Decommissioned Wind Turbine Blade Management Strategies

Prepared by ACP Wind Blade Working Group

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AMERICAN CLEAN POWER

Abstract

Currently, up to 94% of a wind turbine can be recycled.[1]

However, the rotor blades are made of composite materials (e.g., Fiber-Reinforced Plastics, mostly fiberglass and carbon fiber) and pose a more significant recycling challenge to the wind industry and the composite materials sector. As Fiber-Reinforced Plastics (FRPs) are complex to recycle, the majority of rotor blades are currently going to either landfills or incineration facilities.

While blade materials are non-toxic, concerns have been raised about space in landfills and the industry has been investigating options to make disposal more sustainable. Several European countries have banned the landfilling of turbine blades a few years in the future to allow for the validation and scaling up of alternatives,[2] and many U.S states have introduced (but not yet passed) legislation requiring turbine manufactures to take back turbine blades, or outright ban landfilling of blades.

As blade waste continues to grow with other composite waste streams, effective alternatives are needed for End-of-Life (EoL) blade management. The current recycling technology landscape, cost constraints, logistics, and alternative EoL concepts to consider are presented within this whitepaper.

1 ETIP Wind. 2020. An overview of composite recycling in the wind energy industry. https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf.

2 Wind industry calls for Europe-wide ban on landfilling turbine blades | WindEurope

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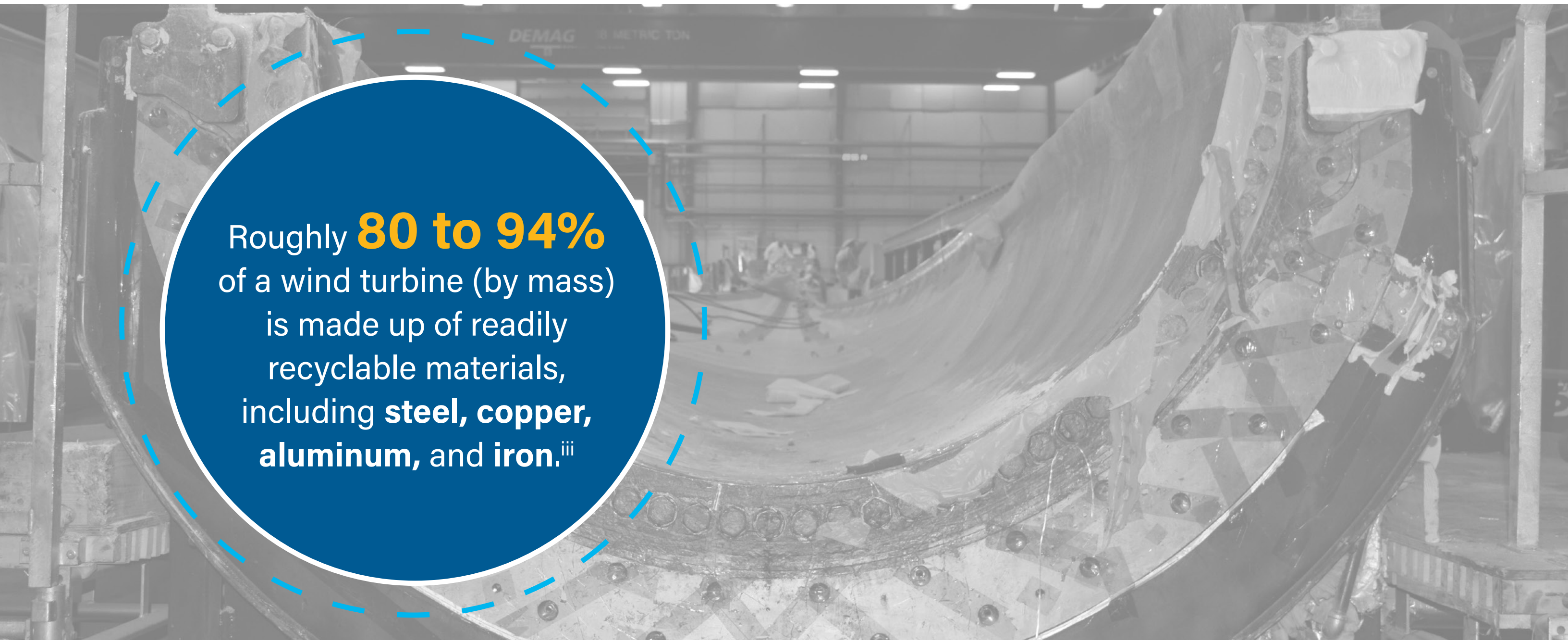
Introduction

Roughly 80 to 94% of a wind turbine (by mass) is made up of readily recyclable materials, including steel, copper, aluminum, and iron.[3] This estimate also includes the steel used in the turbine's concrete foundation. Wind turbine blades make up less than 8% of the total wind turbine's mass; however, recycling of blades has proven to be more challenging because of the materials and methods used to make them. Blades need to be both durable and flexible to withstand sometimes harsh environmental conditions for twenty-plus years while generating electricity efficiently. Modern wind turbine blades are built with a "sandwich" panel design, where fiberglass or carbon-fiber "skins" overlay both sides of balsa wood or plastic foam core. This structure is typically infused with a liquid thermoset resin system that becomes rigid when heated. Once manufactured, separating these materials is difficult and complex; thus, making blade recycling challenging.

