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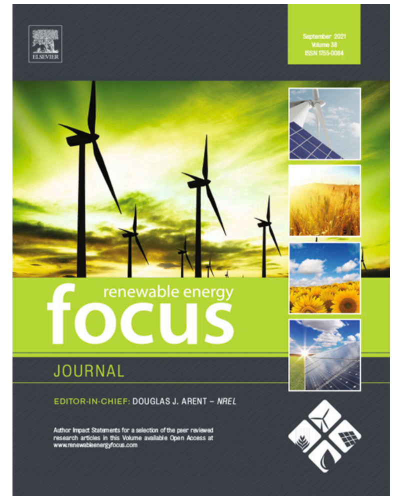

Research Review (blue)

Recycling of wind turbine blade through modern recycling technologies: Road to zero waste

Muhammad Yasir Khalid, Zia Ullah Arif, Mokarram Hossain, Rehan Umer

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Recycling of wind turbine blade through modern recycling technologies: Road to zero waste

Muhammad Yasir Khalid[1*a], Zia Ullah Arif[2a], Mokarram Hossain[3], Rehan Umer[1]

[1]Department of Aerospace Engineering, Khalifa University of Science and Technology, PO Box: 127788, Abu Dhabi, United Arab Emirates
[2]Department of Mechanical Engineering, University of Management & Technology Lahore, Sialkot Campus, 51041, Pakistan
[3]Zienkiewicz Centre for Computational Engineering (ZCCE), Faculty of Science and Engineering, Swansea University, SA1 8EN, Swansea, UK

*Corresponding author: Muhammad Yasir Khalid, Email: yasirkhalid94@gmail.com; 100062624@ku.ac.ae

[a]First two authors contributed equally to this manuscript.

Abstract
Wind is a clean, efficient, fastest-growing, renewable energy source, which is extensively applied for power generation. The expected design lifetime of a wind turbine lies between 20 to 25 years and requires decommissioning at its end-of-life (EOL) stage. In recent years, the global trend is shifted towards power generation through wind turbines and has globally increased the decommissioned wind turbine blades (WTBs). Compared to other components of wind turbines, it is not convenient to recycle the carbon/glass fiber-reinforced composite-based WTBs, due to their complicated nature and inhomogeneity. Additionally, it is extremely dangerous to landfill or incinerate WTBs, as these strategies may result in severe health and environmental issues. Consequently, recycling of WTBs is a viable pathway for the renewable energy sector that ensures the sustainability of wind turbines. To date, only 80% - 85% of the wind turbine materials can be recycled but have potential to reach at 100 % through proper attention required on recovery of all wind turbine materials and adaptation of circular economy (CE) models. The motivation behind this review is to emphasize the importance of sustainable options to treat WTB wastes and minimize the utilization of conventional EOL approaches such as landfilling and incineration. This review also shed lights on the current research and development (R&D) projects, which are related to the adaption of various hybrid recycling technologies and CE models. Moreover, this review also highlights current challenges and future developments of WTB composites. It is concluded that concerted efforts should be made by each of the individuals, such as researchers, policy makers, and legislative and industrialist stake holders to improve the viability and effectiveness of the wind energy.

Keywords: Wind turbine blades, recycling, circular economy, composite waste, glass fibers, carbon fibers

Highlights
- Conventional end-of-life approaches for wind turbine blades (WTBs) cause severe environmental issues.
- Recycling of WTBs is highly imperative for a clean, green, and sustainable environment.
- Circular economy models are needs to be in more practice for zero WTB waste.

Abbreviations

CE	Circular economy

CETEC	Circular economy for thermosets epoxy composites
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymer
EOL	End-of-life
EU	European union
FRP	Fiber-reinforced polymer
GF	Glass fiber
GFRP	Glass fiber reinforced polymer
IACMI	Institute for Advanced Composites Manufacturing Innovation
IGA	International energy agency
PLA	Poly(lactic acid)
rCF	Recycled carbon fiber
R&D	Research and development
rCFRP	Recycled carbon fiber reinforced polymer
rGF	Recycled glass fiber
rGFRP	Recycled glass fiber reinforced polymer
rWTB	Recycled wind turbine blade
SDGs	Sustainable development goals
TRL	Technology readiness level
TWh	Terawatt hour
VOC	Volatile organic compound
WTB	Wind turbine blades
ZEBRA	Zero wastE Blade ReseArch

1 Introduction

Modern technologies have completely revolutionized the world through the development of advanced materials for myriad engineering applications including biomedical, automobile, aerospace, and energy storage devices. Overall, these technologies improve the lifestyle of an individual [1]. It is worth mentioning that the improvement in lifestyle comes at some cost, which is the consumption of vital natural resources [2]. Furthermore, excessive use of non-biodegradable waste and various petroleum-based products release a significant number of toxic gases into the atmosphere [3]. As a result, the world is facing various climate issues, as depicted in Figure 1. According to published sources, the global production of plastic waste was roughly 348 million tonnes in 2017 and is estimated to increase at a rate of 1.4 billion metric tonnes by 2050 [4]–[6]. Most of the plastic waste originates from sources, like plastic bags, and hazardous materials from nuclear waste. However, the role of thermoset plastics in this plastic waste is inevitable [7]–[9]. The heterogeneous composites contain epoxy thermosets and synthetic fibers such as carbon fibers (CF) and glass fibers (GF) are the main complex ingredients in the generation of non-biodegradable plastic waste. These composites are mainly used in various applications, such as aerospace, automobiles, and wind turbine blades (WTB), thanks to their excellent mechanical properties [10]–[12].

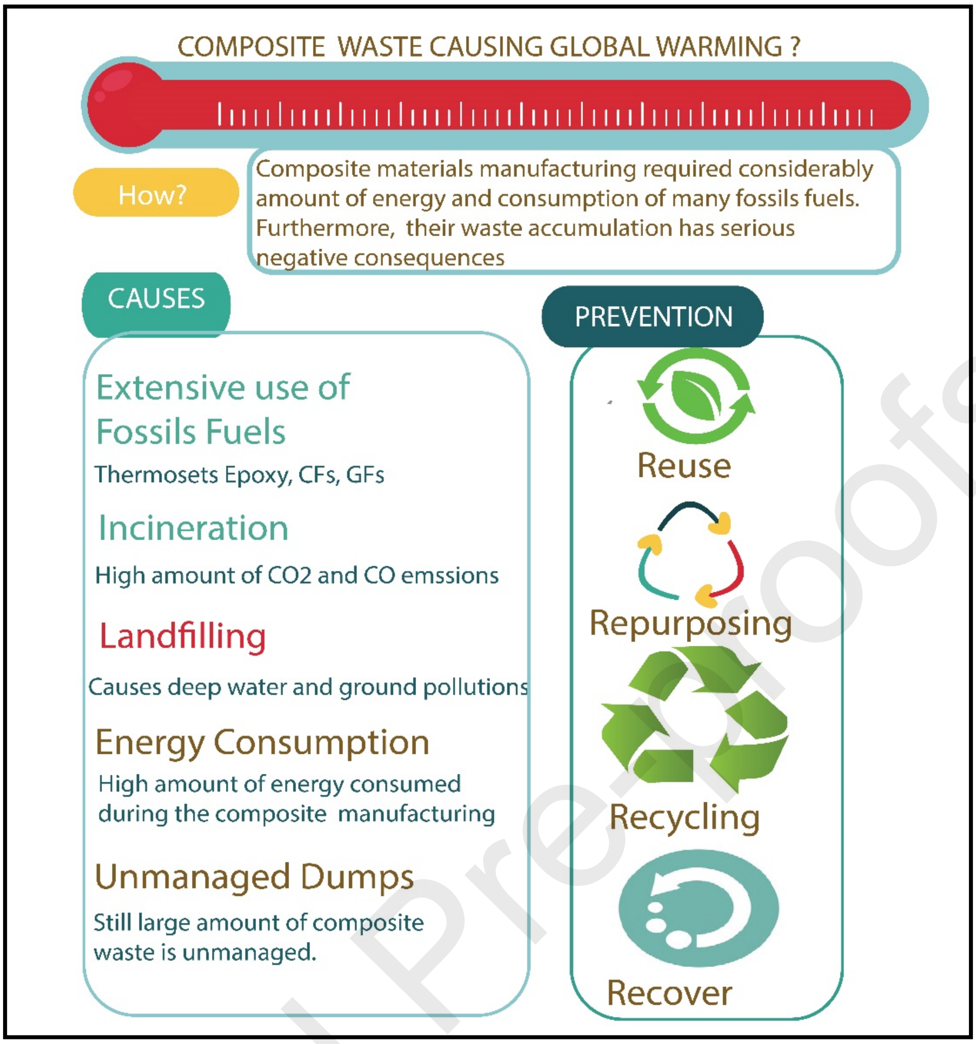


Figure 1. Composite materials causing environmental issues and their possible preventions

Wind is a sustainable, endless, efficient, continuous, and clean energy source, which provides valuable and sustainable alternatives to the widely-used fossil fuel [13]. However, it is necessary to develop a sustainable process for dealing with WTBs at the end of their service (20 years - 25 years) that can help to manage the climate crisis [14]. Figure 2 depicts the major components of a wind turbine and its end-of-life (EOL) options. Some parts like tower, gearbox, foundation, and generator already undergo recycling. However, EOL waste from WTBs is a major concern for the clean environment, due to the rapid growth of wind turbines in the 21st century [15]. WTBs mainly consist of carbon fiber reinforced polymers (CFRPs)/glass fiber reinforced polymers (GFRPs), which offer high strength, high strength-to-weight ratio, as well as low material and manufacturing cost. Nevertheless, it is challenging to recycle WTBs due to thermoset-based various resins and their complex composition [16]–[18].

