ELECTRIC POWER
RESEARCH INSTITUTE

END-OF-LIFE DISPOSAL AND RECYCLING OPTIONS FOR WIND TURBINE BLADES

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THE TECHNOLOGY

The amount of end-of-life waste material from decommissioned wind farms is projected to increase steadily over the coming decade. There is an opportunity for proactive development of new methods for recycling and sustainably disposing of wind turbine blades to address future logistical, regulatory and economic challenges..

THE VALUE

Understanding the costs and benefits of various end-of-life options will help utilities plan for economic disposal of wind turbine waste materials during the decommissioning stage, and obtain more accurate estimates for lifecycle emissions associated with end-of-life processes that are becoming increasingly important to investors, customers and other stakeholders.

EPRI'S FOCUS

EPRI is assessing the current landscape of wind turbine blade recycling and disposal options in the U.S. and Europe, pilot-scale processes that have the potential to evolve into commercial-scale operations, and advanced processes and materials that could be used in the next generation of wind turbine technology.

Executive Summary

A small aging fleet combined with the rapid continued growth of wind power capacity means that waste management solutions could be needed for millions of tons of spent wind turbine blades over the coming decades. This report will put projected waste volumes in perspective as well as review some technological solutions to the non-metallic waste issue, including general processes, resulting material properties, end product examples, and design for recycling solutions for the future. Some regions of the world have driven innovation with national mandates and some researchers or entrepreneurs see a potential for inexpensive or free source material to use in different products. Some areas may ban landfilling of wind turbine blades, while the waste quantities in the U.S. seem of a magnitude that could be handled with few additional landfills. What we will begin to research here, however, are technologies that could eventually provide an alternative path or simply a more cost-effective one.

Introduction

Wind turbine blades pose a challenge to the renewable energy industry, as damaged or spent blades are commonly sent to landfills for disposal. The rapid growth of wind energy capacity in the U.S., Europe, China, and other countries over the past decade means that the electric power industry will need to find waste management solutions for escalating volumes of spent turbine blades over the coming decades.

There are a limited number of studies that have analyzed the options and costs for alternative turbine blade disposal strategies. Wind farm decommissioning (including dismantling of turbines and towers and site remediation) may have a significant impact at the end of life (EOL) or when purchasing a wind farm from a previous owner. There are many practical lessons that can be learned from Canada and some European countries where regulations require wind farm owners to plan and reserve funding for decommissioning activities. Some of these regulations have placed a moratorium on sending spent turbine blades to landfills.

This issue brief will provide wind energy asset owners with insight on current and future turbine blade disposal option while tracking the flow of materials through those processes. The costs associated with these disposal options will also be reviewed and estimated when possible. Ultimately, wind asset owners will be better prepared to plan through the entire project life cycle from installation through decommissioning and disposal.

Issue

As wind turbine technology has developed over the past 10 to 20 years, blade sizes have increased dramatically from an average diameter of 145 feet (44 meters) in 1997 to 367 feet (112 meters) in 2017. [1] Longer blades capture more wind energy that leads to higher efficiencies, capacity factors, and total power output. The engineering challenge turbine manufacturers have faced is minimizing the weight of these larger blades to reduce costs and relieve mechanical stress on the rotor hub, bearings, drive shaft and generator. The pursuit of lightweight turbine blades has led manufacturers to rely on composite materials that typically contain fiber reinforced plastics (FRP) within an epoxy or poly/vinyl ester matrix. Unlike metal components in the gearbox and tower, which can often be reused or recycled, the materials used in turbine blades cannot be easily separated and recovered. The hostile conditions that turbine blades are exposed to over a 20 to 25-year operational life (i.e., high temperatures, humidity, solar radiation, salinity and stress) cause physical degradation that often make them unacceptable for re-use or refurbishment. When blades are damaged in operation or decommissioned at end of life, the vast majority are sent to landfills due to the lack of cost-effective industrial recycling options. The large size of current blades also presents transportation and logistical challenges for delivering waste materials to recycling facilities. The scale of the turbine blade waste management problem can be demonstrated using an illustrate example described below.

The Siemens B75 Quantum blade used for 6MW offshore wind turbines measures 75 meters in length (246 feet) and weights 25 metric tons (27.5 short tons or 55,155 lbs). This translates to approximately 12.5 metric tons (13.7 short tons or 27,560 lbs) per megawatt of capacity. Siemens manufactured the B75 Quantum blade with glass fiber reinforced epoxy resin and balsa wood in a single cast that eliminates seals and glue points to reduce blade's weight. The blade would weigh 10-20% more using traditional manufacturing processes, resulting in 13.7 to 15 metric tons per megawatt of capacity. However, Siemens noted that using lightweight carbon fibers instead of glass fibers could reduce blade weight by 10-20%, resulting in 10 to 11.3 metric tons per megawatt of capacity, but these materials would have increased cost. [2] Blades used on smaller onshore wind turbines have similar weight-to-capacity ratios. For example, blades used for 1.65MW Vestas wind turbines at the Biglow Canyon project in Sherman County, Oregon weigh 15,432 pounds each (23.1 short tons or 21 metric tons for three blades) resulting in an overall weight-to-capacity ratio of 12.7 metric tons per megawatt.