The commercially available End-of-Life (EoL) options for wind turbine blades are currently limited to a few downcycling processes (i.e., the recycled material is of lower quality and functionality than the original material), landfill, and a small number of novel reuse and repurposing solutions. Landfilling is currently the lowest cost solution thereby making it the most common EoL option; however, it is becoming increasingly challenging to landfill blades given policymaker and community concerns and/or regulations. In addition, the industry has been proactive in investigating ways to improve the sustainability of blade disposal.



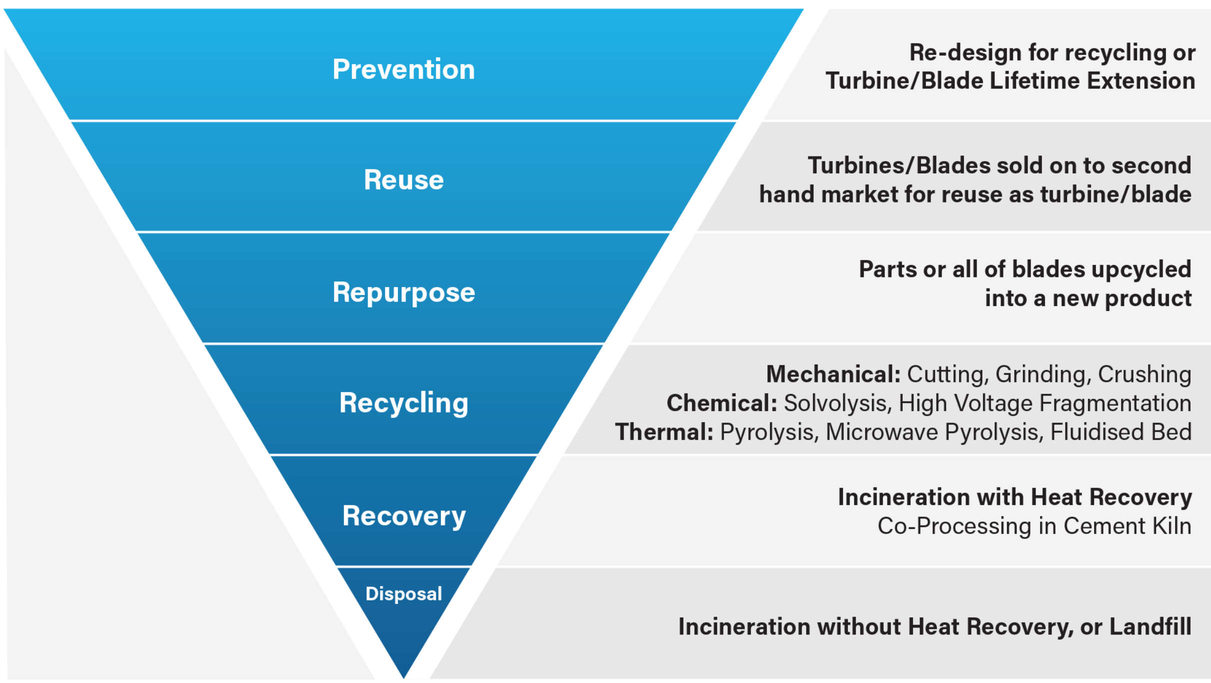
3 ETIP Wind. 2020.

By 2050, global wind assets are estimated to reach approximately 100 gigawatts (GW) per year and it is estimated that 43 million tons of cumulative blade waste will be generated by then, with China leading at 40% of the global waste generated, followed by Europe at 25%, the U.S. at 16%, and the rest of the world at 19%.[4]

Over the next couple of decades this waste stream will most likely be generated from increasing retirements/re-powers of existing wind assets as wind turbine technology advances. According to the European Technology & Innovation Platform on Wind Energy, the wind industry is the fifth largest producer of composite waste in Europe; however, this is expected to increase and will likely be the number one source of waste composites in Europe by 2050.[5] In the U.S., the estimated cumulative blade waste in 2050 is approximately 2.2 million tons. This value represents approximately 1% of remaining landfill capacity by volume, or 0.2% by mass.[6] In comparison, 292.4 million tons of municipal solid waste is generated every year on average and 146.1 million tons is landfilled. Of the 146.1 million tons landfilled solid waste, food was the largest component at about 24%, plastics accounted for over 18%, paper and paperboard made up about 12%, rubber, leather and textiles comprised over 11%. Glass, metals, wood, miscellaneous inorganic waste, and yard trimmings accounted for less than 10% each.[7]

The EoL options presented in this paper are relative to waste management hierarchy by order of preference: Reduce (e.g., blade life extension), Reuse (e.g., second-hand market for repurposed whole or partial intact blades), Recycle including downcycling (e.g., broken down into the raw materials), Recovery (e.g., conversion of non-recyclable waste materials into usable energy), and Disposal (e.g., landfilling). For current blades in operation, EoL options for all levels in the hierarchy exist, but not all are currently financially viable or scalable as discussed in more detail below.