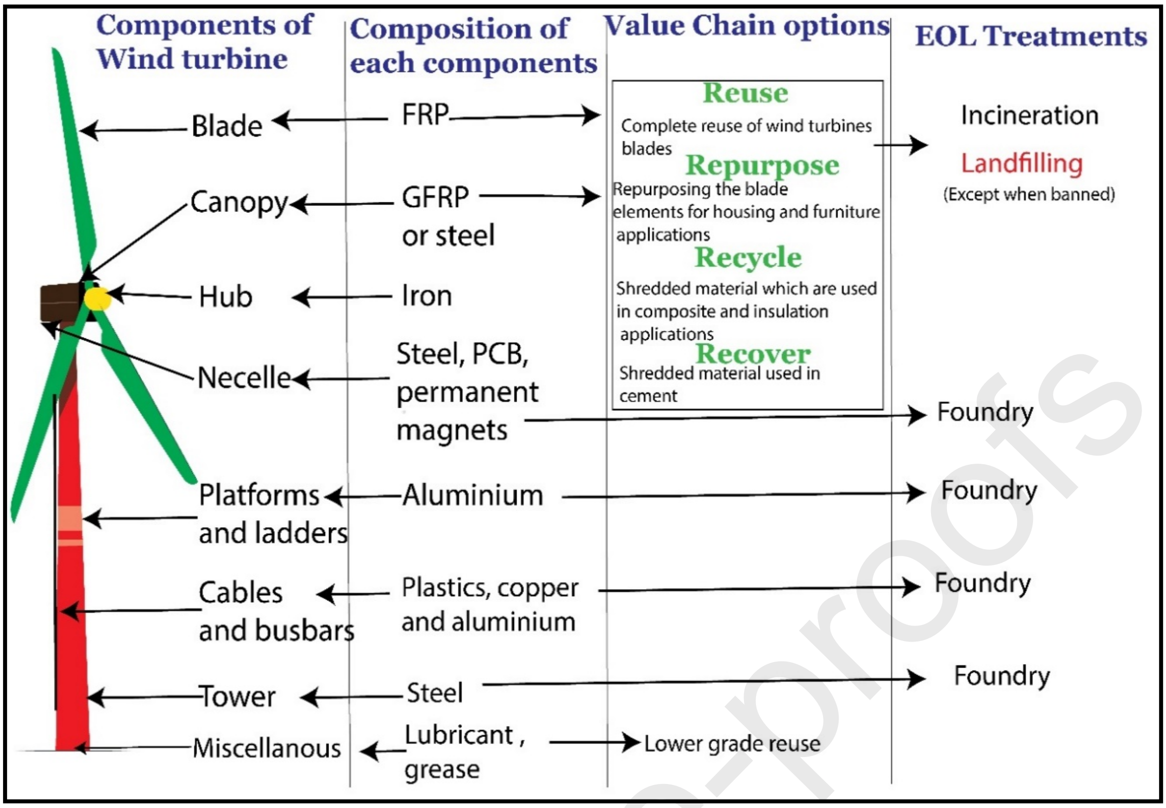


Figure 2. Value chain and EOL options for various components for rotor blades of wind power plants (Figure drawn with the help of [19])

The heterogeneous nature of WTB materials makes them difficult to recycle and lowers their degradability naturally in our environment, thus ending up eventually in landfilling or incineration [20]. Both of these conventional techniques have severe environmental and health-related issues and are largely contributed to the climate change**.** For instance, incineration is generating toxic gases and their inflows into our environment, such as carbon monoxide (CO) and carbon dioxide (CO_2), and are major sources for the global warming [21]–[23]. Landfilling not only takes up clean and arable lands, as shown in Figure 3, but it also produces microplastics, which affect various marine species, cause climate change, and disrupt the food chain. It was reported that 2.6−3.6 Gt CO_2 equivalent of greenhouse gas emissions will be released cumulatively as a result of the offshore wind energy deployment from 2020 to 2040, and synthetic fibers (CFs/GFs) are the main contributor to the climate crisis [24]–[27].

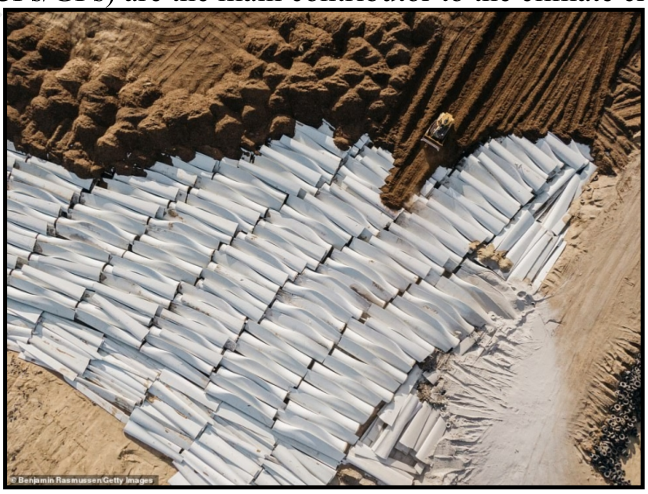


Figure 3. Landfilling of WTB at their EOL in Casper, Wyoming (Photo credit: Benjamin Rasmussen/Getty Images)

The current worldwide capacity of wind power generation is estimated at 743 GW to offset 1.1 billion tons of CO_2 emissions [28]. Wind energy through WTBs is considered a green energy resource and is the fastest-growing energy sector in the world. It is estimated that electricity generation may jump to 30 % in 2050, which is currently only 5 % [29]. Furthermore, the international energy agency (IGA) estimated that wind generation would reach 3317 terawatt hours (TWhs) or more by 2030. Europe consumes most of the WTBs due to their favorable conditions for the generation of wind energy [30]. In Europe, it is expected to increase in the wind energy generation in the next decades that will cover 30 % of the demand for European Union (EU) by 2030. In 2021, USA has started to remove about 8000 WTBs every year and this trend will continue till 2025 [31]. Whereas EU removes nearly 3800 blades every year. The mass of the turbine contains 85 % metallic materials excluding the foundation and can be easily recycled and the remaining 15 % is of fiber-reinforced polymer (FRP) composite-based turbine blades. It is extremely difficult to recycle these blades, which increases composite wastes [32]. Additionally, scientists are constantly looking for ways to improve the wind energy sectors to meet the various clean goals associated with sustainable wind energy. However, extensive wind energy use resulted in the accumulation of a large number of decommissioned WTBs, causing major environmental problems, thus, requiring significant attention after the EOL stage of WTBs [33]–[35].

1.1 Scope of the current review

Given the large consumption of wind energy in the future, it can be predicted that significant WTB waste and its accumulation will pose threats to both humans and the environment equally in the future. From 2033, it is estimated that approximately 200,000 tons of WTB waste will need to be disposed per annum. Thus, there is an unprecedented need to minimize the plastic waste management issues through various existing recycling techniques and circular economy (CE) model and identify the possible sustainable and greener ways to manage the plastic waste of WTB. Some other factors exerted pressure on the adaption of recycling and CE models such as the EU ban on landfilling from 2025. Most wind turbines are reaching their EOL, and rapid growth in the dismantling of aircraft after the pandemic may lead to unsustainable solutions. The recycling and CE models have the potential to reduce our carbon footprint, waste generation, and dependency on fossil fuels. Herein, we summarize and highlight some of the recent state-of-the-art recycling techniques and various research and development (R&D), particularly related to WTBs. This review also sheds light on new CE models for the better usage of composite wastes, especially related to WTB. Thus, leading to a sustainable and cleaner environment for the future.

2 Recycling Technologies

EOL waste management for composite-based WTBs is a complex engineering problem, which must fulfill the four criteria [36]. Figure 4 depicts these criteria which decide the fate of WTBs and their components and require different EOL treatments such as recycling, reusing, decommissioning, and landfilling. Based on recent EU directives, recycling or reusing WTB composite wastes is the best choice to address environmental issues and landfilling must be the least preferable choice [37]. Thus, sustainable recycling approaches or alternative WTB materials are required to deal with the EOL of wind turbines [38]. In recent years, different sustainable recycling techniques have been proposed for composite wastes to recover CFs/GFs from FRPs like mechanical recycling (e.g., crushing, milling, shredding, and grinding), chemical recycling (e.g., solvolysis, glycolysis, and hydrolysis), thermal recycling (e.g., thermolysis, pyrolysis, and fluidized bed process), and hybrid recycling techniques like microwave-assisted chemical recycling [39].

