developing a reinforced cementitious composite at room temperature [66]. Asokan *et al.* verified the increase in mean compressive strength and tensile splitting strength for concrete filled with glass fiber-reinforced plastic waste powder [67].

Yazdanbakhsh *et al.* worked with GFRP mechanically cut from a wind turbine blade shell, substituting 5 % and 10 % of coarse aggregate (by volume) in concrete. GFRP elements, each 100 mm long with a square cross-sectional area of 6 mm x 6 mm, provided enhanced energy absorption ability, while other mechanical properties remained substantially unaffected. Toughness rose from 1.2 J for specimens without GFRP elements to 33.3 J for specimens with 10 % by volume [68].

An example of company that exploits mechanical recycling to produce sound barriers from fiberglass products (Fig.9), including wind turbine blades, is MILJØSKÆRM® [69].

Mechanical recycling is most commonly used for GFRP composites. In fact, the high cost of carbon fiber reinforcements and the drop in recycled fibers' performance make mechanical recycling more appropriate for GFRP. However, in literature there are potential applications for mechanically recycled CFRP composites. Mamanpush *et al.* worked with a mixture of thermoset and thermoplastic recycled CFRP for the production of new composite panels via compression molding [70]. Other studies investigated the influence of mechanically recycled CFRP on concrete. Nassiri *et al*. demonstrated that the addition of shredded CFRP waste improves the durability of pervious concrete [71]. Singh *et al*. studied the incorporation of mechanically recycled GFRP and CFRP to reinforce pervious concrete, showing that the addition of 0.33% GFRP and 1% CFRP resulted in improved flexural strength compared to the control pervious concrete mix. This proposed method could contribute to landfill avoidance, as significant amounts of GFRP and CFRP waste would be recycled in pervious concrete pavement [72].

4.2 Thermal recycling

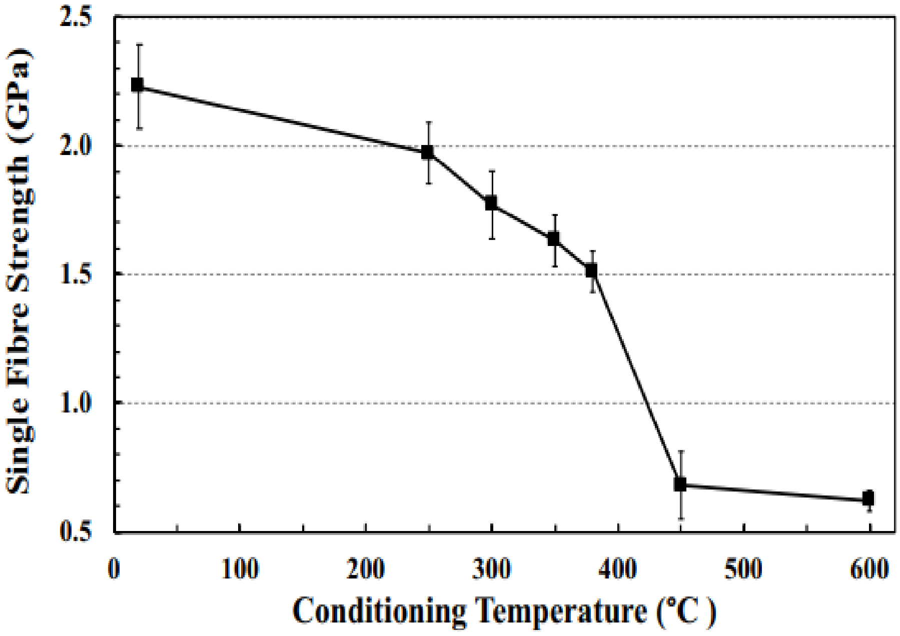
Thermal recycling techniques, such as pyrolysis, microwave pyrolysis, and fluidised bed, take advantage of heat to decompose the composite. The purpose is to burn the polymeric matrix and to reclaim the fibers. The temperature of the process varies based on the type of matrix that constitutes the composite. Polyester resin, for instance, requires lower temperatures than epoxy matrix [73], [74]. This subsection provides a description of different thermal methods available both in literature and in the market.