Description of each level in the context of Wind Turbine Blades



4 Pu Liu, Claire Y. 2017. Barlow, Wind turbine blade waste in 2050, Waste Management, Volume 62, 2017, Pages 229-240, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2017.02.007.

5 ETIPWind Executive Committee. 2020. HOW WIND IS GOING CIRCULAR blade recycling. https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf.

6 Cooperman, A.; Eberle, A.; Lantz, E. 2021. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. Resources, Conservation and Recycling, 168,10. https://doi.org/10.1016/j.resconrec.2021.105439.

7 EPA. National Overview: Facts and Figures on Materials, Wastes and Recycling | US EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials.

Blade Life Extension

Extending the lifetime of existing blades is one of the most economic and environmentally friendly measures wind project operators take to limit landfilling. While blades are very durable, decades of exposure to the elements can slowly chip away at their performance. Improvements to wind resource assessment and modelling allow manufacturers to better understand the loads (i.e. stress) on blades, leading to improvements in life and maintenance costs. Most owner/operators elect to repair their blades for minor to moderate damages that occur within their typical design life (approximately 15 – 25 years). When blade repair is necessary, the cost and time needed to complete the repairs can vary widely depending on the size, location, and specific material(s) that are damaged.

Reactive Methods

Regular inspection and maintenance will increase the installed service life of wind turbine blades. As the industry matures, improvements in maintenance and repair have also advanced. As with proactive strategies, there are several "reactive" maintenance strategies that can be preventative or corrective, including regularly scheduled inspections and health monitoring using permanent sensors that are attached to the blades. Other maintenance strategies include damage reporting and identification, repair procedures (coatings, tapes, shields, filling and sealing, resin injection, plug repair, patch/scarf repair, etc.), and quality control.[8]

Proactive Methods

There are several proactive strategies under development to produce more durable wind turbine blades, which will prevent degradation and increase the service life of the blades. These strategies include self-healing, (or easy healing) lighter materials that can return to their original state. Using techniques such as microcapsulation, hollow fibers, vascular networks and erosion-resistant coatings that prevent surface erosion (e.g., use of more durable composite laminates that include use of lighter, stronger fibers), the blades are able to repair themselves. The use of lighter materials reduces blade weight, thereby lowering gravity loads on the blades and increasing fatigue resistance. Other examples include erosion protection or "erosion safe control," which reduces tip speed during heavy rain events, in turn reducing the load on the blade.[9]

Re-Powering / Refurbishment

As owners and operators assess operating wind assets for retirement and decommissioning or re-powering, they may consider reusing wind turbine blades. If a blade is replaced as part of a re-power of existing turbine(s) to update with the latest technology and extend the useful life of the facility and increase power production (and thus not due to damage or structural weakness) the replaced blade may still have commercial viability. Before decommissioned blades are refurbished for a secondary market, they go through a thorough safety evaluation. This evaluation includes a comparison of operating loads with design loads, verification of structural stability (e.g., load bearing and safety parts, calculation of potential duration of continued operation), and an on-site inspection to document damage or unusual wear and tear. Refurbishment can improve structural parameters and remove defects while enlarging blade size. According to a 2021 study, about 20% of the blades in the Netherlands are refurbished and re-sold within Europe and developing countries.[10] Several companies in Europe provide services to maintain, dismantle, transport, refurbish, and re-commission wind turbines for secondary markets.[11]

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8 Ibid.

9 Mishnaevsky L., Jr. 2021. Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions. Materials (Basel, Switzerland), 14(5), 1124. https://doi.org/10.3390/ma14051124.

10 Ibid.

11 Deutsche Windtechnik; P&J Windpower ApS; DutchWind; Surus.

Because refurbishment can be an economically and environmentally conscious solution to blade waste and disposal – creating a circular economy for wind turbines — future blades should be designed so that they are easy to repair and refurbish. However, it is important to note that refurbishing existing blades on a full re-power of an existing wind asset may not be cost-effective given the number of blades requiring reinforcement to extend the operating life for another 20 years. Therefore, most owner/operators opt for new and often longer blades for full re-power.

Blade Repurposing

Repurposing and reuse of decommissioned wind turbine blades to create utility elements, such as utility poles, small architecture features such as park benches, engineering structures such as bridges, or visual artwork is a relatively low cost, low energy, and low raw-material consumption option compared to refurbishment from decommissioned and fully re-powered wind assets. Most repurposing projects aim to take advantage of the lightweight, strength, durability, and weather-resistant characteristics of blades as well as the unique ergonomic and aesthetic design of the blades, which differs from the more traditional construction materials.

Photo credit: Canvus

Several stakeholder groups including scientists, researchers, national laboratories, independent companies, and environmental collaborators are working with the wind industry to develop innovative methods to repurpose turbine blades. The Re-Wind Network[12] is one of the largest academic groups driving repurposing initiatives including uses for powerline utility poles[13], bridges[14], and roofing material. The Re-Wind Network publishes a "Design Catalog" each year that presents designs and details of structures and products made from EoL repurposed wind turbine blades that are available from the Re-Wind Network.[15]

Additionally, Canvus LLC works with the wind energy industry on sustainable disposal solutions for decommissioned wind turbine blades, upcycling blades into street furniture including benches, chairs, tables, planters, and shade structures.[16]

Furthermore, the U.S. Department of Energy (DOE) is partnering with businesses to research practical ways to repurpose wind turbine blades and several other companies are partnering with industry to offer sustainable options for end-of-life wind turbine components, including blades, which is discussed in more detail below under Blade Recycling and Industry-Led Blade Recycling Programs and Research.