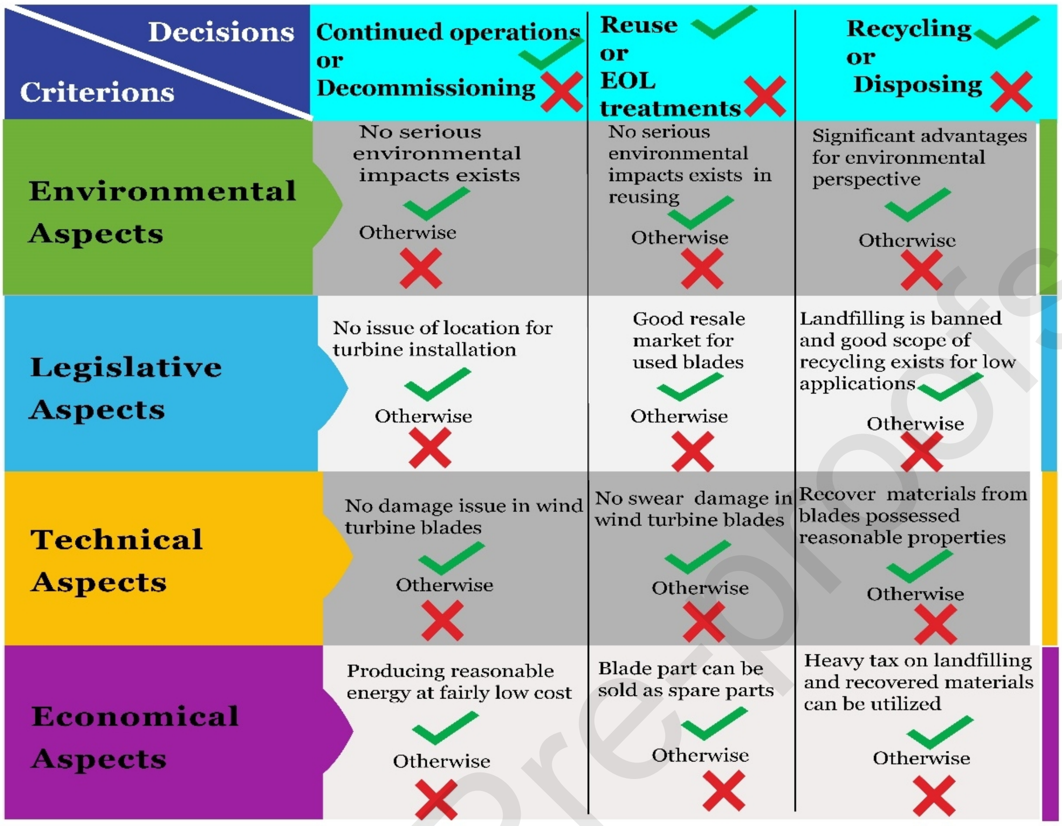


Figure 4. Various environmental, technical, legislative, and economical aspects deciding the fate of various parts of WTB after reaching at their EOL stage. (Figure modified from [37])

Recycling is not only valuable for composite waste management but also adds value to the circular economy and sustainable technology concepts. The term "recycling" refers to the reuse of processed material after some mechanical, thermal, or chemical treatments or combinations of any of these treatments**.** Although reuse of a whole WTB is almost impossible, owing to design limitations. But the waste of WTBs can be reused by converting it into small parts or by reducing the size [40]–[42]. Table 1 briefly summarizes the recycling techniques, which are used to manage the composite waste of WTBs. In mechanical recycling, FRP-based WTBs are milled, crushed, or shredded to small fibrous components (fiber-rich) or powdered materials, whereas chemical recycling uses strong chemical solutions to transform polymer matrices of composite wastes into small molecules for recovering fibers [43]–[45]. In thermal recycling, heat is applied to melt specific parts or constituents and then reclaim the various components in different forms. As discussed above, recycling of GFs or CFs in their composite materials offers several benefits, which are not only limited to their mechanical and physical properties but also save the cost of an additional production phase [46]–[49]. At present, around 85% - 90% proportion of a WTB can be recycled. Numerous challenges exist in achieving the 100 % recycling of WTBs due to the difficulty in remelting and remoulding thermoset resins such as epoxy [50]–[52].

Table 1. Recycling techniques applied for decommissioned WTBs

Recycling processes	**Description**	**Benefits**	**Disadvantages**	**Reuse and application**	**Investment needed in future**	**Ref.**
Mechanical	In mechanical recycling, WTB waste is converted into dissimilar sizes or shapes through cutting techniques. Then, these composites are milled, crushed, shredded, and grinded to form smaller pieces. After this, it is easier to separate short fibers from polymer resins.	**(i)** High treatment capacity **(ii)** Both fibers and resins can be recovered **(iii)** Low cost **(iv)** Loss of high aspect ratio of fibers	**(i)** Degradation of mechanical characteristics **(ii)** Low chances for remanufacturing **(iii)** Provide impure end materials	**(i)** Concrete reinforced through shredded glass or carbon fibers **(ii)** Composite reinforced through recycled short fibers with different lengths **(iii)** Reused to develop products for different applications like dough moulding compound, bulk moulding compound, polypropylene, and nylon matrix composites	Low	[53]
Chemical	Chemical processing involves the chemical decomposition of polymer matrices to recover both short fibers and other degradated products. The solvolysis and the use of subcritical or supercritical fluids are most applied chemical recycling methods. However, high cost and hazardous chemicals are the potential downside of this recycling approach.	**(i)** Complete segregation of fibers and resins from WTB composites	**(i)** Lesser tolerance against contamination **(ii)** Negative environmental impact upon the use of hazardous and aggressive chemicals **(iii)** High cost	**(i)** Composite reinforced through recyclates **(ii)** Fuel gas	High	[54]
Pyrolysis	In pyrolysis, WTB waste is heated at between the temperature range 450^{o}C - 1000^{o}C based on the composition of waste materials. The polymer resins are converted into vapor or gas and the remaining fibers remain unaffected	**(i)** Inexpensive and straightforward process **(ii)** Can recover chemical feedback from the resin **(iii)** Ability to recover both material and energy simultaneously	**(i)** Highly sensitive to process parameters	**(i)** Pyrolytic oil or gas **(ii)** Organic liquid fuel **(iii)** Composite reinforced through recovered short fibers	Low-medium	[55]

	and are finally retrieved.	**(iv)** Chemical solvent is not required				
Oxidation in fluidized bed	In the fluidized bed technique, WTB composite wastes are cured in the presence of an oxygen-rich environment and hot air of temperature (450°C - 550°C) to segregate polymer resin from the fibers. As a result, polymer matrices undergo combustion, thus, separating fibers.	**(i)** Quick heating due to the presence of bed **(ii)** Good quality of recovered fibers **(iii)** Low economic viability	**(i)** Low mechanical properties of the recovered fibers **(ii)** Short fibers **(iii)** Low efficiency	**(i)** High-modulus composites **(ii)** Electromagnetic shielded materials **(iii)** Bulk moulding compound	Medium	[56]

2.1 Mechanical recycling

Mechanical recycling of WTB composite waste is a straightforward, solvent-free, and mature technology and is most extensively applied for the commercial recovery of glass or carbon fibers [57]. In this technology, FRPs undergo shredding, crushing, milling, or grinding, and the resulting materials may appear in the form of fibrous products and powdered fillers. The major steps in mechanical recycling are milling, washing, and pelletizing. Large-scale composites like large WTBs require pre-cutting before crushing [58]–[60]. Mechanical recycling for wind turbines involves crushing or shredding of WTBs to acquire small fragments and then, ground them to fine materials. Fibrous materials and fine powders (resin-rich) are separated through mechanical sieving. This technique is cost-effective, uses the least amount of energy among all the recycling techniques, and effectively reduces environmental risk caused by WTB-based wastes [61]. Mechanically shredded WTB composites contain a mixture of long fibers impregnated with resins, individual fibers, and clusters of materials. Thus, shredding is the most important aspect of the recycling of composites. Such a recycling approach cannot be used to obtain continuous and long fibers [62]. Additionally, this process considerably reduces the intrinsic mechanical properties of the recovered fibers. To overcome the issue, recycled fibers are used in combination with virgin fibers in the secondary as well as high-end applications. For instance, in the construction sector, asphalt and cement can be reinforced by using a combination of recovered materials and new resins [63].

Another suitable way for WTB waste is to reuse them for lower structural applications. WTBs would generate approximately 200,000 tons of composite waste between 2024 and 2034 [64]. Thus, it is feasible to use WTB waste as a powder through mechanical processing for improving the moisture and aging resistance of asphalt mastic. Reusing of WTBs after some treatment makes them an ideal candidate for many structural applications such as bridges and fillers for other applications, as depicted in Figure 5 and Figure 6. This ultimately adds to the momentum from sustainable environmental perspectives [65]–[67]. Researchers at Michigan State University have developed composites from WTB waste that can be recycled into unique things, sweet treats such as gummy bears, as presented in Figure 6(b).