Blades used for 2.3MW Siemens wind turbines installed in 2010 as part of an expansion to the Biglow Canyon project weigh 20,944 pounds each (31.4 short tons or 28.5 metric tons for three blades) resulting in an overall weight-to-capacity ratio of 12.4 metric tons per megawatt. [3]

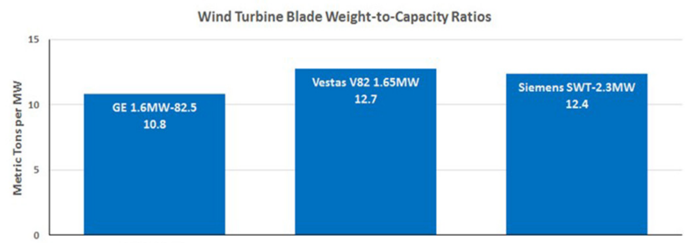


Figure 1 – Wind turbine blade weight-to-capacity ratios for three common onshore models

Assuming a 25-year operation life, the Biglow Canyon Wind Farm would generate ~5,620 metric tons (or nearly 6,200 short tons) of turbine blade waste materials by 2035. This is roughly equivalent to the combined weight of 620 city transit buses (assuming a curb weight of 20,000 pounds) and would fill 690 average-sized garbage trucks and incur $545,000 in landfill tipping fees based on Oregon's statewide average fee of $56/ton in 2015 with annual increases of $1.60/ton through 2035 (not including transportation costs). [4, 5] This amount of waste material is about 60% of the daily volume received at the Columbia Ridge Landfill (Oregon's largest waste disposal facility) [6] but it is also more than the annual amount of landfill waste produced in three rural California counties, according to data collected by the California Department of Resources Recycling and Recovery in 2015. The scale of the turbine blade waste management challenge becomes readily apparent when viewed from the state, regional and national level. Applying a weight-to-capacity ratio of 12.5 metric tons per megawatt to the U.S. Energy Information Administration's (EIA) wind capacity growth forecast results in cumulative blade waste volume of 1.2 million tons by 2040 and nearly 2.1 million tons by 2050. The cumulative amount of projected turbine blade waste is 76% of the total amount of waste that was disposed of in Oregon in 2015 (2.74 million tons). [7] The cost of landfill disposal based on 2015 national average tipping fees would be $112 million.

Figure 2 illustrates the looming influx of turbine blade waste material that will require coordination between wind turbine manufacturers, operators, and the waste management industry to implement sustainable disposal, reuse, and recycling options. While landfill

disposal is the most common strategy for turbine blade disposal today, it could become cost prohibitive in the future if tipping fees increase, or if new regulations are enacted to divert turbine blade waste material to more sustainable practices. The following sections will provide an overview of recycling and other waste management processes that are currently available along with next generation processes and materials that could become available in coming years. Calculating the amounts of turbine blade waste in combination with information on locations and regional waste management capacity will be critical for assessing the optimal location of recycling facilities based on regional demand and transportation routes.

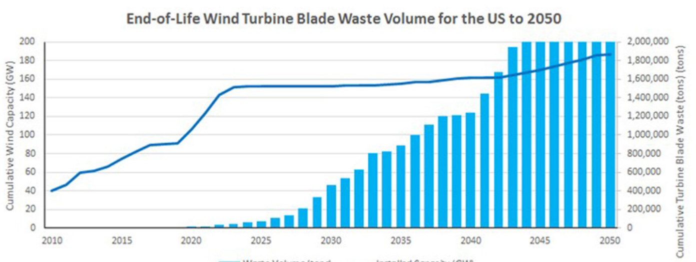


Figure 2 – Estimated wind turbine blade waste volume in the U.S. based on capacity growth forecasts in the U.S. EIA 2016 Annual Energy Outlook, a 20-year operational life for all wind turbines, and a weight-to-capacity ratio of 12.5 metric tons/MW.