There are limitations, however, to repurposing blades including commercial availability and market demand for the end-product. In addition, blades that have reached the end of their functional life or because of a rare event of catastrophic structural failure renders them structurally unsuitable for this type of reuse (estimated to be only 2 – 5% of the total decommissioned blade waste).[17] While there are many potential repurposing options for decommissioned blades, these are likely to face scalability and timing challenges due to the increase in volume of blades expected to enter the waste stream over the next two decades.

12 The Re-Wind Network.

13 The Georgia Institute of Technology has successfully created a prototype using an entire blade for a 230 kV transmission line tangent pole and is planned for first installation at the Smokey Hills Wind farm in Kansas in 2022.

14 The first Re-Wind designed pedestrian and bicycle footbridge was installed by Anment and GP Renewables Group in western Poland in October 2022.

15 Ibid.

16 Canvus | Functional Art Made From Wind Turbine Blades (gocanvus.com).

17 Defining the landscape for wind blades at the end of service life | CompositesWorld.

Blade Recycling

Although life extension and refurbishing efforts may extend the operational life of wind turbines blades, this life extension is not infinite, and repurposing may not be the appropriate option once the blades reach their EoL. Therefore, recycling is the next option in the waste management hierarchy and is considered the first economically viable option for large volumes of waste composites from either re-powering or decommissioning. There are currently four recycling techniques that are commercially available and have moderate to high technology readiness levels: mechanical grinding, pyrolysis, solvolysis, and cement co-processing.

Mechanical Process

Mechanical grinding takes decommissioned blades and breaks them down to small fragments/pellets through shredding, crushing, or milling. The pellets can then be used as fillers or reinforcement in other composite and cement products. This is a low-cost recycling option, with a breakeven cost of $0.32/kg. However, it is struggling to cost-compete with existing carbonate fillers ($0.1-0.5/kg).[18]

While mechanical grinding is technologically viable, there is a limited number of companies[19] providing these services. This process also results in downcycling of the final product and the expected market for these products is currently unclear (as referenced above, the cost is one factor in the uncertainty about market opportunity).

However, in 2021 REGEN Fiber began developed a 100% mechanical process that converts wind turbine blades into fiber-reinforced polymer (FRP) fibers, micro-fibers, and chopped glass fibers for use in the concrete, asphalt, mortar applications, soil stabilizer, and other composite materials.[20] A new manufacturing facility to accommodate large, commercial-scale operations for the recycling is currently being constructed in Fairfax, Iowa. According to REGEN Fiber, once commercial-scale operations in Fairfax reach full production levels, they anticipate having capacity recycle over 30,000 tons of shredded blade materials per year.[21]

18 BloombergNEF. 2020. Composites Recycling: Performance Meets Sustainability.

19 Waste Innovation Company, LLC.

20 Regenfiber - REGEN Fiber Press Release: Groundbreaking recycling solution for wind turbine blades unveiled.

21 Ibid.

Pyrolysis

Pyrolysis is a form of thermal recycling of composites that separate the resin from the fiberglass / carbon fibers by heating the material in a vacuum at very high temperatures (between 450 and 700°C)[22]. This process converts the polymer matrix into gas, oil, and char, leaving the fibers that can be later recovered. However, due to the considerably high pressures and temperatures needed within the reactor vessel, the recycled fibers can become mechanically degraded and contaminated with char. This "char" must then be removed during a further oxidation step. However, it is important to note that there are multiple ongoing research and design efforts to optimize the process to preserve fiber integrity and overcome the energy intensity challenge.

Pyrolysis is relatively cost effective for carbon-fiber composites due to their high resale value; however, commercialization of pyrolysis for fiberglass composites is challenged by the lack of established commercial markets for recovered glass fibers and the lower value of glass fibers in comparison to carbon fibers.[23]

BloombergNEF suggests that pyrolysis currently costs approximately 10 to 90 times more than mechanical grinding. It is also possible that the market for the recovered glass fibers will saturate with the expected volume of blades over the coming years. Research is on-going to improve recovered fiber quality and overall process cost.

A DOE funded collaboration between Carbon Rivers and the University of Tennessee, Knoxville has recycled a few thousand metric tons of blades using this process with plans to expand capacity at a new facility. The new facility is expected to process approximately 200 metric tons of blade waste (equivalent to 5,000–7,000 fiberglass wind turbine blades) per year, depending on blade size and generation. The recovered fiberglass can then be reused in new composites production.[24]

Solvolysis

Solvolysis is a form of chemical recycling of composites which is the decomposition of material using a reactive solvent to separate the composite materials into resin and fiberglass / carbon-fiber. Different solvents may be used and heated to critical temperatures to break the bonds of the resin and fiber materials (e.g., nitric acid, ammonia or glycol are heated below critical temperature, approximately 100°C; water or ethanol are heated to near critical temperature, approximately 240 – 374°C).[25] Challenges to this process include the fact that blades are made up of multiple materials compared to pure thermoset based composites and this process is currently energy intensive (e.g., requires a higher reaction temperature and a longer reaction time). Research on this process is ongoing to improve the quality of the recycled product such as modified pyrolysis methods using lower temperatures for carbon fibers, higher temperature for thermolysis to achieve low char residue on recovered fiber or using additional chemicals to resize recovered fibers or remove residues.[26] Therefore, solvolysis may offer a cost-effective, scalable solution capable of delivering higher value products from the recycling of waste composites.