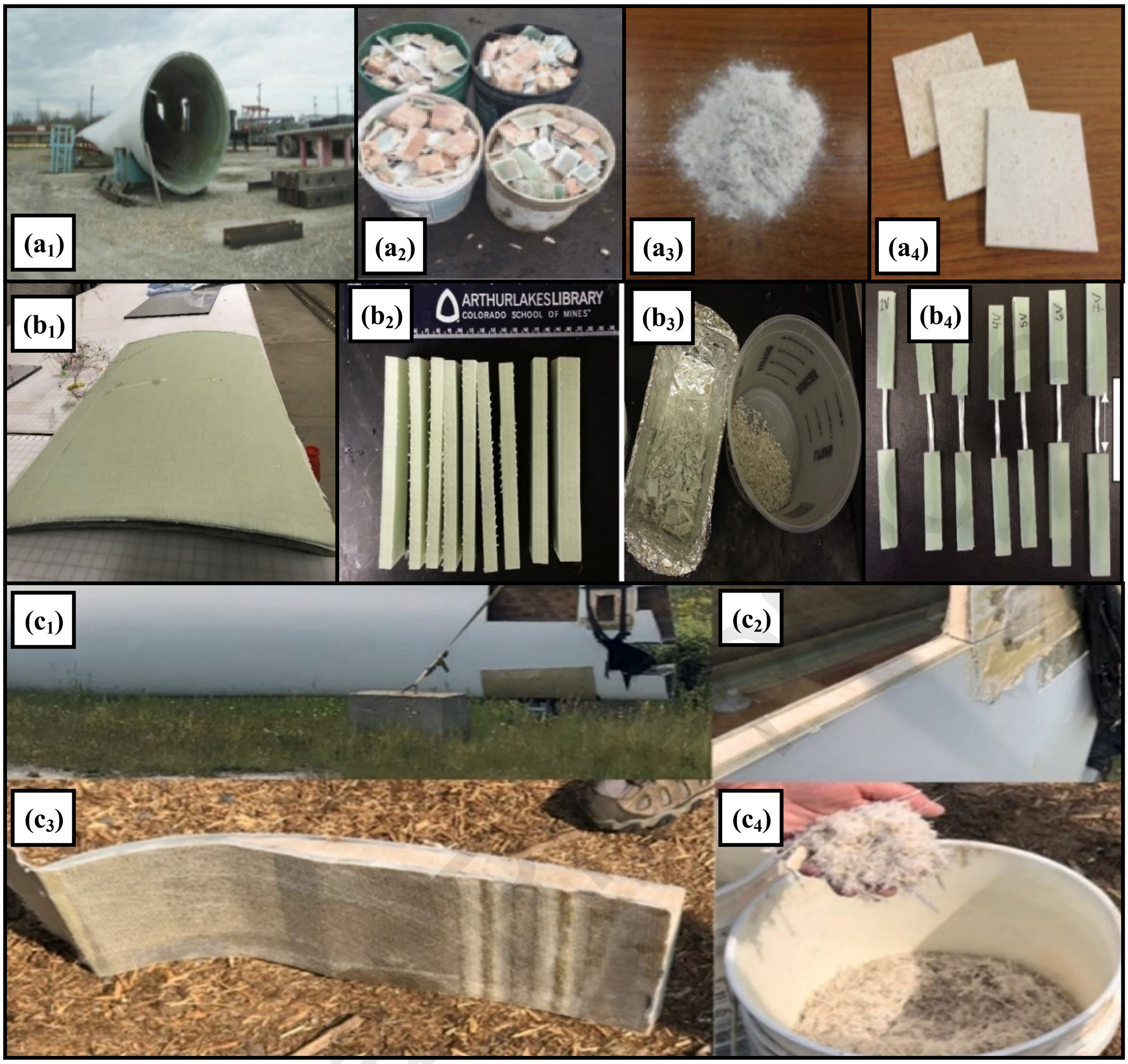


Figure 5. Recycling strategies for WTBs, (a_1) Recycling of WTB for getting rGFRP composites, (a_2) EOL of WTB, (a_3) Mechanical recycling of GFRPs, (a_4) Recycled composites after hot pressing (adapted with permission from [68], copyright, 2018 Elsevier Ltd.); (b_1) Elium spar cap component, (b_2) Strips of spar cap component, (b_3) Standard mesh screen (foil pan), (b_4) Recycled tensile specimens (adapted with permission from [69], copyright, 2018 Elsevier Ltd.); (c) Material processing of WTB wastes; (c_1-c_2) WTB, (c_3) Cutting of WTB, (c_4) Fiber extraction (adapted with permission from [70], copyright, 2021 Elsevier B.V.).

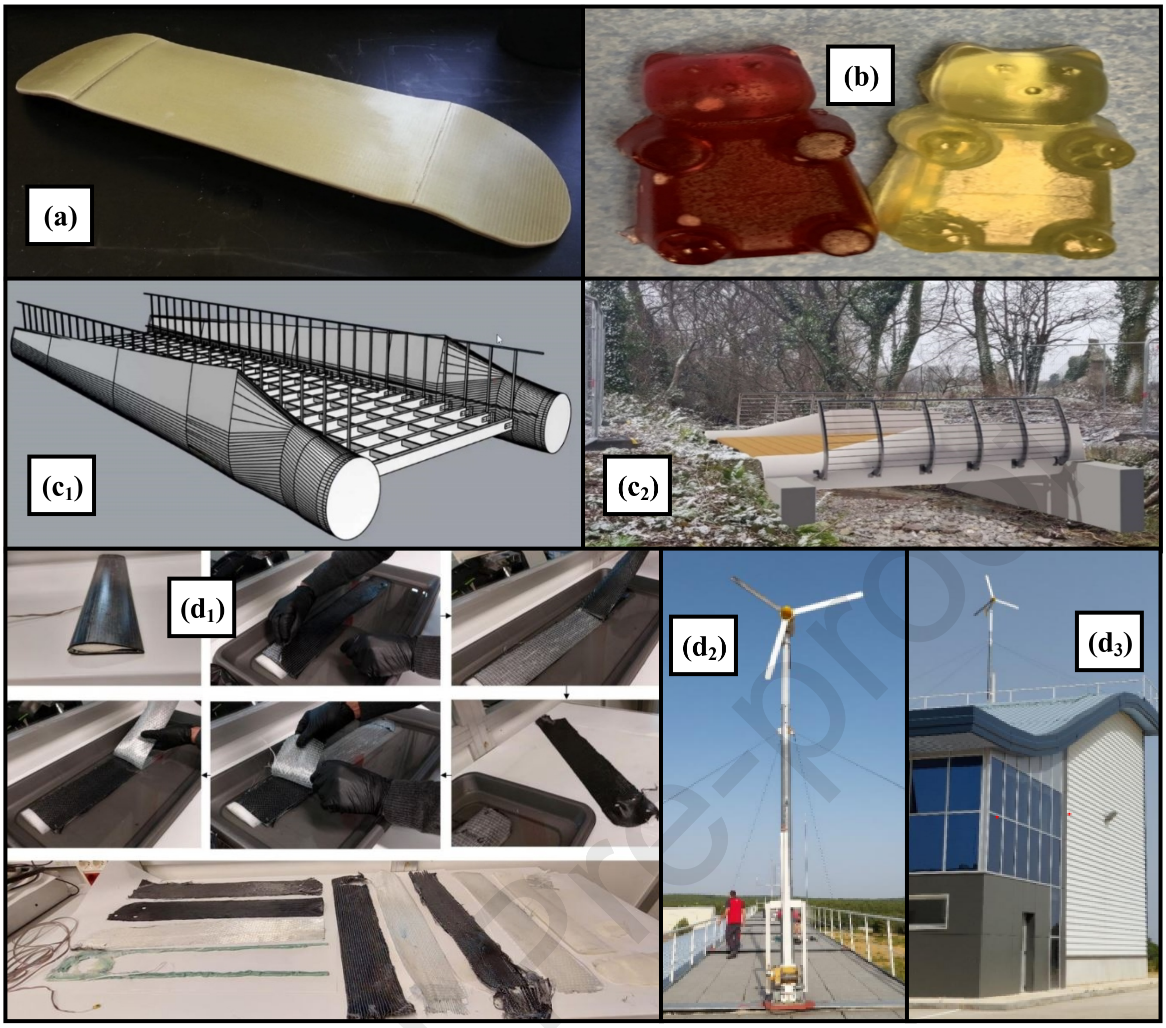


Figure 6. Reusing techniques for WTBs, (a) A prototypical skateboard manufactured part by thermoforming of Elium/glass (adapted with permission from [69], copyright, 2018 Elsevier Ltd.); (b) Gummy bears produced from recycled WTB material (Picture credit John Dorgan, Ph.D., Michigan State University [71]); (c_1) Preliminary render of blade bridge design showing Nordex N29 blade sections as primary load bearing members, (c_2) Render of blade bridge at Roxborough, Midleton, Cork (Image Courtesy: Asha E. McDonald & Alexander D. Poff, Georgia Tech [72]); (d_1-d_3) Recycling and reusing of Akelite wind blade to develop new wind turbine blade (adapted from [73], under creative commons attribution 3.0 license).

2.2 Thermal recycling

Thermal recycling techniques being efficient are extensively used for separating carbon or glass fibers by incinerating epoxy resins, and recyclates are reused in secondary composite products. Due to heating in thermal recycling, composite wastes are decomposed into various solid and gas products [74]. These techniques allow rapid and continuous waste throughput while remaining tolerant of contaminated waste streams. Thermal recycling consumes more energy than mechanical recycling but lesser than chemical recycling [75]. This recycling approach is more suitable for CFs than GFs, thanks to the high-temperature resistance of CFs. Thermal treatments on GFs result in a significant loss of fiber strength (50% - 90%), which limits the use of these fibers in high-strength components. Recycled fibers demonstrate optimum environmental performance and a significant drawback is the high-temperature decomposition of epoxy that produces toxic substances in the atmosphere [76]. Thermal recycling technology is further classified into pyrolysis, fluidized bed recycling, and microwave pyrolysis [77].

Pyrolysis is a promising recycling technology that is used to reclaim fibers from EOL WTBs by decomposing resins into small organic molecules under an inert gas heat (nitrogen). This process is usually performed between 300°C and 500°C [78]. Additionally, some specific catalysts can help in lowering the processing temperature. Heating rate, reaction temperature, and pyrolysis duration are critical parameters for reclaiming GFs as well as for decomposing polymer resins [79]. Post-oxidation is required to obtain clean fibers from the solid products containing residual char layers. These recovered fibers are used to produce short FRP composites with properties comparable with virgin FRPs. Pyrolytic oil or gas produced from WTB materials can be used as fuels, which makes this process highly sustainable [80]. The load transfer capability of FRP composites relies on interfacial shear strength and intrinsic mechanical properties of the reinforcing fibers. Both factors contribute to the final characteristics of the recyclates [81]–[83]. Recently, Rahimizadeh et al. [84] employed both mechanical and pyrolysis recycling processes to reclaim GFs from WTB scrap.