4.2.1 Pyrolysis

In pyrolysis, composite wastes are heated between 400-700°C in absence of oxygen [74]. Under an inert atmosphere, usually nitrogen, the organic polymeric part undergoes transformation into low-molecular weight molecules that can be used to generate heat in pyrolysis process. Alternatively, these molecules can be reused as potential feedstock for chemical processes [75]. Recycled fibers exhibit carbonaceous char residues arising from matrix breakdown, which can be removed through post-treatment, with the addition of oxygen in a second phase of the process [76].

Recycled fibers are discontinuous, fluffy and unsized [76]. Prior to pyrolysis, the components are mechanically reduced in size for the easy elimination of organic fraction. These recycled fibers can then be utilized in the production of semi-finished products, such as nonwoven mats. Furthermore, it should be considered that even components fabricated with recycled semi-finished products will need to be recycled, resulting in a further shortening of fibers lengths [14], [75].

Pyrolysis is a mature technology capable of recycling both GFRP and CFRP composites. While it is used, even at industrial scale, to recycle CFRP composites, there are ongoing research studies investigating the feasibility of GFRP recycling. However, several obstacles persist in this process [77], [78]. The major challenge is the reduction in the strength of glass fibers when exposed to high temperatures, hindering their successful reuse for new composites production, as observed by Cunliffe *et al*. The use of 100% recycled fibers for new DMCs manufacturing caused a loss of mechanical performance [79]. Fig. 10 illustrates the large reduction of average glass fiber strength after high temperature treatment for 25 minutes [80].



The tensile fracture stress can be lowered by 50-80%, depending on the temperature and heating time. Feih *et al.* studied the mechanism of strength loss in thermally recycled E-glass fibers. Elevated temperatures, exceeding 250°C, resulted in a decline in fiber fracture stress. They provided evidence that growth of surface defects is the mechanism responsible for strength degradation during thermal recycling [81].

In the literature, regeneration treatments, aimed at recovering strength of thermally degraded glass fibers, are subject of research. Yang *et al.* proposed a successful chemical approach involving a 1 v % HF aqueous solution and post-silanisation treatment [82]. Alternative approaches to enhance the strength of thermally recycled glass fibers involve the use of KOH, NaOH and LiOH solutions. Alkaline treatment induces a modification of the glass fiber surface, either by removing surface defects or lowering their degree of severity, leading to enhanced fiber strength [83], [84]. Thomason *et al.* demonstrated that chemical treatment with NaOH solution can recover up to 75 % of the strength loss [85].

Although regeneration techniques result in improved mechanical performance of recycled glass fibers, these treatments require additional steps to reclaim valuable reinforcements, leading to increased costs. Furthermore, thermal recycling is more energy intensive [60], resulting in higher overall costs compared to mechanical recycling. Considering the low cost of virgin glass fibers, pyrolysis may not to be economically viable. Despite this, the company ReFiber [86] uses thermally recycled glass fibers from wind turbine blades in the production of insulation materials.

On the contrary, in case of CFRP composites, pyrolysis is able to retain approximately 90 % of the properties compared to virgin carbon fibers [87]. Control of process conditions is critical for production of clean, high-quality reinforcing fibers. Minimisation and removal of char is fundamental, as this remaining residue compromises adhesion with new polymeric matrices and the quality of dispersion during production of nonwovens [17].

For complete resin decomposition without damaging the fibers, temperature and oxidation post-treatment time are decisive parameters. Irisawa *et al.* demonstrated that heat treatment in air at 600 °C reduces fiber strength, whereas longer treatment times facilitate flaw growth [88]. Hao *et al.* discovered that with high gas flow rate at 550 °C and heating rate below 100 °C/min, char content is lower, resulting in shorter post-processing times, energy savings, and higher mechanical performance of recycled fibers [17].

Experimental investigations have focused on determining the best parameters for two-stage pyrolysis process. Hadigheh *et al.* concluded that pyrolysis up to 425 °C followed by oxidation up to 550°C, to clean fibers from polymeric residues, provides high quality recovered fibers [89]. In a further investigation, pyrolysis at 600 ℃ for 30 minutes and oxidation post-treatment at 450 ℃ for 15-20 minutes led to recovery of clean recycled fibers. Compared to virgin fibers, tensile strength and tensile modulus retention were about 90% and 84%[90].