Upcycled Glass Fiber Pellets

Upcycled Glass Fiber Wet-Laid Mat

Compounded Injection Molding-Grade Recycled Glass Fiber-PP Pellets

Photo credit: Carbon Rivers

22 Mishnaevsky. 2021.

23 Coughlin, Daniel, Ludwig, Charles, Ozcan, Soydan, Hartman, Dave, and Ginder, Ryan. 2021. "Controlled Pyrolysis: A Robust Scalable Composite Recycling Technology". United States. https://doi.org/10.2172/1762486. / https://www.osti.gov/servlets/purl/1762486.

24 Carbon Rivers Makes Wind Turbine Blade Recycling and Upcycling a Reality With Support from DOE | Department of Energy.

25 Mishnaevsky. 2021.

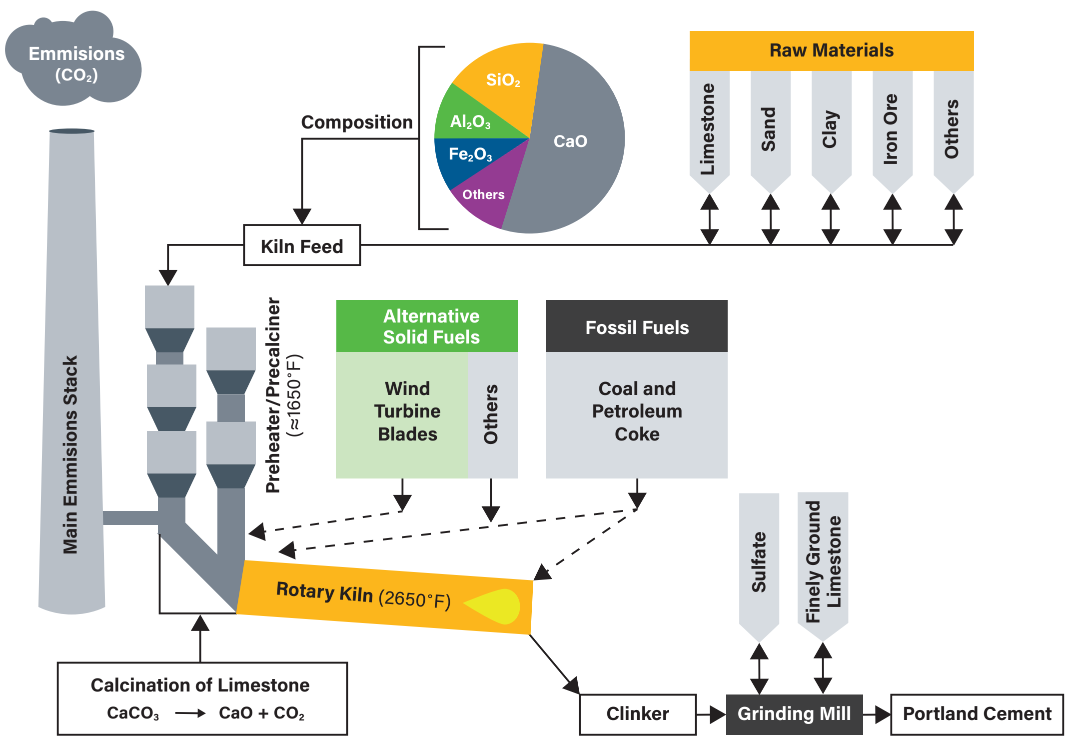
26 Ibid.

Cement Co-processing

Cement co-processing is currently the most cost-effective, scalable, and commercially viable recycling option. However, this option is lower on the waste management hierarchy scale due to downcycling of the recycled fiber. The approach originated in Germany and is being developed through partnerships with manufactures and recycling companies (including GE, Veolia North America, Holcim, RiverCap, and Vestas). Cement co-processing involves mechanical shredding of the blade and feeding the shredded pieces into a cement kiln. The resin and core components of the blade provide energy for the chemical reaction, thus reducing the quantity of coal required for the traditional cement kiln.[27] The fiberglass ash (silica) contributes to the sand fraction and Calcium Oxide (CaO) in the blade is a key component of the setting agent in Portland cement (conventional production of CaO is carbon intensive).[28]

According to GE, a 7-ton blade recycled through co-processing enables a cement kiln to avoid consuming 5 tons of coal, 2.7 tons of silica, 1.9 tons of limestone, and approximately one ton of other raw mineral based materials.[29] More than 65% of the blade weight will replace the sand, clay, and other raw materials that would otherwise be added to the kiln to create the cement, and approximately 28% of the blade weight takes over the role of coal in the heating process. An analysis by Quantis U.S. found that this could help cement manufacturers reduce CO_2 emissions by 27% compared to the traditional process and reduce water consumption by 13%.[30]