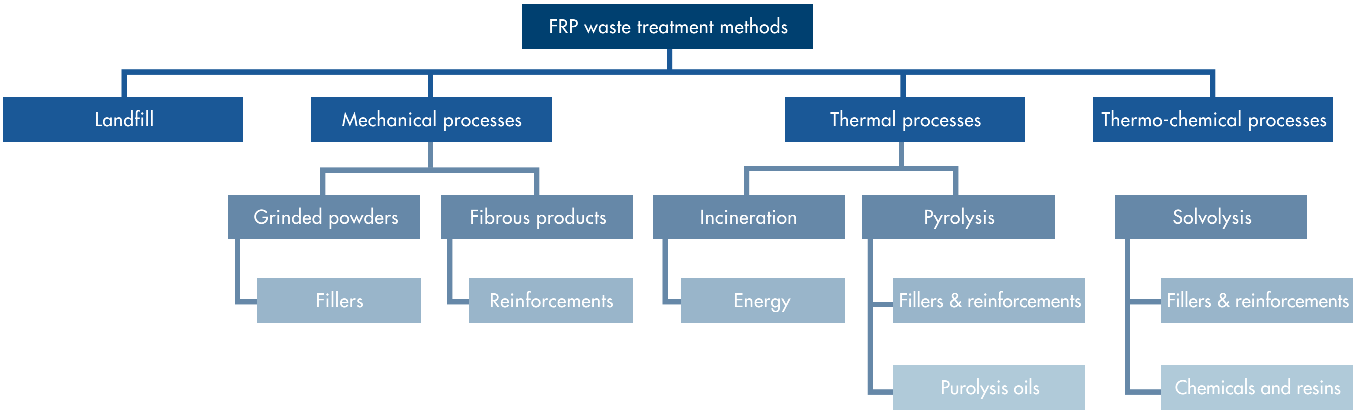
Current Turbine Blade Waste Management Options

As mentioned earlier, the materials used to manufacture current generation wind turbine blades are chosen to maximize strength, stiffness, and minimize density and cost to achieve a high strength-to-weight ratio at a reasonable cost. Blade material composition varies across blade types, manufacturer and vintage, but most blades are generally composed of the following:

- Reinforced fibers made of glass, carbon, aramid or basalt
- Thermoset polymer matrix made of expoxies, polyesters, vinyl esters, or polyurethane
- Sandwich core made of balsa wood or polyvinyl chloride (PVC) foams
- Surface coatings made of polyethylene (PE) or polyurethane (PUR)
- Metals such as copper wiring, steel bolts or other fasteners

The most common turbine blade designs use a thermoset matrix infused through glass fiber to form a glass fiber reinforced polymer (GFRP). Wind turbine manufacturing accounted for ~6% (about 300,000 metric tons) of the 5 million metric tons of global glass fiber production in 2015, approximately 70% of which was used to manufacture thermoset GFRP. [8] By comparison, demand for carbon fiber was 14,500 metric tons for turbine blade manufacturing out of 91,000 metric tons of global production, meaning the wind industry utilized 16% of carbon fibers globally. [9] GFRP is often chosen over carbon fiber reinforced polymers (CFRP) because it provides sufficient strength and stiffness properties at lower cost. Although, blades manufactured with CFRP can be up to 35% lighter due to the much higher stiffness of the fibers. [10] In either case of fiber selection, thermoset polymers support the chosen fibers. They start as a two-part liquid and then, when mixed, become cross-linked while undergoing an irreversible curing and solidification process. This irreversible phase change is one aspect that makes recycling quite difficult; they cannot be melted down again like a "thermoplastic". Wind turbine blades are a complex structure made of different parts and materials depending on the manufacturer and vintage. When a wind turbine is decommissioned, the blades will be found in many different conditions depending on their design, stress and environmental conditions. The variability across turbine blade composition and end-of-life physical conditions present a challenge to the development of large-scale waste management processes.

The inherent challenges and high costs associated with recycling composite materials has resulted in landfills becoming the most common destination for end-of-life turbine blades. The U.S. has not enacted any federal regulations that prevent landfill disposal of turbine blade waste materials. Some more stringent regulations could be established at the state level as already exist in other locations around the globe. The European Union (EU) Landfill Directive provides an example of a regulatory framework that has affected turbine blade waste management decisions at the national level. Each member country has interpreted the Landfill Directive in different ways to apply criteria and procedures for the acceptance of certain types of waste at landfills. Since June 2005, Germany has enforced a landfill ban for untreated municipal solid waste (MSW) with total organic carbon content higher than 3% of total mass. [11] The Canadian provinces of Nova Scotia and Prince Edwards Island have also implemented landfill bans on MSW with high organic content and Quebec is working to implement a similar landfill diversion program for organic waste by 2020. [12] These landfill bans have