The fluidized bed recycling method employs a rapid stream of hot air gas in a fluidized bed reactor to disintegrate the WTB composite wastes through a high-temperature airflow. The operating temperature of this recycling approach lies between 450°C - 550°C. This process is highly suitable for recovering good quality recyclates (GFs/CFs) from EOL WTB composite wastes. Overall, the strength of fibers is low compared to virgin fibers and shows only 60% - 70% strength of recovered GFs/CFs. These recyclates can be reused to develop composite for high-end applications [85].

2.3 Chemical recycling

Chemical recycling technology is the most advanced and efficient recycling method for processing of FRP waste, yet it is not commonly implemented on an industrial scale because it requires a considerable amount of energy in comparison to other recycling processes [86]. It involves the chemical decomposition or modification of the WTB composite matrix in useful chemical solvents at low-medium temperature (< 350°C) to reclaim both degradation products and fibers, which could be applied for other high-end applications [87]. Chemical solvents such as tetralin, nitric acid, subcritical/supercritical fluids, and subcritical/supercritical water are used to decompose resin matrix. Supercritical fluids, which are typically applied in chemical recycling must possess strong solvent properties. Furthermore, these fluids should increase mass transfer rate with low viscosity and high diffusion constant under specific conditions (above critical point) [88].

Initially, this technique is considered suitable for recovering fibrous reinforcements. However, recent studies have indicated that low molecular weight oligomers could be recovered by chemically decomposing thermoset resins under mild conditions [89]. In comparison to other recycling technologies, this approach is considered best for fiber recovery, even though it is technically difficult and costly to apply this recycling technique to composite wastes. In a recent study, an Akelite WTB was recycled by immersion in acetone at room temperature for 24 hours. The purpose of chemical recycling was to recover both fiber and thermoplastic resin. Plies were separated through a gentle pull through hand and later left to dry at room temperature. The recovered resin was poured into rotavapor equipment at 50°C for the separation of dissolved polymer and solvent for their reuse [73]. Recovered fibers and resins were reused to develop new WTB, as presented in Figure 6(d).

To date, various chemical recycling processes have been applied for the recycling of WTBs, but only short, random, and fluffy fibers are reclaimed even with the most advanced process [90]. Chemical recycling may destroy size, surface, and braided order of fibers. Thus, recycled fibers are mainly suited for secondary applications. Chemical recycling is classified into low temperature solvolysis and sub-supercritical solvolysis [91]. Various supercritical fluids such as water and alcohol are often employed in chemical recycling and use substances above their critical temperature and pressure. Such supercritical fluids are commonly characterized by their diffusivity and by high solubility, resulting in the decomposition of composite wastes. This recycling approach is not yet commercialized. More efforts are required for commercializing this technology for WTB waste. Furthermore, it is necessary to use expensive and strong solutions in solvolysis and glycolysis, due to the heterogeneous nature of WTBs [92].

2.4 Hybrid recycling

Hybrid recycling techniques such as the combination of thermal, mechanical, and chemical recycling are highly efficient strategies to recover fibers, which possess mechanical properties comparable to virgin fibers [93]. Likewise, the microwave is considered highly effective for volumetric heating. Microwave irradiation helps to improve performance by reducing reaction time. In recent times, microwave-assisted synthesis has gained significant attention in the recycling of composite wastes [94]. A plethora of studies has shown that microwave irradiation accelerated the chemical rates compared to traditional heat sources. Some authors used a microwave-assisted chemical recycling approach to reclaim GFs/CFs from composite wastes [95]**.** Microwave-assisted pyrolysis, a particular type of pyrolytic method, decomposes the resin matrix of WTB composite wastes through microwave radiation. In this mini-equipment, WTB composites internally absorb microwave energy, which increases the decomposition rate, and reduces processing time. It is a clean, efficient, and environmentally benign technique, which could permit the efficient recovery of glass or carbon fibers [96]. For instance, Jiang et al. [97] recycled CFRP composites at 500^{o}C for 30 minutes with a nitrogen flow of 0.70 m^3/min. The recycled carbon fibers (rCFs) obtained by using microwave-assisted pyrolysis exhibited a clean fiber surface with mechanical properties comparable with virgin CFs.

Table 2 summarizes some of the work on the recycling and recovery of CFs and GFs from WTBs, as well as contains different adopted recycling procedures and mechanical properties of recycled fibers.

Table 2. Literature works on reclaiming or reusing of CFs and GFs from WTB using different recycling routes along with their mechanical properties and key findings

Recycler(s)	**Year**	**Fibers**	**Description about recycling process**	**Mechanical properties of recycled fibers / composites**	**Key findings**	**Ref.**
Rani et al.	2022	GFs	The microwave assisted chemical recycling was performed using solvent ratio (oxidizing agent/acid:30/70, 50/50) along with microwave exposure of 180s.	A maximum tensile strength of 3025 MPa and tensile modulus of 77.86 GPa were reported for rGFs.	The microwave-assisted chemical recycling technique was a feasible EOL approach to recycle the WTB waste (GFRP composite).	[98]
Ma et al.	2021	CFs	The closed-loop (chemical) recycling was performed for resin and CFs from CFRPs.	A maximum tensile strength of 330 MPa and tensile modulus of 34 GPa were reported for rCFs.	The high efficiency closed-loop recycling provides high-performance composites.	[99]
Smolen et al.	2022	CFs	The recovery of CFs from WTB through pyrolysis technique at 500–600 ◦C in a non-oxidizing atmosphere.	Composite panels with the pyrolytic CFs demonstrated higher flexural of 274 MPa which was 35% higher than original CFs (203 MPa).	rCF-based composites panels gave potential to be used in the production of elements for pipelines footbridges, or structural elements of buildings and roofing.	[100]
Rahimizadeh et al.	2020	GFs	Mechanical recycling was performed through grinding integrated with a double sieving mechanism.	A Young's modulus of 3.35 GPa was noted during tensile testing.	The results showed 16 % and 10 % improvement in the elastic modulus and ultimate strength of the reinforced composite filament, respectively, compared to the commercially available pure PLA filament.	[101]
Haider et al.	2021	GFs	Mechanical recycling was done, and the laminates milled into shreds in a hammer mill with a 12.7 mm screen	A maximum flexural toughness of 1.12 J and residual strength of 4.8MPa were reported for recycled GFRP.	Results showed that recycled GFRPs were promising materials and used as a partial replacement of sand in mortar.	[102]
Pender and Yang	2020	GFs	Thermal recycling was performed through fluidized bed process	A maximum 15 MPa interfacial shear strength was reported.	NaOH treatment on rGFs significantly improved tensile properties.	[77]
Moslehi et al.	2021	GFs	Mechanical recycling was utilized for shredding of turbine blades	A maximum stiffness of 4.7 GPa and strength of 75 MPa were found during tensile testing of rGF/PLA composites.	Chemical treatments significantly improved mechanical properties.	[75]

Joustra et al.	2021	GFs	Segmentation approach was employed on blade model for reusing in structural applications	Maximum flexural modulus and strength were found in the range of 52.2 – 99 GPa and 8.1-13.3 MPa, respectively for spar cap beams component of WTB.	Reusing technique was successfully employed in the fabrication of picnic table.	[103]
Tahir et al.	2021	GFs	Mechanical recycling was performed through grinding for converting GF of WTB materials into reduced-size fibers or resin powder.	Maximum tensile strength of 1132.2 MPa and modulus of 81.2 GPa were reported during tensile testing.	Recycled fibers drastically improved the specific modulus of the 3D-printed samples reinforced with rGFs components.	[104]
Mattsson et al.	2020	GFs	Chemical recycling through solvolysis process was employed using sub/supercritical water at 250-370 °C at100-170 bar with catalyst (acid and base) and additives (alcohols and glycols).	-	rGFs from real WTB and a hydrocarbon fraction can be employed as a refinery feedstock	[87]
Baturkin et al.	2021	GFs	Thermal recycling through pyrolysis was used at 600^{o}C.	Maximum compressive strength of ~29 MPa and flexural strength of ~ 6.5 MPa were reported.	rGFs from WTBs have the potential to be used for valorization in concrete construction to allow the transition to carbon neutrality in the cement and concrete sector.	[70]
Mamanpush et al.	2018	GFs	Mechanical recycling was done with hammer mill by using different screen sizes. rGFs were obtained which later compressed to a final thickness.	A maximum 5254 MPa modulus of elasticity was found during flexural testing	Mechanical recycling is a feasible approach to recycle WTBs for producing high-performance composite.	[68]
Cousins et al.	2019	GFs	Mechanical recycling was performed through grinding and thermal recycling was performed using pyrolysis technique.	A maximum stiffness of 12 GPa and strength of 150 MPa were found during tensile testing for injection molded regrind material.	Results showed that 50% of the rGFs and 90% of recovered resin can be sold at a price of $0.28/kg and $2.50/kg, respectively.	[69]

3 Circular economy model for wind turbine blades

A global economic model which strives to decouple economic growth from the consumption of finite resources is considered a circular economy (CE) model [105]–[107]. This model further overcomes the disadvantages associated with linear economic models such as "take, make, and dispose of" [108]–[110]. The different sustainable development goals (SDGs) can be achieved through the CE model without affecting the performance of materials, products, or designs. Thus, these models reduce carbon footprints, maintain an overall sustainable environment, as well as provide satisfactory products [111]–[113]. The idea of CE has been considered to recover valuable CFs/GFs from EOL turbine blades**.** Furthermore, these fibers are allowed to reenter the cycle by retaining the highest possible quality [114]–[116]. The implementation of the CE model for WTBs helps to replace the EOL idea with restoration, as well as eliminate toxic chemicals and composite wastes [117]. Figure 7 depicts the CE model, which has gained attention in the renewable energy sector. The wind energy sector can take considerable advantages by adapting various CE models for the efficient reusing of WTB waste in other high-end applications.