A 2022 evaluation of wind turbine blade co-processing conducted by the Electric Power Research Institute (EPRI) suggests one ton of wind turbine blade material could replace 0.4 tons of coal, 0.3 tons of silica, and 0.2 tons of limestone in cement production.[31] EPRI's review indicated that approximately 2% of CO_2 emissions from the cement kiln process would be avoided if wind turbine blade material replaced 30% of the coal typically used, and for composites made from bio-derived fill and resins, about 14% of CO_2 emissions from the cement production would shift from fossil to biogenic.



Source: EPRI

27 Decommissioned wind turbine blades used for cement co-processing | CompositesWorld

28 Concrete Benefits: Recycling Old Wind Turbine Blades Could Help Cement Industry Cut CO2 Emissions | GE News.

29 Ibid.

30 Veolia and GE Renewable Energy Recycle Wind Turbine Blades (waste360.com); Wind turbine blades are now recyclable | Up To Us (veolia.com); GE Renewable Energy Announces US Blade Recycling Contract with Veolia | Veolia North America

31 Electric Power Research Institute (EPRI). 2022. Co-Processing of Decommissioned Wind Turbine Blades in Cement Production: Literature Review and Evaluation of Wind Turbine Blade Sample Tests. (Report No. 3002022690). Co-Processing of Decommissioned Wind Turbine Blades in Cement Production: Literature Review and Evaluation of Wind Turbine Blade Sample Tests (epri.com).

Additionally, Vestas is part of a cross-sector initiative (DecomBlades project) to increase blade recycling practices by fostering pathways for commercialization of the processes, which includes cement co-processing. DecomBlades initiatives are discussed in more detail in the Industry-Led Blade Recycling Programs and Research section below.

The transport of the waste blade material from the wind farm to the shredding facility remains a challenge given height, weight and turn radius limits on roads and bridges means few choices on routes to move blades; however, onsite mobile composite shredding services may be available in certain areas. The shredded material must then travel to the cement processing location, which may not be in the same region as the wind farm or shredding facility, adding to transportation costs. Although there are 96 cement kilns in the U.S., only a few kilns accept composite waste as an alternative material. The current lack of infrastructure in place (e.g., number of shredding facilities) and the geographic distribution of both shredding facilities and cement kilns that can accept composites is a constraint to scalability of this recycling option.

Transportation Challenges

While there are multiple techniques currently available for both recycling and repurposing, a large driver of the cost for any EoL solution is the transportation of the waste blades to their destination.[32] Operating wind assets are spread across the rural U.S. but infrastructure for blade waste disposal and recycling is limited. Landfills that accept waste blades are limited in location and number, facilities that have re-purposing or recycling capabilities may be located a significant distance from a wind farm. Some waste blades may have to travel upwards of 1,600 miles to reach their final EoL destination.

The road-based transportation of the blades and/or blade materials can be a primary cost driver for any EoL solution but is also a noteworthy source of carbon emissions.

32 Nagle, Angela J., Emma L. Delaney, Lawrence C. Bank, and Paul G. Leahy. "A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades." Journal of Cleaner Production 277 (2020): A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades - ScienceDirect.

Blade Disposal – Landfill

In the waste management hierarchy, landfilling ranks the lowest because there is no material recovery. It is also the cheapest option for blade disposal, where permitted by regulations. In many locations, blade disposal in a landfill may be the only available option because transporting the blades to a recycling facility is cost prohibitive. However, while safe for the environment and the public, disposing of blades in landfills is not a viable long-term option. For example, the European wind industry (WindEurope) supported a "Europe-wide landfill ban on decommissioned wind turbine blades by 2025"[33] and this initiative may eventually extend to other parts of the world. In the U.S., some states have pursued legislation that would either ban landfill disposal of blades or require a percentage of blade waste to be reclaimed by manufactures through a take-back program (e.g., Washington state attempted legislation in 2020 but it did not pass).

Alternatively, some community groups have approached their city councils about creating blade recycling programs to divert blades from the local landfill (e.g., a coalition of twelve companies in Casper, Wyoming told the Casper City Council that they are interested in finding a use for wind turbine blades that have been disposed of in the Casper Regional landfill[34]).

Even if landfilled, **turbine blades represent an exceedingly small portion of the waste going into U.S. landfills** and are among the least environmentally harmful materials entering them as they are made from non-toxic materials. Therefore, they are safe for landfill disposal.

33 Wind industry calls for Europe-wide ban on landfilling turbine blades. 2021. https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/.

34 Citizen approaches city about recycling wind turbine blades disposed in Casper landfill, seeing potential for more profits - Casper, WY Oil City News.