Company Name	Country	Operations Began	Service Provided
Geocycle	Germany	2011	Mechanical Recycling
LafargeHolcim	Germany	2011	Mechanical Recycling/Waste Material Utilization
ReFiber ApS	Denmark	2007	Pyrolysis Recycling
Ucomposites	Denmark	2013	Mechanical Recycling/Waste Material Utilization
Global Fiberglass Solutions	United States	2015	Mechanical Recycling/Waste Material Utilization
exVentus	United States, Canada	2016	Waste Management Logistics
Spares in Motion	US, Germany, Spain, Netherlands	N/A	Re-use and Re-sale of Used Blades

Figure 3 – Waste management strategies for wind turbine blade waste materials (Source: Wind Europe, 2017)(Source: Green Ener Tech)

forced turbine blade waste (which often contains balsa wood as a major organic component) toward alternative disposal processes outlined in Figure 3. A short list of companies providing "conventional" waste management services is shown below.

Reuse and Refurbishment for Secondary Markets

The simplest and least costly end-of-life alternative for decommissioned turbine blades is to refurbish them for reuse or sale in secondary markets. Depending on the amount of wear and tear experienced over a 20-year operating life, some turbine blades may still have adequate strength and stiffness properties to be used as replacements at other wind energy projects. Research conducted by Sayer et al., (2009) in Germany investigated the effect of service life on turbine blades by evaluating their performance beyond 20 years of operation. The study reported no significant damages by visual inspection and no significant lost in stiffness of the blade. [13] This will not be an option for all sites. Several companies such as exVentus (Canada), Green Ener Tech (Denmark), Repowering Solutions (Spain), and Spares in Motion (U.S., Germany, Netherlands and Spain) have developed business models based on selling refurbished wind turbine components, including blades. Refurbishing turbine blades for sale on the secondary market provides access to a wide range of sometimes defunct components, short supply lead times, and lower costs. Standardized turbine blade refurbishment procedures can include visual inspection, ultrasonic testing, and natural frequency measurements of the blades. The blades can also be repaired, repainted, weighed and balanced. [14]

Figure 4 – Used wind turbine blades following decommissioning

Incineration at Waste-to-Energy Facilities

Incineration and combustion at waste-to-energy facilities represent a second alternative waste disposal pathway for end-of-life wind turbine blades. This solution is currently used in Denmark and Germany where the aforementioned ban on MSW with high organic carbon content has diverted turbine blade waste materials from landfills. However, the economic viability of waste-to-energy depends on the calorific value of the material being burned. Since the total mass of composite materials used in turbine blades can contain up to 70% glass fiber, which are inert and incombustible, the amount of energy produced from incineration is low compared to other materials with higher organic carbon content. Mixing other MSW waste materials with turbine blades can improve combustion efficiency to the point where waste-to-energy becomes economically viable. Incineration of turbine blades can also produce hazardous air emissions from the combustion of plastics (i.e., polyurethane and polyethylene). Fine particles of glass and carbon fibers may also be present in the flue gas emissions from waste-to-energy facilities that can damage emissions controls. [15] Carbon monoxide and formaldehyde have been linked to thermal degradation of epoxy resins contained in wind turbine blades, and about 60% of post-combustion material remains as fly ash that is often classified as hazardous waste requiring disposal in specialized landfills. [16] Thermal processing techniques for turbine blades also requires sectioning and fragmentation of waste materials into smaller pieces through mechanical shredding or crushing before being fed into the incinerator. Mechanical shredding and crushing equipment and processes are energy-intensive and result in higher life cycle greenhouse gas (GHG) emissions and exposure to particulate matter, such as epoxy or polyester and fiberglass dust. Given the low combustion efficiency and presence of hazardous emissions and combustion waste byproducts, incineration does not represent an environmentally sustainable alternative to landfill disposal.

Mechanical Crushing, Grinding and Shredding

Mechanical crushing, grinding and shredding represent the third waste management option with currently available commercial operations in the U.S. and Europe. The process begins by dismantling the blades from the rotor hub and cutting them into smaller sections for transportation to waste treatment facilities. Sectioning turbine blades can be done in several ways depending on local environmental requirements, and the size of the blades. The most common methods are; 1) water jet cutting, 2) wire saw cutting, 3) circular jaw cutting, and 4) use of jaw cutters. [17] Jet cutting uses high pressure streams of water mixed with abrasive substances to slice through composite materials and metals with relatively low noise and dust emissions, but very high water use compared to other methods described below. Wire saws with diamond teeth can cut through any size and type of blade material with relatively low noise and dust emissions. Water used to cool the saw blades can be recycled and cuttings can also be collected, but the process is time consuming and blades must be firmly secured to avoid pinching and damaging the wire saw blade. Hand held or hydraulic driven circular saws with diamond tipped blades can be used to make independent cuts in any direction that increases speed while facilitating the extraction of select materials like laminates or balsa wood. However, more cuts produce increased dust emissions that can be collected using water or vacuum systems. Finally, hydraulic jaw cutters can be used to create very rough cuts that also crush material in the cutting zone which cause high levels of dust pollution that must be controlled with water mist. The cutting area must be thoroughly cleaned upon completion and the rough cut blade sections are prone to emit additional dust pollution during transportation. Each field cutting method carries occupational health and safety risk that must be addressed by the waste management company.