Downsizing implies a loss of fiber architecture. Avoiding the shredding step could therefore be fundamental to maintain the interwoven feature of the carbon fiber fabric. Researchers have shown that pyrolysis at 550 °C for 1 hour can separate the organic polymeric part from carbon reinforcements [91]. He *et al.* also tested the preservation of fiber architecture, concluding that inner layers of recycled CFRP exhibited more polymeric residues compared to outer layers[92].

Nowadays, different companies, such as Gen 2 Carbon [93] and Rymyc [94], successfully exploit the pyrolysis of CFRP composites. A Life Cycle Analysis (LCA) on ELG Carbon Fibre, recently turned into Gen 2 Carbon, demonstrated that the environmental impact of recycled carbon fibers is lower compared to virgin fiber production. Less than 10% of the energy required to produce virgin carbon fiber is needed to recycle waste [95], [96]. Nonwoven mats, produced from carbon fibers recycled through pyrolysis, find applications in prepregs, products that combine recycled fibers with a thermoplastic matrix, or in sandwich structures. These materials could be used in the automotive and marine industries [97]. Moreover, they might be of interest in the wind power sector, particularly for specific areas in new blade production.

4.2.2 Microwave pyrolysis

Microwave energy, as a source for heating composites core, can be exploited to decompose the polymer matrix and to recover clean fibers [73]. This approach enables a very rapid heat transfer, reducing energy input, saving time and raising process efficiency, as evidenced by Deng *et al.* [98] . According to their study, microwave energy offered a 56.67% reduction in reaction time and a 15% increase in recovery ratio, compared to conventional CFRP thermolysis. Literature provides different examples of CFRP composites recycling through microwave pyrolysis [99], [100], [101]. Lester *et al.* conducted experiments on CFRP composites using a multi-mode microwave cavity powered for 8 s at 3 kW under an inert atmosphere, thereby avoiding fibers combustion. As a result, they demonstrated the potential of microwave pyrolysis to recover relatively clean fibers with higher strength compared to other processes, such as fluidised bed [100].

Hao *et al.* used microwave pyrolysis to recycle cured carbon fiber/epoxy prepregs. The samples were heated in an inert atmosphere at different temperatures (i.e., 450°C, 550°C, 650°C) for 15 minutes and then exposed to air at 550 °C for 30 minutes for char removal. Treatment at 450°C resulted in the greatest strength retention (87%), while tensile modulus was practically unchanged [101].

Regarding GFRP composites, Akesson *et al.* reclaimed fibers from a wind turbine using microwave pyrolysis. The tenacity of recycled fibers was reduced by 25% compared to virgin ones. Furthermore, they manufactured hybrid laminates with nonwoven mats of virgin and recycled fibers. Composites containing 25 wt % of recycled fibers exhibited acceptable mechanical performance [102].

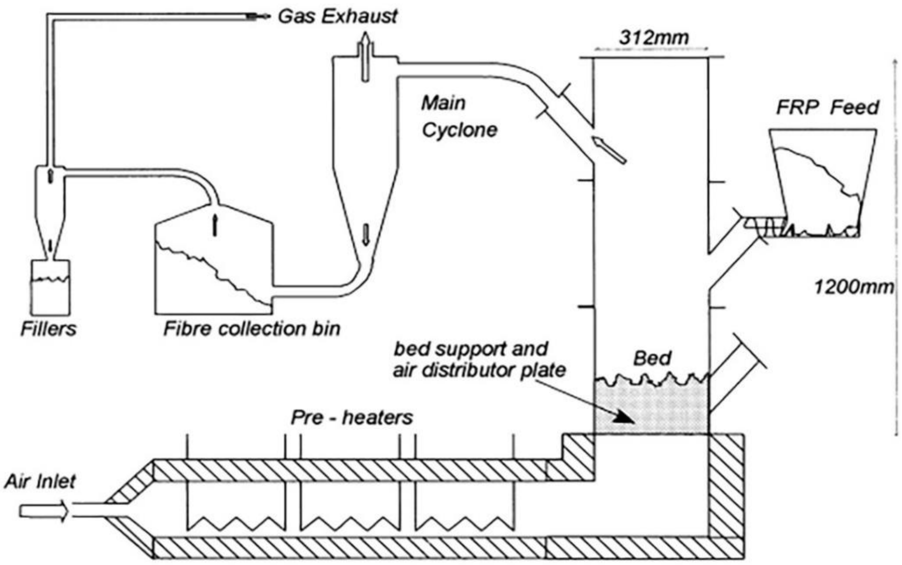
While microwave pyrolysis offers several advantages, the above mentioned studies were conducted on a laboratory scale. Scaling up microwave pyrolysis will be a future challenge. The ability to reduce energy input and costs would be advantageous for GFRP composites waste management, enhancing the cost-effectiveness of this process compared to other recycling methods, such as conventional pyrolysis.