Industry-Led Blade Recycling Programs and Research:
Designing for a Circular Economy

Many wind turbine manufacturers are developing alternative resin systems to aid in recycling wind turbine blades. These initiatives aim to create a new thermoset resin that can be easily separated from the fibers in lower cost recycling processes. Manufacturers are also developing reversable, recyclable thermoplastic resins that support stronger, less expensive, and longer wind turbine blades, which in turns would increase energy capture and blade reliability and recyclability, while decreasing energy and transportation costs. The individual approaches vary in the potential uses of the products recovered from the recycling process. In many cases, some of the recovered products (fibers or resin) may be used in new wind turbine blades, but other recovered products require new markets to be developed.

Siemens Gamesa Renewable Energy (SGRE) RecyclableBlade

SGRE has launched their RecyclableBlade product for both offshore and onshore wind turbines in Germany.[35] RecyclableBlade uses a new reversable thermoset resin with a trigger that can be extracted from the composite using solvolysis with minimal additional damage to the fibers. According to SGRE, "the RecyclableBlade is made from a new type of resin, the blade is produced the same way as a standard blade and is based on the same IntegralBlade® manufacturing process, meaning that there is no increased implementation risk associated with the new resin system." This new resin, Recyclamine, is commercially available[36] and will see its first commercial application at the Kaskasi Offshore wind project in Germany.[37]

However, due to limited production capacity, using this resin may add costs to a wind turbine's capital expenditures. Additionally, the recovered materials cannot be recycled into new blade construction; therefore, alternative markets need to be sought. According to SGRE, "separating the resin, fiberglass, and wood, among others, is achieved through using a mild acid solution. The materials can then go into the circular economy, creating new products like suitcases or flat-screen casings without the need to call on more raw resources."[38]

Vestas Zero-Waste Initiative

Vestas is actively working on the development of composite recycling technologies to achieve their zero-waste goal by 2040.[39] By 2030, they are aiming to reduce the amount of manufacturing waste ending up in landfills to less than 1% (from 25% today), waste incinerated to less than 1% (from 12% today), and waste incinerated with energy recovery to less than 5% (from 11% today), with the majority of landfill reductions planned to occur before 2025. According to their material recovery plan, their goal is to increase their recycling rate of blades to more than 94% recycled by 2030 (from 52% of materials being recycled today). Their efforts are concentrated on two major initiatives DecomBlades and CETEC, which are discussed in more detail on the next page.

35 Siemens Gamesa launches recyclable onshore wind turbine blades (electrek.co).

36 A winning collaboration behind the RecyclableBlade (siemensgamesa.com).

37 RWE tests world's first recyclable wind turbine blade at its offshore wind farm Kaskasi.

38 World's first wind turbine with recyclable blades is up and spinning (electrek.co).

39 Zero-Waste (vestas.com).

LM Wind Power

LM Wind Power, a GE Renewable Energy Business, is dedicated to manufacturing zero waste blades by 2030. To achieve a true circular economy, this means sending zero packaging and materials from blade manufacturing to landfill or incineration.[40] LM Wind Power faces the same challenges as other manufacturers in achieving zero waste; however, LM Wind Power also participates in the DecomBlades Project and the ZEBRA Project that are discussed in more detail below.[41]

DecomBlades Project

The DecomBlades project is a cross-sector 10-partner European consortium (DecomBlades project), including Vestas, SGRE, and GE, that is working to increase the adoption of recycling practices by developing pathways for commercialization and supporting the adoption of a circular economy across the wind industry.

Circular Economy for Thermoset Epoxy Composites (CETEC) Project

The CETEC project is a consortium of academic and industry leaders including Olin, Danish Technological Institute (DTU), and Aarhus University, seeking to commercialize a new circularity technology for turbine blades. The CETEC project aims to address the lack of available recycling technology for epoxy resins. The new technology being developed as part of this project is a two-step process: thermoset composites are broken down into reinforcement fiber and resin (epoxy) and then, using a new chemcycling process, the resin is further broken up into base components having the same quality as the original materials. These materials can then be reused in the manufacturing of new turbine blades, creating a full circularity path for epoxy resin.[42] CETEC's aim is to develop industrial production within 3 years, with a commercial product on the market in 6-7 years.

Zero wastE Blade ReseArch (ZEBRA) Project

The ZEBRA project is a consortium of industrial companies, including Arkema, CANOE, Engie, LM Wind Power, Owens Corning, and SUEZ, led by French research center IRT Jules Verne. Their goal is to demonstrate the technical, economic, and environmental relevance of thermoplastic wind turbine blades on a full scale. Arkema has developed a thermoplastic resin (Elium®) which LM Wind Power has used to develop and manufacture thermoplastic turbine blades as part of the ZEBRA project. Blades constructed from thermoplastics allows for other innovations including different repair techniques, thermal welding of sections and potentially lower cost recycling through solvolysis and full recovery of both resin and fibers.[43] Thermal welding could lower blade weight and cost compared to the use of adhesive, as well as enable on-site assembly of longer blades eliminating the constrained transport logistics.

Photo credit: Ryan Beach/NREL.

To date, researchers at the National Renewable Energy Laboratory (NREL) first constructed a 9-m turbine blade using Arkema's Elium® resin system to demonstrate manufacturability and then manufactured a 13 m blade that they tested to validate the blade for strength, stiffness and

40 Zero Waste Blades | LM Wind Power.

41 Blade Recycling | LM Wind Power.

42 CETEC initiative established to commercialize technology for full composite wind turbine blade recyclability | CompositesWorld.