The most successful example of thermal breakdown operations was developed by the German cement company Holcim in a partnership with Zajons Logistik. From 2008 to 2010, the companies developed a commercial scale production facility that achieves complete thermal and material recycling of turbine blade waste materials. Turbine blade sections are delivered to the Melbeck facility by truck or train and are cut into 3 feet (1 meter) pieces by automated saws along a conveyor belt before being sent to two shredding units that crush the waste material into pieces with an edge length of <50mm. During the shredding process, ferrous and non-ferrous metals are separated automatically from the material flow by eddy current magnets. The resulting mixture of pelletized turbine blade waste material is transported from the Melbeck facility to Holcim's cement production plant in Lägerdorf where it is used as a substitute for coal in high temperature calciner (kiln). High temperature combustion in the cement kiln leaves no toxic residuals or harmful emissions of glass fiber particulates that can block flue gas emission control systems such as those at waste-to-energy facilities with lower combustion temperatures. [18]

According to Holcim, the useable thermal energy content of turbine blade waste material is about 6,020 Btu/lb (14 MJ/kg) compared with 14,280 Btu/lb (33.2 MJ/kg) for coking coal. [19] This means that each metric ton of turbine blade waste burned in the Holcim cement kiln offsets nearly one half ton of coking coal. Combustion

waste from turbine blade material has a very high ash content of around 50% that mainly consists of silica and calcium oxide that can be mixed with gypsum as filler during cement production. This ash is used as a partial substitute for sand in cement production. Holcim has found that the quality of cement produced with turbine blade waste material does not differ at all from other cement. [20] In 2012 the Holcim-Zajons Logistik facilities reprocessed about 400–500 metric tons of turbine blade waste material per month (or 5,000 to 6,000 metric tons per year), which is roughly one-third of the facility's maximum processing capacity. [21, 22] The cost of recycling at the Lägerdorf facility is around €114/metric ton of waste, but this does not include waste transportation costs that can vary widely depending on distance and other factors. [23]

Figure 5 – The Holcim Lägerdorf cement plant in Germany (Source: ZKG International)

The Holcim-Zajons Logistik recycling and cement production facility is the only industrial scale option for turbine blade waste disposal in Europe, although a handful of other companies have developed pilot-scale projects that will be discussed in the following section. In the U.S., the absence of landfill bans for waste with high organic carbon content and the relatively low current volume of wind turbine blade disposal has resulted in limited development of commercial and industrial scale solutions for turbine blade recycling. The only company currently offering turbine blade recycling services is Global Fiberglass Solutions (GFS), a Seattle-based company that use a patented chemical process to transform shredded composite waste into a building material called Ecopolycrete. This building material can be used in the construction of walls, foundations, or as a substitute for plywood and sheetrock. As of June 2017, GFS has recycled 564 turbine blades (about 3,950 metric tons assuming `~7 tons per blade) under a partnership with General Electric. [24] It is unclear how much turbine blade waste volume GFS can currently handle, but the company has indicated that it will scale operations to meet industry demand with the goal of becoming a worldwide leader in fiberglass recycling. The capacity of GFS in the U.S. and Holcim-Zajons Logistik in Europe is sufficient for today's low amounts of turbine blades waste, but additional capacity and geographic coverage will be needed to handle the projected waste volumes expected in the mid 2020's and beyond. The looming increase in turbine blade waste volumes combined with the severe lack of recycling capacity has stimulated efforts in the U.S., Canada and Europe to develop other cost-effective and scalable solutions.

The main challenge impeding the development of widespread recycling or re-use of wind turbine blade material is the lack of high-value applications for the resulting material. Mechanical crushing, grinding and shredding of an already cured fiber reinforced matrix creates a material of much less structural value than the original. Some structural damage occurs to the fibers themselves. and they are physically cut shorter from long organized bundles into chopped strands, thereby reducing their usefulness in high value products. For example, a study conducted under the GenVind project investigated the quality and performance of composites manufactured with shredded waste material. The study highlighted a challenge that the shredded waste fiber material exhibited poor adherence to the new polymer matrix because the recycled fibers were still covered with old matrix material, which resulted in very low tensile strength (Toncelli 2014). One possibility that has proven favorable is using the shredded fiberglass waste material in non-structural applications. So far, some trials have resulted in high quality sound insulation, such as in-wall or on-wall sound insulation panels and automotive exhaust silencing systems, like those developed by Danish companies Miljøskærm and Ucomposites, respectively, although mass production of these products is not yet available. Ultimately, the success of existing and demonstration-scale recycling processes depends on a steady supply of turbine blade waste materials and consistent demand for products manufactured with recycled materials. The following section will provide an overview of several pilot-scale alternatives to mechanical recycling.