4.2.3 Fluidised bed

The fluidised bed process, developed at the University of Nottingham, exploits a high temperature airflow (around 450 °C) for recycling composites. Similar to conventional pyrolysis, this technique initially involves the reduction in dimensions of the composite waste. Subsequently, the fragmented material is introduced into a bed of silica sand, which is previously fluidised by hot air. Through this mechanism, the polymer matrix undergoes thermal decomposition. The resulting products of polymeric matrix decomposition, along with released fibers and charges, are transported by the gas flow. The next step involves separating the fibers using a cyclone. Finally, the gas is introduced into the afterburner, where the combustion of the polymer is terminated. A schematic representation of the procedure is shown in Fig. 11. The advantages of this process include heat recovery, recycling of both GFRP and CFRP, and the ability to process contaminated waste, as the metal parts sink into the fluidised silica and can be successively removed. On the other hand, short fibers with reduced strength are recovered [103], [104].

Glass fibers are sensitive to high temperatures, as demonstrated in Section 4.2.1. The tensile strength of glass fibers recovered via fluidised bed is dramatically reduced compared to virgin fibers, as also reported by Kennerley *et al.* Higher treatment temperatures (i.e., above 450°C) cause a further decrease in strength [103]. In a subsequent experimental study, Pickering *et al.* verified that both temperature and process duration affect the strength of recycled glass fibers, while Young's modulus remains comparable to that of virgin fibers. They manufactured veil products and concluded that complete replacement of virgin fibers with recovered ones significantly lowers the strength [104].

Yip *et al*. investigated the recycling of CFRP composites via fluidised bed. They recovered fibers between 5 and 9 mm in length, exhibiting reduced strength compared to virgin fibers. The retention of tensile strength was 75%, while modulus remained unaffected by the recycling process [105].



4.3 Chemical recycling

Chemical recycling involves the use of chemicals to degrade the polymer matrix into monomers or oligomers, resulting in the retrieval of high-quality recycled fibers, with mechanical properties similar to virgin ones [106], [107]. Moreover, the decomposed matrix can be partially used to prepare new resin [108], [109], [110], [111].

However, substances like nitric acid and sulphuric acid involved in chemical recycling can be harmful and have a significant environmental impact. As a result, recent approaches based on solvents at supercritical conditions have emerged. High temperature and high pressure conditions [60] that are typical of the latter processes, however, involve both expensive equipment and high energy consumption. Environmentally friendly methods that can operate at mild conditions are therefore being researched. Solvolysis is commercially used to recycle CFRP composites, as demonstrated by the company Extracthive [112]. Extracthive process can recover long fibers and even woven recycled fabrics, while maintaining high mechanical properties.

The elevated cost of solvolysis hinders its feasibility for GFRP composites. A recent study by Liu *et al.* evaluated the total recycling costs, recyclate values and net profits of different EoL GFRP solutions, focusing on wind industry. The analysis revealed that chemical recycling is a profitable option, assuming that even high-value resin can be recovered [113].

In literature, authors have generally proposed a classification for chemical recycling. Oliveux *et al.* considered low temperature (<200°C) and high temperature (>200°C) solvolysis [73]. Gharde *et al.* divided chemical recycling into two subgroups: low temperature and sub-supercritical solvolysis [106].

This latter classification was also adopted in this review to organise the state of the art related to the chemical approach.

4.3.1 Low temperature solvolysis

Low temperature solvolysis is typically carried out at temperatures below 200°C and low pressure, making it suitable for both GFRP and CFRP composites. Nitric acid solution was used to recycle GFRP composites, recovering high-quality glass fibers[108][114]. In another study, authors proposed acid digestion by means of a mixture of acetic acid and hydrogen peroxide solution at 110 °C and at atmospheric pressure, but this led to the degradation of glass fibers [115].

In literature, methods based on CFRP composites recycling through sulfuric acid [116] and nitric acid solutions were proposed [117], [118]. Current research on low temperature solvolysis of CFRP composites has focused on investigating environmentally friendly approaches capable of recovering fibers with performance comparable to virgin fibers. In this regard, typical chemicals used in the literature include a mixed solution of monoethanolamine (MEA) and potassium hydroxide (KOH) [110], macrogol 400 with potassium hydroxide as catalyst [119], $ZnCl_2$/ethanol solution [109].

Other experimental investigations have explored the oxidative degradation of CFRP composites using hydrogen peroxide. Xu *et al.* proved that it is possible to retain more than 95 % of the fibers' original tensile strength [120]. Das *et al.* used a combination of hydrogen peroxide and pure acetic acid for recycling CFRP waste. The recovery of valuable fibers, the polymer matrix, and solvent for further reuse, makes this method eco-friendly [111].

4.3.2 Sub-supercritical solvolysis

Solvents above their critical point, defined by critical temperature and critical pressure, exhibit particular intermediate properties between liquid and gas, such as increased mass transport coefficients, low viscosity, high diffusivity, and solvation power. The supercritical state of water requires high temperatures ($T > 374°C$) and high pressures ($P > 221$ bar). Other supercritical organic solvents (e.g., acetone, methanol, ethanol) can also be used to recycle composites [106], [121], [122]. Research studies indicate that successive washing step is necessary because recovered fibers present an organic residue [123], [124], [125], [126], [127].

Temperature negatively influences the performance of recovered glass fibers. Indeed, Oliveux *et al.* observed a reduction in tensile strength up to 65 % for subcritical hydrolysis at high temperature (350°C)

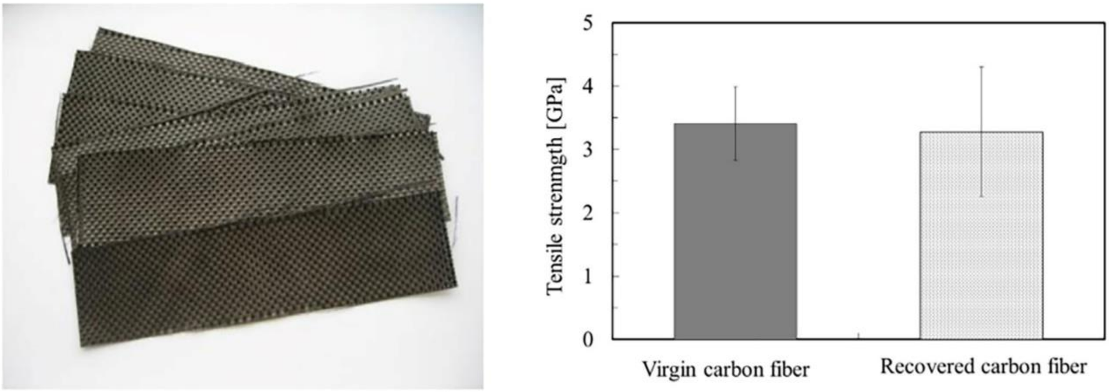
[123]. Kao *et al.* confirmed this detrimental effect on reclaimed glass fibers through subcritical water [128]. Depending on the type of fibers, the choice of the correct solvent is fundamental to recover high quality reinforcements. The use of supercritical acetone enabled the achievement of a higher tensile strength retention (89%) for recycled glass fibers compared to near-critical water (50-35%). The authors explained the detrimental effect of water by considering the generation of micro-cracks on the surface of the fibers as a consequence of the reaction between alkali oxides on the glass fibers' surface and water [124].

Catalysts are often employed in reactions, as in the previous reported studies[123], [128]. The presence of a catalyst necessitates the separation of the catalyst from the products after recycling. Souza *et al.* proposed the use of biodegradable and low toxic D-limonene at sub- and supercritical conditions, without catalyst or other molecules, to recycle polyester-based GFRP. They concluded that approximately 85% of the original strength can be preserved under subcritical conditions [121].