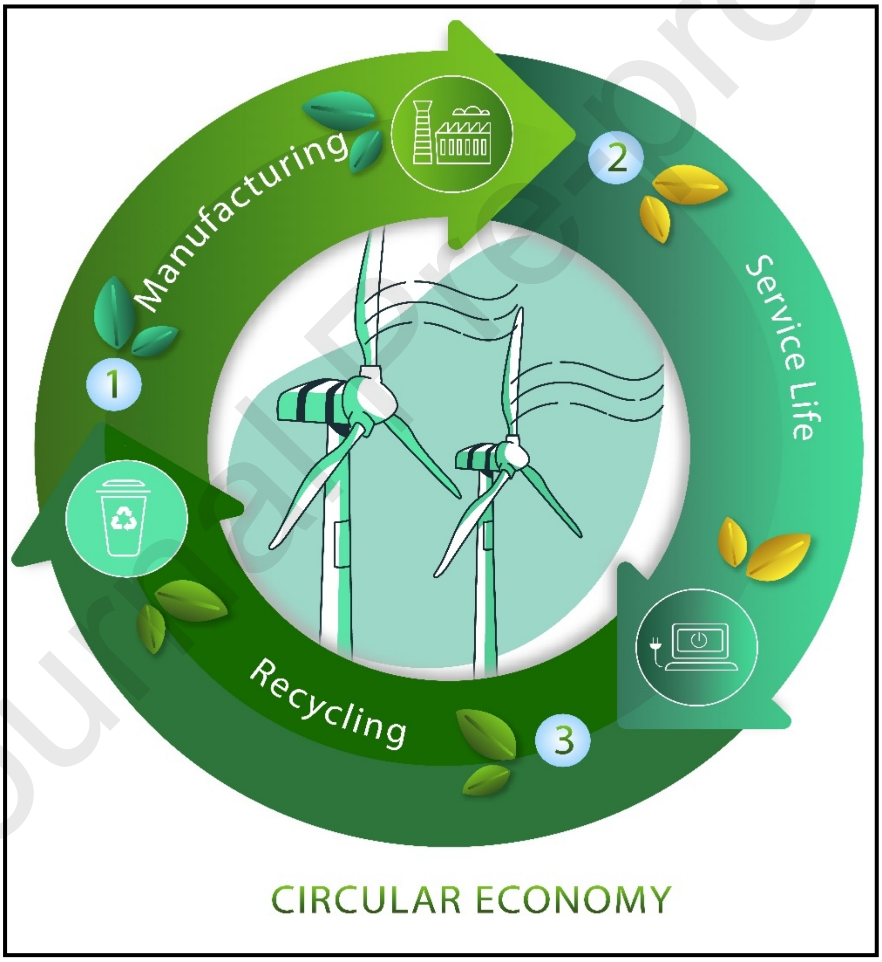
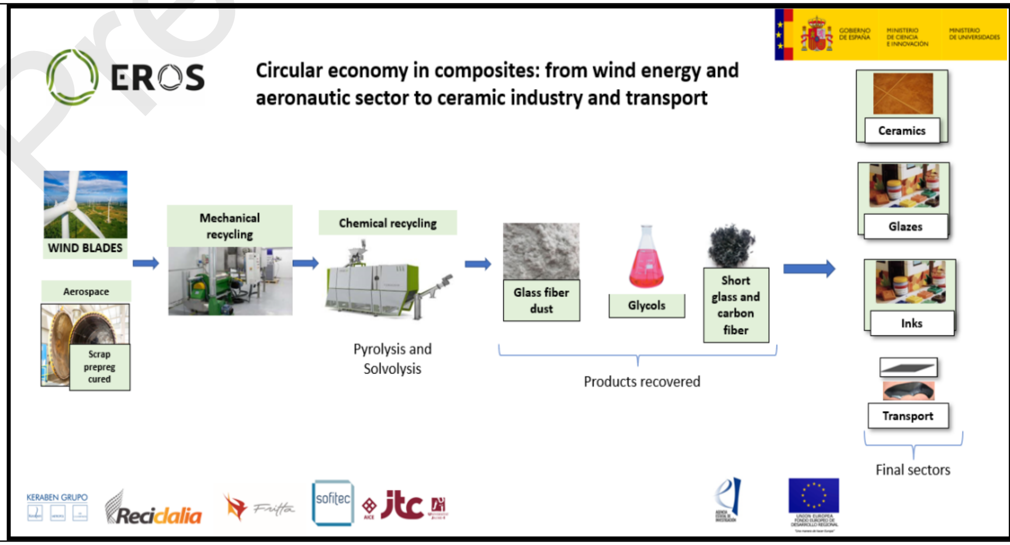
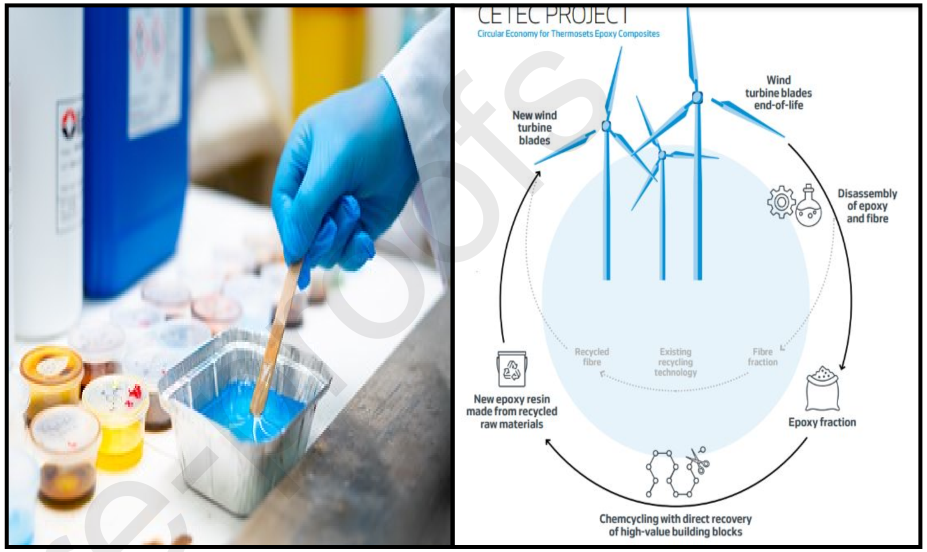
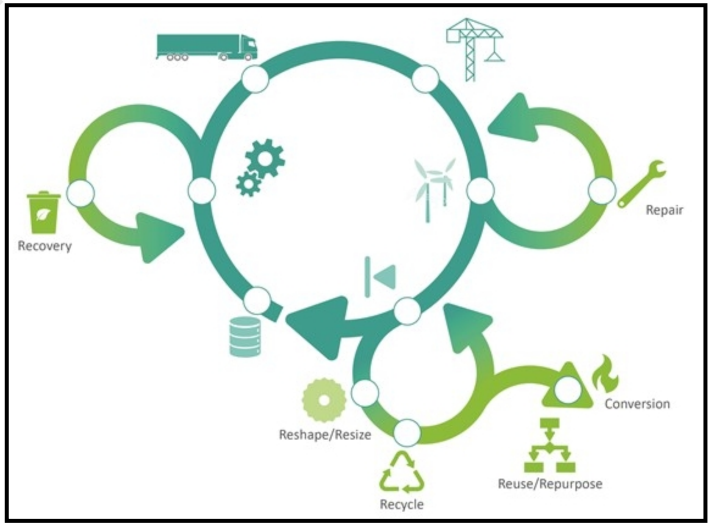


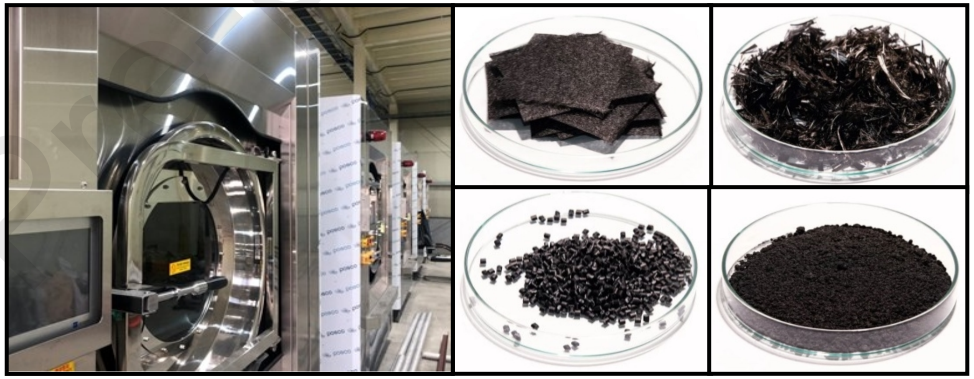
Figure 7. General Circular Economy (CE) model adapted for the better handling of wind turbine waste

Jensen and Skelton [31] highlighted the importance of implementing the CE model on WTBs and considered this approach an effective way to reclaim fibers. A recent study also showed that chemical recycling has the potential to recycle CFs, hybrid laminates, or GFs of WTBs with no compromise on their quality [118]. Nowadays, companies have invested billions of dollars to recycle and implement CE models to reduce environmental impact. For instance, the main aim of GENVIND project (Danish innovation consortium) is to reuse wind turbine waste besides producing energy [119]. Table 3 incorporates current R&D projects on recycling and CE models for WTB adopted by various companies.