Demonstration Scale Waste Management Processes and Technologies

Several decades of research have resulted in practical methods for recovering and recycling glass and carbon fibers from turbine blade waste materials. However, high investment and processing costs

cause recovered fibers to be prohibitively expensive compared with pristine ones. As a result, commercial applications have been limited. This section will provide an overview and examples of demonstration projects using the following recycling processes; 1) pyrolysis, 2) fluidized bed oxidation, and 3) chemical recycling using solvolysis. Several pilot-scale applications for reuse of waste material from mechanical recycling will also be discussed.

Pyrolysis Recycling Process: Waste composite materials are heated to 300–700°C (572 to 1,292 °F) in the absence of oxygen to vaporize polymeric resins into hydrocarbon gas, while glass/carbon fibers remain intact for recovery because pyrolysis temperatures are well below their degradation temperature. Research conducted by Akesson et al (2012) determined that microwave pyrolysis is technically feasible for recovering glass fibers from turbine blade waste material, but the recycled fibers lost 25–50% of their tenacity when compared against pristine glass fibers. The future applicability of microwave pyrolysis depends on whether useful products can be derived from the residual hydrocarbon oils and recovered fibers at costs that are competitive with pristine fibers. Pyrolysis oil can probably be used as a fuel and the recovered fibers could be used as reinforcement in thermoplastic resins. [25] While microwave pyrolysis processes have not moved out of the prototype phase of development, traditional pyrolysis has been used in demonstration-scale projects.

The Danish company ReFiber ApS developed and patented a process for recycling GFRP and CFRP using traditional pyrolysis (as opposed to microwave pyrolysis discussed above). The ReFiber process combines energy recovery through the combustion of pyrolysis gases in combustion in combined heat and power (CHP) plants with the reuse of recovered glass fibers as raw materials for new raw products. Recovered fibers can be used in wool insulation, short fibers for reinforcing casting compounds, plastics, and high strength concrete. According to ReFiber, three metric tons of fiberglass waste material contains the same thermal energy content as one metric ton of fuel oil. Similar to the Holcim-Zajons Logistik recycling process, ReFiber's pyrolysis process leaves no toxic residues behind when turbine blades are treated through gasification. Once the turbine blade waste material has been shredded, it is fed into a rotary kiln for gasification at 500°C (932°F). The gas produced from the rotary kiln is burned in a separate furnace at 1,100°C (2,012°F), or in a CHP radial gas turbine to generate electricity. After the organic material has been gasified, incombustible materials (i.e., metals, fillers and glass or carbon fibers) can be recovered and separated. Fibers recovered after following pyrolysis lose 25-50% of their initial strength, which means they cannot be used to manufacture new turbine blades or other high value products. Instead, ReFiber combines the recovered fibers with polypropylene fibers to create stable insulation slabs. After five years of operation the company shuttered in 2007 due to poor financial performance, a fate that demonstrates the economic headwinds facing the turbine blade recycling industry. [26]

Figure 6 – Cross section of a wind turbine blade before (left) an after (right) the ReFiber pyrolysis process (Source: ReFiber).

Fluidized Bed Recycling Process: This recycling process is derived from fluidized bed combustion where waste materials are combusted in an oxygen rich airflow at 450–650°C (842–1,202°F). The fuel or waste material is suspended in a bubbling bed of ash and other particulate materials (such as sand or limestone) that is oxygenated with jet streams of air to facilitate combustion or gasification. The mixing of solid particles with gas promotes rapid heat transfer and chemical reactions within the fluidized bed reactor. These reactors are capable of burning a variety of low-grade solid fuels, including most types of coal and woody biomass, at high efficiency and do not require expensive fuel preparation processes like pulverization. The presence of limestone particles in the combustion chamber facilitates precipitation of sulfate from flue gases, thereby reducing SO_2 emissions and improving the efficiency of thermal energy transfer from the boiler to the heat recovery unit. [27] Despite the demonstrated benefits for efficient combustion of low-grade biomass materials, the fluidized bed recycling process requires high energy consumption and glass fibers recovered in laboratory tests have exhibited undesirable mechanical properties. [28] Research conducted by Kennerley and Pickering et al., (2000) demonstrated the inverse relationship between retained fiber strength and various temperature levels during fluidized bed treatment. Significant reduction of fiber strength in recycling materials recovered under different fluidized bed treatment conditions and temperatures was observed. In the most extreme case, fibers that underwent fluidized bed treatment at 650°C (1,202 °F) exhibited a 98% loss in strength when compared against their original properties. A handful of predominantly biomass and biofuel companies have constructed fluidized bed combustion facilities to convert various agricultural feedstocks into biofuel, but it is unclear whether turbine

blade waste materials could be added into the fuel mix, or whether recycled fibers could be recovered from these facilities.