In literature, there are several examples of CFRP composites recycled through sub-supercritical chemical approaches, leading to high quality recycled fibers. Water is a commonly used for this purpose. Ibarra *et al.* achieved decomposition rates for epoxy-based composites of 89.1% and 93.7 % using supercritical water and subcritical benzyl alcohol, respectively [125]. Kim *et al.* removed more than 99% of epoxy resin from CFRP composites using supercritical water without any catalyst or oxidant [129]. Bai *et al.* added oxygen to water to enhance the degradation of epoxy-based CFRP during supercritical water treatment [122]. In another research study, subcritical water and sulfuric acid as catalyst were used to recover clean carbon fibers with a tensile strength retention of about 98.2% [126]. Liu *et al.* evaluated the combination of phenol and KOH to recycle epoxy-based CFRP in subcritical water [127].

Other researchers have focused on recovering carbon fibers through solvents such as supercritical n-propanol or supercritical n-butanol [130], [131], demonstrating that recycled fibers can maintain high tensile strength.

The ability to recover long recycled fibers and preserve fiber architecture are key features of chemical recycling. Okajima *et al.* used subcritical acetone to recycle composites, successfully recovering high quality carbon fiber sheets while preserving the shape of plain fabric, as depicted in Fig. 12a. Additionally, the tensile strength of recovered fibers remained practically unchanged compared to virgin reinforcements (Fig. 12b) [132].



(a) (b)

4.4 Alternative methods

Researchers are investigating alternative methods for recycling thermoset composite materials. An example is high-voltage pulse fragmentation (HVF), which employs pulse electrical discharges between electrodes to disintegrate the composite material when immersed in a dielectric liquid, such as water. This creates a spark channel, generating a shock wave that imparts an internal mechanical stress higher than the tensile strength of the composite [133], [134].

Mativenga *et al.* studied the GFRP composite recycling by high-voltage pulse fragmentation, while comparing it with mechanical recycling. Cleaner fibers with a lower resin content can be obtained with HVF, especially when a high number of pulses is used. Additionally, unlike mechanical recycling, a wider fiber length distribution can be achieved through HVF. Nevertheless, fragmentation with high voltage pulses is more energy intensive than mechanical recycling [133], as also confirmed by Leißner *et al.* [134]. According to the latter authors, using HVF as an alternative to mechanical recycling beyond the laboratory scale poses barriers, such as investment costs and high energy demand.

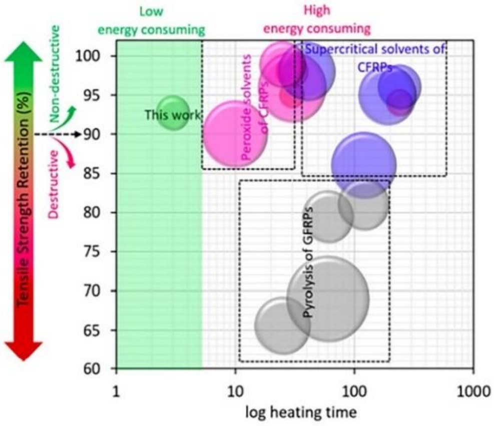
An innovative recycling method is high-voltage application for carbon fibers recovery, that was investigated by Oshima *et al*. They applied an electrical treatment to unidirectional CFRP exploiting a two-electrode cell. Composite laminate was the anode, whereas a carbon rod served as the cathode. They proved that a high weight loss of the composite is correlated to the high voltage application, which leads to the elimination of the resin from CFRP. This phenomenon was associated with a detachment caused by the gas produced at the anode. Extended treatment time, however, caused damage to carbon fiber [135].

Another study similarly focused on chemical swelling and electrochemical oxidation to separate the polymeric fraction from fibers. Composite was the anode, whereas a stainless steel plate was the cathode of the experimental system. For enhancing conductivity, DMSO and ammonium acetate served as electrolyte solutions. Successful results were achieved, since this technique retrieved clean fibers with unaltered length compared to original ones. Furthermore, tensile strength retention reached approximately 93%, whereas interface shear strength was 118.76% compared to original fibers [136].