43 ZERO WASTE BLADE RESEARCH PROJECT - IRT Jules Verne (irt-jules-verne.fr).

other performance characteristics.[44] The resin can be used in current manufacturing facilities with some modifications, and the in-situ polymerization process can speed up the manufacturing and eliminate the requirement for expensive heated blade molds.

Thermoplastics also open the possibility for 3D printing of blades. NREL suggests that 3D printing and new designs could reduce turbine blade weight and cost by 10% (or more) and production cycle time by at least 15%. New manufacturing and new resin will require extensive quality assurance prior to being financeable for commercial use. The unit cost implications of using thermoplastic resins are currently unknown.

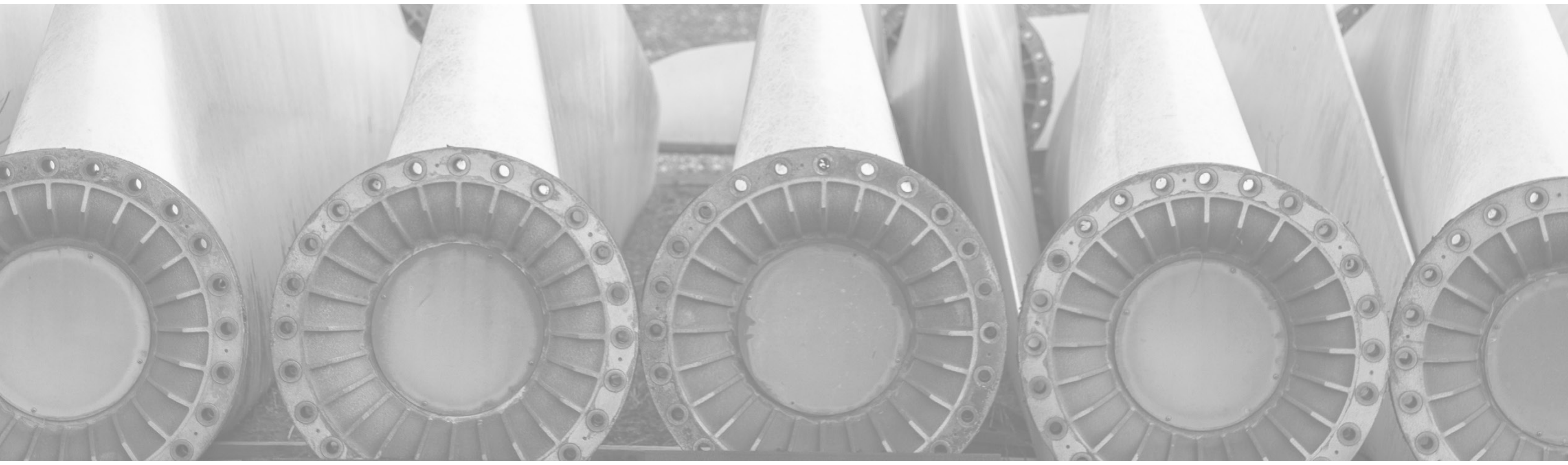
Conclusion

Wind energy composites are an important application in the much larger composite materials sector. Recycling is a challenge faced by the entire composite materials sector and is not unique to wind energy applications. Wind energy stakeholders are playing a leading role in developing recycling solutions for composite materials. The recycling solutions developed for wind turbine blades will likely be available and applicable for recycling other composite materials, leading the way for a true circular economy of composite materials. **Although there are limited alternatives available today that are cost-effective and scalable, several are currently under development that are showing promise for the future of EoL solutions for wind turbine blades. However, selection among these alternatives involves complex tradeoffs. Conducting a full life cycle analysis (LCA) is a potentially valuable tool in comparing many alternatives available.**

Transportation is a key source of cost and CO_2 emissions for all wind turbine blade recycling systems. A wider distribution of recycling centers has the potential to reduce both cost and ww emissions associated with recycling blades and other composite materials compared to recycling activities concentrated at a few locations. **Adoption of common recycling technologies across many different composite applications may enable development of more recycling centers rather than developing specialized recycling technologies exclusively for wind energy.**

Many recycling technologies under development produce materials that do not have existing markets and will require additional market development in order to be economically viable options. **Support for developing markets for reclaimed fiber and resin will be important to developing these recycling technologies.**

The range of turbine end-of-life technologies will continue to expand, given the continued focus on solutions from industry, along with public and private organizations. Continued collaboration with the various composite materials industries, including the marine and aerospace sectors to understand their current composite EoL options and solutions, is an important tool in advancing wind turbine blade circular economy solutions. The U.S. wind industry remains committed to protecting the environment by delivering carbon-free power through responsible development and sustainable solutions.



44 [Advanced Thermoplastic Resins for Manufacturing Wind Turbine Blades | Advanced Manufacturing Research | NREL](#).

Additional Resources

Wind Power. 2014. Repower or Refit? That is the question, By Paul Dvorak. https://www.windpowerengineering.com/repower-refit-question/.

Joeman, Iref. 2019. Alternatives on afterlife use of amortized wind turbine blades in the Netherlands.

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