Solvolysis Recycling Process: Polymeric resins are decomposed into oils which free the fibers for collection in process called solvolysis. The main difference between pyrolysis sand solvolysis lies in what results from the degradation of polymeric resins. Byproducts from pyrolysis are mainly gases and oils, while solvolysis causes organic materials in the turbine blades to dissolve. Research conducted by Oliveux et al (2015) used a 2.2 liter mixture of water and acetone heated to 320°C (xxx°F) over 1.25 hours and maintained at that temperature for an additional 2 hours followed by a 20 hour cooling period to complete the process for waste composites made with CFRP. Carbon fibers recovered from the solvolysis reactor showed very good properties that could replace virgin carbon fibers at a lower price. [29] However, the study did not compare the cost of recovered carbon fibers against virgin glass fibers, or evaluate the economic viability of the solvolysis process. The energy requirements, use of hazardous chemicals, and long reaction/cooling time demonstrated in this study present significant challenges to commercial development of a solvolysis recycling process for wind turbine blades.

The three recycling techniques described above are designed to enable the reuse of recycled glass and carbon fibers in new polymer composite materials. However, the decreased tensile strength of the fibers, the degraded surface properties (loss of the silane coupling agent) and the cost of these fibers, present serious challenges to achieving widespread commercialization. The economic conditions are especially difficult in the U.S. where the low cost of landfill disposal provides little incentive to pursue alternative disposal strategies. Turbine blade recycling processes will need to compete with against landfill tipping fees that range from \$37–\$84 per metric ton in the U.S. (not including transportation costs), which represents a difficult challenge moving forward. Finding high value products besides concrete filler is another path to commercialize recycling. The following section describes two pilot-scale recycling processes being developed by The Danish firm Ucomposite, and the Iberdrola LIFE-BRIO project.

Ucomposite developed a glass fiber recycling project in Denmark using funding from the European Commission's LIFE+ program. The project developed a functional machinery system to process glass fiber waste from manufacturing processes (not end-of-life turbine blades) into feedstock materials that could be used as substitutes for virgin materials in insulation bats, non-woven E-glass fiber, and car exhaust silencers. A pilot-scale facility was constructed and became fully operational in 2013 with an annual processing capacity of approximately 1,000 metric tons of manufacturing waste. Pilot-scale production of exhaust system silencers for the automotive industry was also undertaken to test the practicality of substituting recycled products for virgin glass fibers using industry approved product standards. These exhaust system components were brought closer to commercialization than other pilot-scale products, such as the use of recycled glass fibers as a substitute for cellulose fibers in asphalt production. The exhaust silencers developed during the course of the pilot project achieved better acoustic and sound-deadening capabilities while using half of the material measured by weight to create the same or better noise reduction.

The project developed a novel business model for a new composite waste recycling company that employed four people by the end of the project and indicated growth potential across Europe. However, the economic viability of the business model was strained by transportation and logistical costs due to the aggregator waste collection model. The aggregator business model required shipment of waste material from multiple European countries to the pilot-scale recycling facility in Denmark for processing followed by distribution of exhaust silencers and other recycled products to vendors in several countries. [30] This experience highlights several barrier to successful development of an industrial-scale wind turbine blade recycling industry; transportation costs, economics of scale, market value for recycled products, and regionalization of waste management facilities. While the Ucomposites process offers hope for recycling manufacturing waste, it is unclear whether it can also be applied to recycle glass fibers from end-of-life turbine blades.

Another potential recycling program for turbine blades waste material has been developed during the LIFE+-BRIO project, which was managed by Spanish wind project developer Iberdrola. The LIFE+-BRIO project completed pilot-scale demonstrations in 2016 that used mechanical recycling processes to produce three types of precast concrete products that were inspected, tested and installed under real life conditions. Observations and results obtained from the prototype testing process validate the use of recycled glass/carbon fiber in precast concrete elements. Use of recycled fibers can slightly reduce the use of other materials and does not affect the manufacturing process. In addition to the three precast concrete products, LIFE+ BRIO also developed two types of multilayer panels (thermoset and thermoplastic nature) with cores made of recovered materials. The technical performance of the multilayer

panels is closely related to the type of outer peels. So, cores would be adhered to different layers (gypsum, wood, aluminum, reinforced composites, etc.) depending on requirements of final applications. The prototype products where produced using 0.8 metric tons (1,760 lbs) of turbine blade waste material was obtained from the Coal Slough Wind farm operated by Scottish Power. Iberdrola partnered with Spanish research organizations GAIKER IK4 and Tecnalia for the duration of the three-year project, but it is unclear whether the processes or products will move toward commercial scale implementation. [31]