Table 2. Different R&D Projects and companies working on the recycling of WTB composite wastes

Company/ project	**Recycling Technology**	**Country**	**Highlights**	**Illustration of product (s), facility/ technology or CE models**	**Ref.**
The ZEBRA project	Chemical and mechanical recycling	France	• Thermoplastic Elium® resin is used. • Potential to reach at 100% recycling rate due to thermoplastic resin. • Arkema's Elium® thermoplastic resin-based 6 2 meter blade, which is completely recyclable having high performance GF from Owens Corning (as presented in next column) (adapted with permission)		[120]
AIMPLAS and EROS group	Mechanical, pyrolysis and solvolysis	Spain	• Evaluate existing methods to determine which method results in the purest fiber (free from VOC). • Recycle both WTBs and aerospace manufacturing scrap, AIMPLAS and EROS project partners aim to optimize mechanical and chemical recycling operations with the goal of reuse for specific end markets. CE model is presented in next column (Photo Credit: AIMPLAS)		[121]–[123]

CETEC group	Solvolysis	Denmark	• The CETEC project is working toward solvolysis reclamation of epoxy resins from WTB. • The goal is to not only reclaim the material for reuse but to add it back into the wind industry and the manufacture of new wind blades. • As of spring 2022, the CETEC partners had developed a proof of concept ready to be commercialized. • When fully developed, the solution may also have an impact on other industries that rely on thermoset composite in production, such as automotive and aviation. (Figures presented in next column Source: Vestas/CETEC)		
SUSWIND/ National Composite Center Project	-	UK	• The ultimate goal is to design WTB for recyclability or circularity. Developing models to assess the cradle-to-grave impacts of alternative materials and manufacture, as well as novel circular design methods. • A winding path to circularity. There are many ideas for the best way to repurpose, reuse and/or recycle WTB and their materials, for new industry applications or even toward the production of new WTB in a circular economy solution. (Photo Credit: National Composites Centre)		[124]–[126]

Siemens Gamesa	Chemical recycling	Germany	• Allows full reclaim of the blade's components at the end of the product's lifespan. • Separating the resin, GFs, and wood, among others, is achieved through using a mild acid solution. • Drop-in replacement resins like Elium and Recyclamine show promise as first solutions (Siemens Gamesa's Recyclable Blade shown here). (Photos Credit: Siemens Gamesa)		
CATACK-H group	Chemical recycling	South Korea	• Chemical solvents used for breaking epoxy-based resins in CFRP parts to recover fibers to reuse as a chopped or milled fiber product presented in next column (Photos Credit: CATACK-H). • The company plans to quickly scale this up to 1,000 tons per year with the installation of a second, 700 tons/year line for batch treatment of "harder" materials like cured prepregs and EOL CFRP parts, expected to go online in January.		[127]–[130]
Carbon Rivers	Pyrolysis	USA	• Recycling capacity of 50,000 metric tons annually. • Carbon Rivers has achieved 99.9% recycled GFs purity from different EOL waste streams like WTBs presented in next column (Photo from Carbon Rivers). • The high purity also opens the potential for remelting-allowing recycled GFs to be incorporated		

			into virgin GFs thereby closing the material loop and creating a CE		
IACMI group	Chemical recycling	USA	• Used recyclamine is a thermoplastic epoxy - a thermoset resin that, unlike a traditional thermoset, dissolves with heat and a mild acid solution such as acetic acid.		[131]

4 Summary, current challenges and future outlook

CFs from FRP composites are used in WTBs, due to the high energy generation capability, and strong and hard nature of CFs. These include excellent mechanical properties especially in terms of fatigue cycles to failure of CFs [132]–[134]. However, the incorporation of CFs in WTB caused major concerns about sustainability since CFs are hard to recycle. It is worth mentioning that the EOL of CFs-based WTB through landfilling and incineration has serious environmental issues. More importantly, these conventional techniques are not suitable from a CE perspective even in the long run [135]–[137].

Apart from various sources about the current trend and future prediction of WTB waste, there is still uncertainty in accurately predicting the future of WTB waste and the best solution to tackle it. Currently, the recycling of WTB is one of the highest priorities around the globe [138]–[140]. Many environmental issues can be resolved through policy interventions like allocating funding to WTB manufacturing and disposal projects, providing incentives to recycling companies, and issuing policy directives to the renewable energy sector [141]–[143]. Modern recycling technologies have been found as viable and sustainable options for the effective utilization of EOL composite wastes. However, significant efforts are required to address some existing challenges.

According to existing literature, mechanical, chemical, and thermal recycling technologies show drawbacks like surface defects, fiber length, equipment costs, and process suitability according to the composition of WTB composites. To overcome these limitations, the focus of researchers is diverted towards hybrid recycling technologies [144]–[146]. Currently, the research is going on microwave-assisted chemical hybrid recycling, which is a highly efficient technique to recover high-quality fibers. However, more focused research is required to make it an industrial scale recycling process. The design, composition, testing, and maintenance of WTBs is an important active research arena and scientists must provide accurate designs so that these materials after recycling retain straight and long fibers and maintain high-performance potentials.

Evidences suggest that CE-based various models do not always provide optimum solutions from economic, social, and environmental perspectives. CE models mainly focus on the usage of waste materials repeatedly, thus targeting only decarbonization in our eco-system [147]–[149]. However, it is envisaged that some parameters must be considered in designing a better and may be more appropriate CE model, such as toxicity, acidification, biodiversity loss, and eutrophication [150]–[152]. Not limited to this, there are still a lot of questions that come to mind about perfect CE models, which are presented in Figure 8. Thus, taking into account all of these considerations while designing, a CE model will provide a complete framework for researchers, industrialists, legislative, and policymakers [153]–[155].

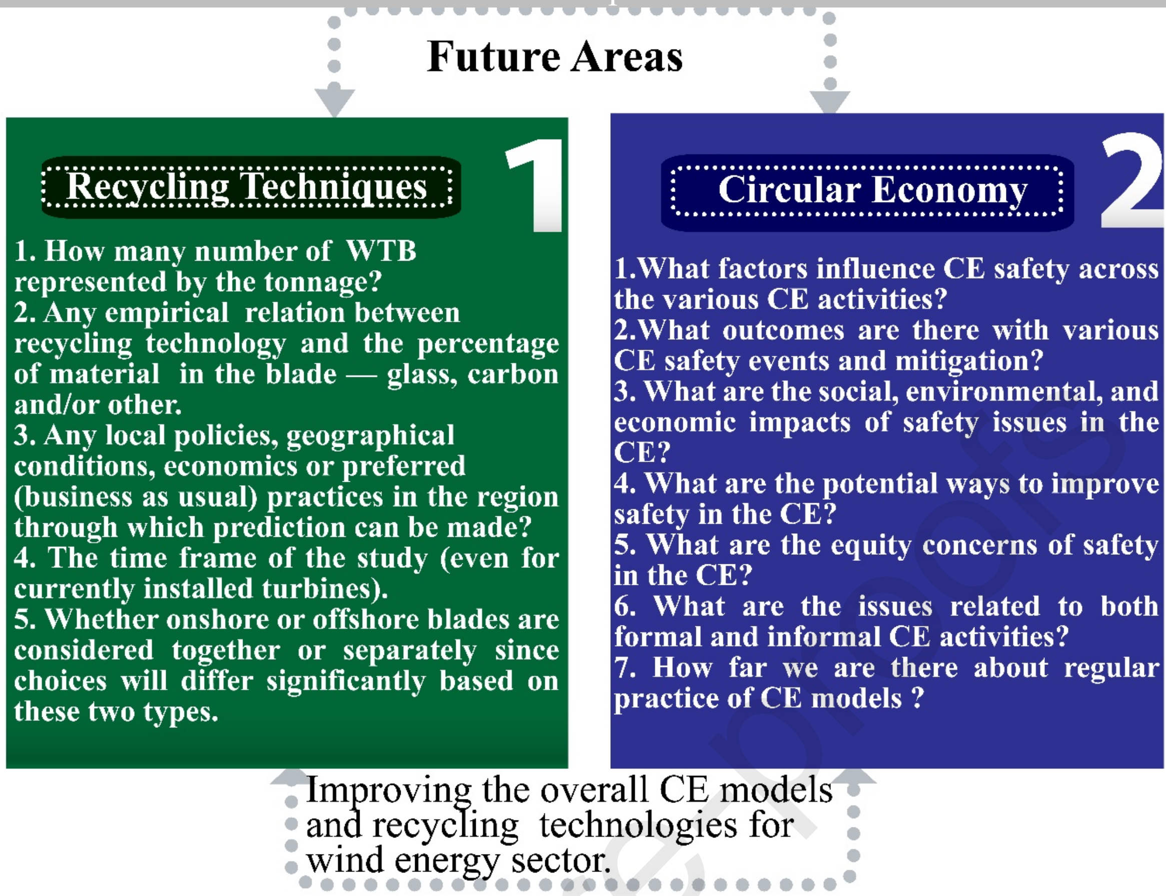


Figure 8. Future areas and research questions must be addressed for improving the overall recycling rate of WTBs. (Information in figure is collected from [38], [56], [142], [156])

The current major constituents of WTBs are thermoset composites, which create challenges in manufacturing, disposal, and recycling treatments. The road to zero WTB waste can be possible by replacing synthetic materials with natural resources [157]. Recently, some attempts were made to evaluate the suitability of WTB applications at the laboratory level by using environmentally benign natural fiber-reinforced composites. Spruce bamboo, jute, birch, sisal, and Douglas fir are appropriate green fibers for developing WTBs [158]–[160]. However, the mechanical properties of bio-based green composites are lower compared to synthetic FRP composites. These mechanical properties can be enhanced by developing hybrid composites [161]. Thus, these green composites have got an enormous scope in the renewable energy sector. Figure 8 also depicts the potential areas or questions which must be explored by the futurist recyclers.