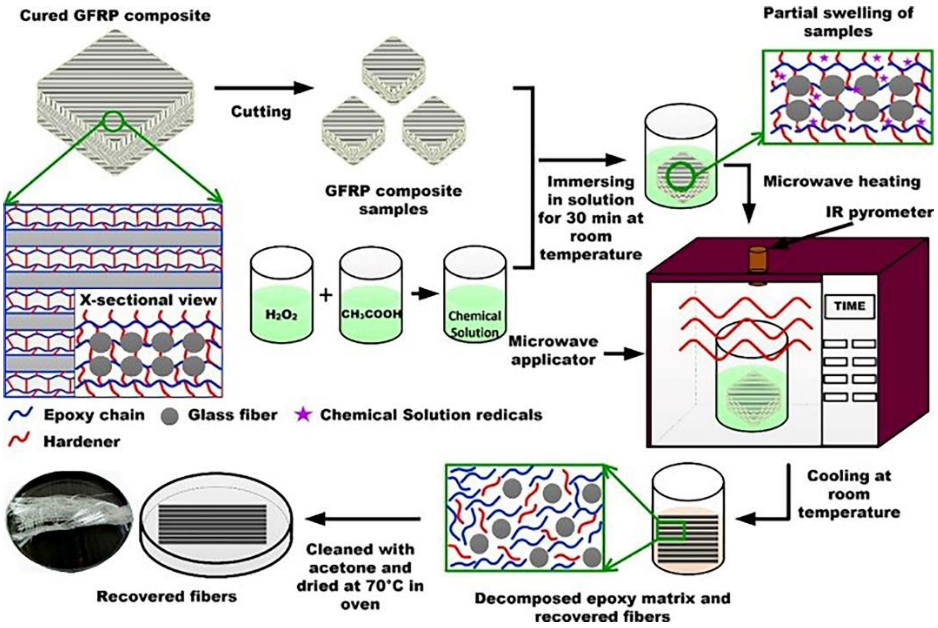
Recently, researchers proposed a hybrid process, microwave-assisted chemical recycling, to develop a sustainable, cost-effective and efficient method for handling GFRP composite waste. Zabihi *et al.* successfully decomposed epoxy-based GFRP using hydrogen peroxide and tartaric acid, exploiting three-minutes microwave irradiation. Mechanical properties of recycled fibres remained almost unchanged, as tensile strength, Young's modulus and strain at break retention were 93%, 99% and 96%, respectively. Advantages of microwave-assisted chemical recycling over other procedures are shown in Fig. 13a, which highlights the process' ability to both be energy-saving and preserve high mechanical performance [137].

Rani *et al.* used hydrogen peroxide and acetic acid in combination with microwaves as a heating source to recycle GFRP, achieving an epoxy decomposition rate of approximately 97%. Fig. 13b shows a schematic representation of the procedure. Authors investigated the influence of chemical solvent ratio and exposure time. They proved that microwave-assisted chemical recycling can lead to only a slight drop in fibers mechanical performance [138].

The review has primarily focused on the experimental techniques documented in the literature to address the problem of composite recycling. This work has omitted the utilization of computational methodologies in the recycling of composite materials, given the limited number of studies found on this subject [139], [140], [141]. As also highlighted by Liu *et al*. [142], research in composite recycling has not yet directed on developing mathematical methods to optimise the processes. In this regard, integration of experimental investigations with the formulation of mathematical models could help to industrialise certain methods and obtain recycled materials with higher performance.



(a)



(b)

5. Conclusions and future perspectives

The review analyses potential EoL strategies for managing the increasing amount of composite waste generated from decommissioned wind turbine blades in the growing wind energy sector. Blades are made from fiber reinforced thermoset polymers, mainly GFRP composites, which pose challenges in recycling. CFRP composites are also used in specific areas, especially in blades longer than 45 meters, leading to a considerable amount of CFRP expected from EoL blades. This study focuses on addressing the waste management issue of EoL blades, exploring recycling processes available in literature and in the market for both types of composite materials.

The European Waste Framework Directive (2008/98/EC) establishes a waste management hierarchy. While prevention, reuse, and repurpose are more favourable options than recycling, they come with certain constraints. Study of new materials, and in particular, polymer matrices to facilitate future recycling is crucial. However, handling large quantities of wind turbine blades made from traditional fiber reinforced thermoset polymers still remains a challenge. A detailed study of solutions for both prevention and recycling is a key aspect of current and future waste management.

GFRP is typically recycled through the cement kiln route or mechanically due to its low cost. Loss of fiber shape in cement kiln and short fibers derived from the mechanical process prevent its reuse for high load structural purposes. Other approaches, such as pyrolysis, are not cost-effective and result in fibers with low mechanical properties. Chemical recycling, although expensive, holds promise in retrieving high-quality fibers and resin, making it a potentially profitable solution. There is a need for low-cost methods that can recover valuable glass fibers. Research efforts should focus on exploring cost-effective approaches, such as microwave pyrolysis, and innovative techniques like microwave-assisted chemical recycling.

Conversely, the cost of carbon fiber reinforcements makes CFRP recycling more economical than the production of virgin fibers. Despite the higher costs associated with certain recycling methods, they become justifiable for CFRP. CFRP is also recycled commercially through pyrolysis or solvolysis. Pyrolysis recovers discontinuous, fluffy, unsized fibers with high mechanical properties, suitable to manufacture intermediate products such as nonwovens. Further investigation is needed to preserve fabric fiber architecture during pyrolysis, potentially eliminating the shredding step. Furthermore, exploring techniques like microwave pyrolysis, could help to reduce the energy demand. However, the latter process needs to be scaled up, as it has been studied at laboratory level.

Solvolysis is effective in recycling fabrics. Environmental compatibility, cost and energy are key parameters for developing new chemical approaches. Recently, electrochemical recycling, based on chemical swelling and electrochemical oxidation, has been proposed. Further investigations are needed. As a result, the latter method could recover fibers with unchanged length, a critical aspect for reusing recycled fibers in new composites.

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Declaration of Competing Interest

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Figure Captions

Fig.1. Wind Energy trend in Europe in last years: (a) Electricity mix in EU-27 [2]; (b) Wind energy total installed capacity in Europe in the timeframe 2012-2021 [3]

Fig. 2. Cross section structure of a typical wind turbine blade. Blade is made by joining of two aerodynamic shells. Unidirectional (UD) composite material is used in spar caps, whereas sandwich structures form shear webs and aerodynamic shells

Fig. 3. Decommissioned blade weight (including repowering) in Europe by 2030. In the following years, European countries will have to face an increasing amount of composite waste derived from wind energy sector [13]

Fig. 4. Global quantity of CFRP composite waste derived from EoL wind turbines up to 2050 (reproduced by [18] with permission of Elsevier)

Fig. 5. Waste management hierarchy. Section 3 of this review provides a detailed description of each approach

Fig. 6. Schematic representation of chemical recycling for vitrimer composite. Starting with composite waste (a), after the immersion in a suitable chemical medium (b), the reinforcing fibers and polymeric matrix can be separated (c). Subsequently, decomposed polymer (d) and recycled fibers (e) can be potentially reclaimed to produce new composites (f), thus facilitating the material's circularity

Fig. 7. Examples of repurpose strategy: (a) Wikado playground in Rotterdam (photo by Denis Guzzo, 2014) [48]; (b) Bicycle and pedestrian footbridge made with repurposed blade material (credits to Anmet) [49]

Fig. 8. Classification of recycling technologies available in literature and in the market. Four different categories can be identified (i.e., mechanical, thermal, chemical and alternative approaches)

Fig. 9. Example of application for mechanically recycled composite material. Sound barriers produced with shredded blade material by the company MILJØSKÆRM®. Adapted from Ref. [69] (credits to MILJØSKÆRM®)

Fig. 10. Temperature effect on glass fibers' strength. Glass fibers exposed to high temperature experience a significant reduction in strength [80]

Fig. 11. Schematic representation of fluidised bed recycling process for scrap composite material. A bed of silica sand, fluidised by hot air previously heated through electric heaters, is at the basis of the technology. The procedure allows the separation of the reinforcing fibers and fillers from the polymeric

matrix. The reinforcing fibers and fine particles are recovered through a cyclone, and collected separately (reproduced by [103] with permission of Elsevier)

Fig. 12 Chemical recycling method: (a) Carbon fiber sheets recovered using subcritical acetone (b) Tensile strength of virgin and recycled carbon fibers recovered by Okajima *et al.* (reproduced by [132] with permission of Elsevier)

Fig. 13 Microwave-assisted chemical recycling method: (a) Proposed method compared to other recycling approaches, in terms of energy consumption and tensile strength of recycled fibers [137]; (b) schematic procedure for GFRP microwave- assisted chemical recycling using hydrogen peroxide and acetic acid. The samples are placed in the recycling solution at room temperature for a half-hour, leading to swelling and separation of composite layers. Afterwards, microwave energy (700 W) is used for gradual heating of the solution. Cooling, cleaning and drying of the fibers are the final steps of the recycling procedure (reproduced by [138] with permission of Elsevier)