Prices for glass reinforcing fibers used in polymer matrix composites range from $1.30 to $2.60/kg (€1.10 to €2.20/kg). The prospects for recycling carbon fiber composites are considered to be a more attractive because of their higher monetary value and wide range of end-use applications. Prices for carbon fiber were estimated at $15.40 to $24.20/kg (€13.10 to €20.50/kg). [32]

Figure 7 – Image of the NREL/IACMI thermoplastic wind turbine blade prototype (Source: Composites World)

Next Generation Turbine Blade Materials

Next generation solutions to the looming turbine blade waste management problem will likely come from experts working in materials science rather than innovative recycling processes. Progress on commercialization of the alternative recycling processes discussed in the previous section (pyrolysis, fluidized bed oxidation and chemical recycling) will likely be incremental, and their future success is inexorably tied to increased waste material volume and demand for recycled materials in high value products. Development of next generation materials for use in turbine blades that are easier to recycle or remold into new blades at the end-of-life represent a new frontier for research that has the potential to radically improve the sustainability of wind turbine blades from a life cycle perspective.

Blade materials are evolving and thermoplastic resin, a potential substitute for thermoset plastic resins described earlier, are currently undergoing testing for use in turbine blades. Although thermoplastic resins are new to the wind industry, they have been used extensively in other industries. Similar to metals, thermoplastic materials soften when heated to certain temperatures and can eventually melt and then re-harden into new molds under controlled cooling processes. The most important property of thermoplastics is the material's ability to thermo-weld, repair, and recycle. Thermo-welding may also allow for certain types of repairs where long fibers are undamaged. The time and cost savings associated with thermo-welding repairs could be significant, and it would also divert a source of waste material from recycling and disposal processes.

The use of thermoplastics for manufacturing turbine blades is a subject that the National Renewable Energy Laboratory (NREL) and the Institute for Advanced Composites Manufacturing Innovation (IACMI) are investigating at the Composites Manufacturing Education and Technology (CoMET) facility. The CoMET (located in Boulder, CO) will support advanced composite materials research projects, rapid prototyping of blade materials, and testing for new production methods. NREL has already produced a 27 foot (9 meter) prototype turbine blade made from thermoplastic materials using a process developed with and molds provided by TPI Composites. The next step is to manufacture full-scale thermoplastic turbine blade components using tooling systems donated by GE Energy. It is unclear at this time when these thermoplastic products will become commercially available, or whether they will be cost-competitive with thermoset plastic materials. A concerted effort would have to be made and new blades designed by a wind turbine OEM specifically involving the use of the new materials. Other project partners include Arkema, Convergent Manufacturing Technologies, the University of Tennessee and Purdue University. [33]

Next Steps and Collaborative Opportunities

Material innovations will continue to have positive effects on the production, cost, maintenance, and life time of next generation wind turbine blades. Manufacturers are starting to consider the overall sustainability of the materials chosen, including their impacts on recyclability and compatibility with future recycling processes. Continued private and public support for advanced materials research to develop next generation wind turbine blades is beginning to include life cycle sustainability as a guiding principle. Future development in this area will be highly dependent on industry support and collaboration.

On a continuing basis, EPRI scans the horizon for new technology options and assesses the current and future cost and environmental characteristics of wind energy technologies. Identification of technologies with game changing potential may lead to focused R&D relevant to turbine blade manufacturers, wind farm developers and operators, electric utilities or waste management companies. A critical technical challenge in the development of GFRP and CFRP recycling technology is the 80%–90% drop in the performance (and value) of recycled fiber compared against pristine fibers. [34] Development of an economically-viable process for regenerating the properties of thermally-recycled glass fibres would have major technological, societal, economic and environmental impacts.

Pending the interest of key stakeholders and its members, EPRI may become involved in observing the development and testing of prototype wind turbine blades and recycling processes, collaborating in the development and demonstration of pilot-scale systems, and/or early commercial deployment. This type of research would complement EPRI's existing research portfolio on wind energy full lifecycle issues, which includes promising new wind turbine technologies and forward looking, innovative projects aimed at identifying game-changing solutions. The results from these projects will inform end-of-life decision making, improve the accuracy of end-of-life cost estimates, and enhance life cycle analysis studies of wind energy.

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