The technology readiness level (TRL) feature can be used in the recycling of WTBs for evaluating and estimating the maturity of these technologies with values ranging from 1 to 9 [118]. Figure 9 presents TRLs of different recycling technologies based on established knowledge about the application of each recycling technology, their recent advancements, and real-world applications. This figure also shows that the TRL of microwave pyrolysis-based hybrid technology is low with a high waste management score. Considering the high waste management score and low TRL, a significant amount of research funding will be required for further developments of hybrid recycling techniques.

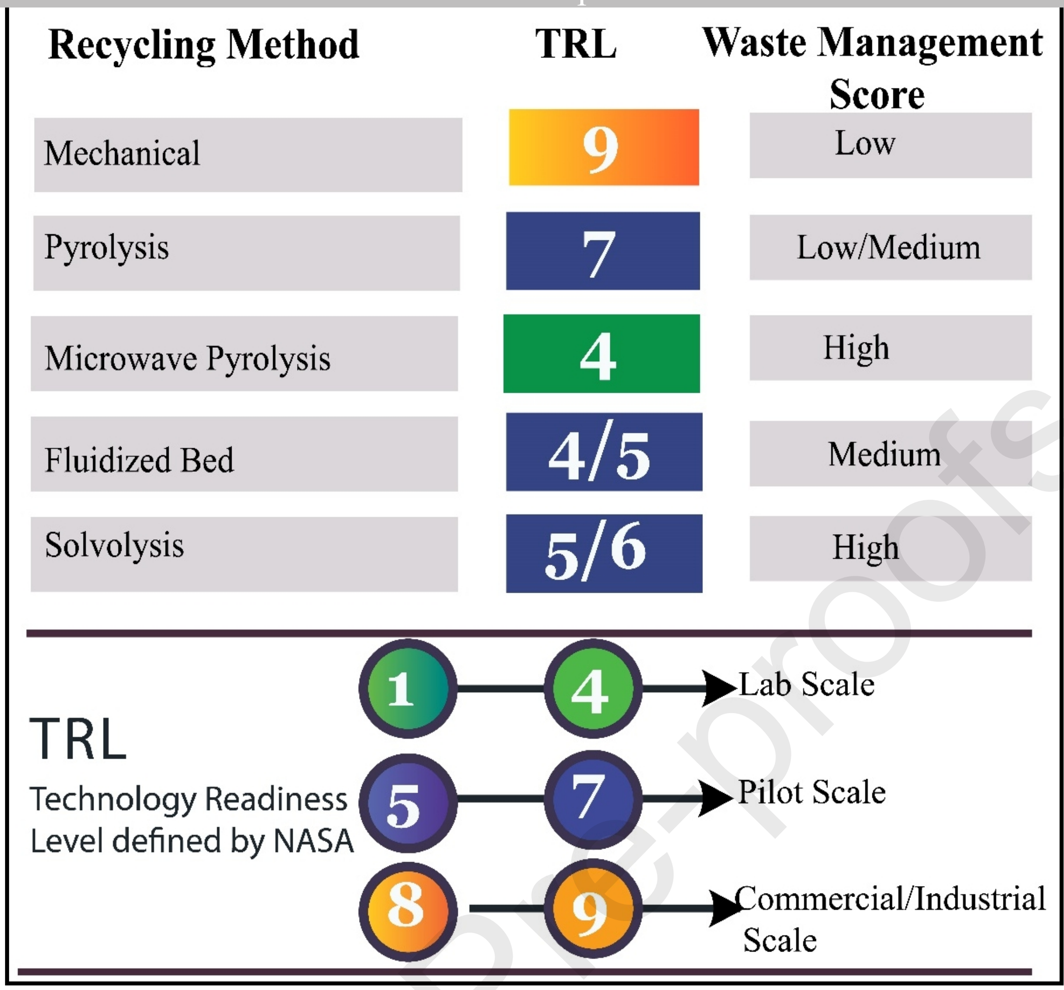


Figure 9. TRL and waste management scores of different recycling technologies used to manage WTB waste

There is a significant upsurge being developed in various sustainable technologies due to the high consumption of carbon-based fossil fuels. Wind energy is considered one of the most efficient forms of renewable energy, but there is a significant threat associated with the form of WTB waste. Since wind energy is an integral part of the total renewable energy landscape, much efforts are required to reduce the threat associated with it. It is challenging but not impossible to achieve zero waste of WTBs. Conceptual reuse of WTBs (Figure 10) would decrease the composite waste. Finally, it is concluded that various CE models, which are adapted for the efficient usage of waste materials, can subsequently reduce the WTB waste. It would be better for the world if "*trash should be treated as a treasure*" to make this planet clean.

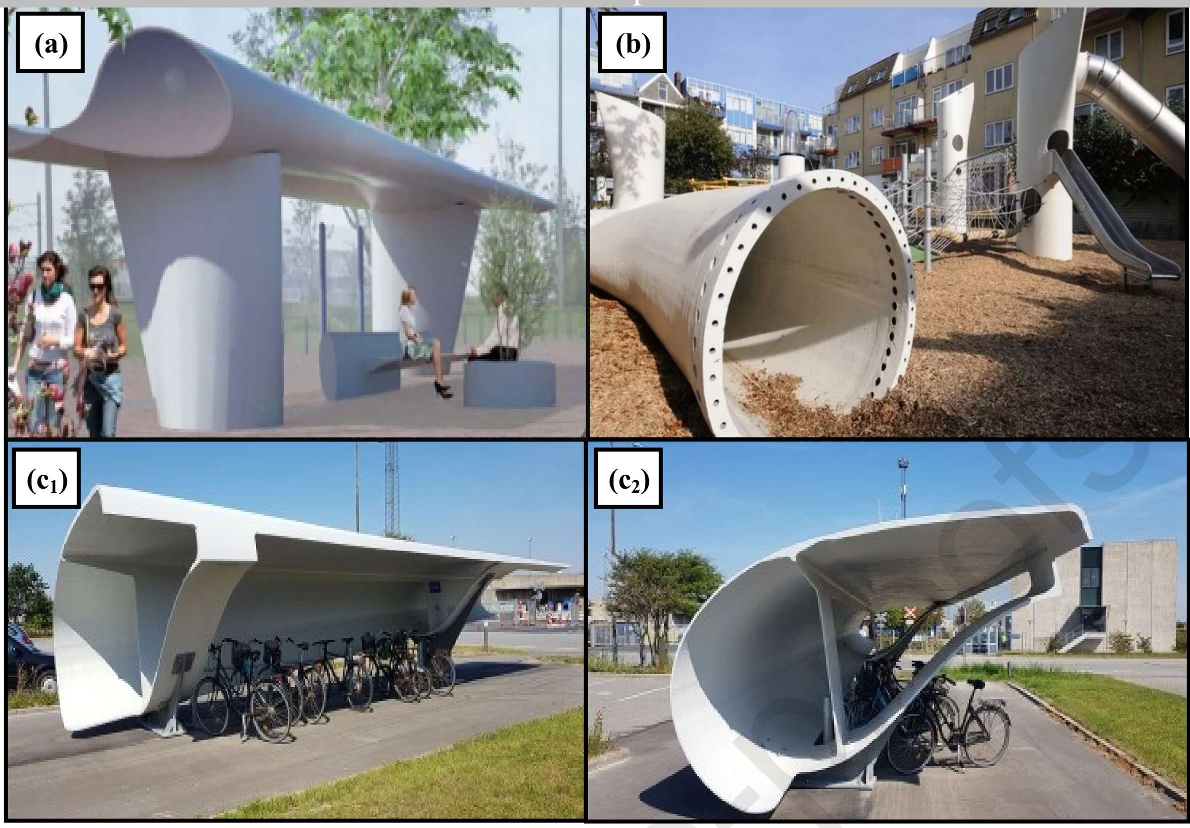


Figure 10. Conceptual reusing of WTB after EOL stage, (a) Public seating, (b) Playgrounds (adapted from [118], under creative commons attribution-non-commercial 4.0 license), (c_1-c_2) WTB are used to bike shed at the Port of Aalborg in Denmark (Photo Credit: Siemens Gamesa)

Conflict of interest statement

The authors declare no conflict of interest.

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Graphical Abstract

Highlights

- Conventional end-of-life approaches for wind turbine blades (WTBs) cause severe environmental issues.
- Recycling of WTBs is highly imperative for a clean, green, and sustainable environment.
- Circular economy models are needs to be in more practice for zero WTB waste.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: