A Report to the Legislature
December 2023

Wind Turbine Blade Recycling in Washington: A Feasibility Study

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Energy Program

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A Report to the Legislature
Submitted December 1, 2023

To the Washington State Senate
Environment, Energy and Technology Committee,
Senator Joseph Nguyen, Chair
Senator John Walsh, Ranking Minority Member

and

The Washington State House
Energy and Environment Committee
Rep. Beth Doglio, Chair
Rep. Mary Dye, Ranking Minority Member

ABSTRACT

Introduction

As of mid-2023, there are approximately 1,822 operational wind turbines in Washington sited at roughly 21 commercial wind farms, stretching between the coast near Aberdeen to the far eastern Palouse. These wind farms may be owned directly by a local utility, such as Puget Sound Energy's Wild Horse and Skookumchuck developments; by an out-of-state utility, such as Portland General Electric or the Los Angeles Department of Water and Power (LADWP); or by a private development firm such as Avangrid and Iberdrola. According to the United States Energy Information Administration (EIA), these assets provided more than 9.1 gigawatt hours of energy in 2022, or enough to power more than 850,000 homes.

While all the power is generated here, a significant proportion of it may be exported to other states if the farm is owned by an out-of-state interest. For example, LADWP owns the Linden wind farm in Klickitat County, but it is exported directly to Los Angeles utilizing the Pacific Intertie, a high voltage DC connection between the Tri Cities and northern Los Angeles. Several other farms may utilize similar export schemes, such as those owned by the Eugene Water and Light Board, or they may sell their power to local utilities, such as assets owed by Florida Power and Light on the Columbia River.

While the most significant growth of our state's wind energy fleet occurred in the late 2000's, the late 2020's are poised to see another spurt of growth as utilities are mandated to reduce the carbon intensity of energy generation in line with the Clean Energy Transformation Act, a landmark effort by the state of Washington to decarbonize the electricity sector by 2045. The Energy Facility Siting Council, an executive division of the state government, notes two active applications for new utility scale wind, and many of the currently active wind farms. In addition, utilities such as Puget Sound Energy and Avista have indicated their intention to expand generation through wind in the coming years, whether from repowering a retiring turbine site with larger units or from the development of new resources. Avista is developing new resources in Whitman County, and PSE is expanding operations in central Washington. With over 23% of Washington's electricity currently being generated by fossil fuels, further deployment can be expected as utilities decarbonize in advance of CETA deadlines.

Wind Farms first appeared in Washington in 2001 with the construction of the Stateline Wind Project near the confluence of the Columbia and Snake Rivers on the Washington/Oregon border. Construction peaked in about 2009, with nearly half a gigawatt of generation capacity installed across four project areas. 2020 saw the construction of the first new facilities since 2014, with Rattlesnake Flat's construction on the east side of the state and the first major wind farm on the western side, Skookumchuck, on the border of Thurston and Lewis County.

Turbine Construction

A wind turbine is a seemingly simple concept that is underpinned by complex technologies. When the wind blows, an airfoil is moved, which in turn spins a generator to make electricity. In wind turbines, the generator is substantively similar to other mechanical generators like would be found in natural gas turbines, nuclear generating stations, hydropower dams, and coal plants, though made smaller and lighter to fit within the confines of a nacelle and handle the different forces at the top of a tower. This power is moved from the towers to a series of transformers where it is stepped up to transmission voltage, where it then enters the grid to move to the end user.

While there are a variety of manufacturers, they all follow similar design utilizing similar materials. There are three main components visible from the outside: the tower, typically a hollow steel and concrete structure over 100 feet tall; the nacelle, a bean or box-shaped shroud at the top of the tower holding electronic and mechanical equipment as well as servicing areas; and the blades, generally three long (100 foot +) fan vanes made of a complex mix of fiberglass, balsa wood, and carbon fiber. The blades have more in common with an airplane wing than a traditional windmill blade or fan blade, with a focus on strength, durability, and weight reduction that leads to using similar materials and design processes.

With the differing technologies, materials, and operating stresses for the components, they experience different levels of wear and often have different lifetimes. Towers are relatively simple and made of strong, sturdy materials. They're more resistant to the vibration and oscillation that's inherent in a large, spinning structure than some of the other components. There have not been many reports of structural issues or wear from typical service, and similar structures such as bridge piers may last 50-100 years without needing major work. Towers also contain ladders and wiring to move people and electricity up and down, which will likely not require extensive refurbishing and maintenance for decades. When these towers do reach the end of life, the components are readily recyclable utilizing existing channels; metal scrap of that quality will be eminently valuable and concrete from the foundation can be turned into fill.

The nacelle has some of the more wear-intensive parts in a wind turbine. There is the gearbox which changes the rotation from blade speed to generator speed much like a vehicle's transmission, braking equipment used to slow or stop blades and other moving equipment, and motors to adjust the position of the turbine and catch the wind more effectively. The gearbox is subject to much stress, increasing the rotation of the blades to nearly 1600 RPM to match common generator needs. Similarly, there are several bearings in the nacelle to reduce friction from the hub as it rotates, as well as the entire nacelle. Gearboxes are known to have limited mid-life failures, typically lasting roughly 20 years according to Wind Power Engineering magazine.. The most common failures for gearboxes and bearings is due to lubrication issues, which can typically be managed with good maintenance practices. Generally, the entirety of the gearboxes, bearings, and generating equipment can be readily recycled utilizing existing metal waste, and the vast majority of industrial lubricants have approved safe disposal methods.

The blades, or airfoils, are a seemingly simple but extremely complex piece of engineering. They are massive, typically between 150 and 300 feet long, and made of layers of fiberglass, adhesive, and sometimes structural foam or lightweight balsa wood. They're typically hollow, with the thin fiberglass skin providing a lightweight, slightly flexible structure. There are some metal fittings to attach the airfoil to the hub of the turbine, as well as some wiring for lightning protection, but they're otherwise almost entirely made of a composite.

Composites such as fiberglass and now carbon fiber are formed by stacking layers of lined-up fiber on top of each other at an angle and use a resin to bind these layers together. Most airfoil manufacturers utilize a glass substrate woven like a piece of cloth to impart more rigidity to the structure, and most of the resins known to be used in the industry (especially historically) are most similar to a two-step epoxy, with a chemical process “activating” the resin to turn it solid. While exact proportions of epoxy to fiber differ from manufacturer to manufacturer, they’re typically in the 40% resin to 60% glass ratio. Similarly, binding resins may vary from manufacturer to manufacturer, but chemically-set epoxies have been historically used. During manufacture, the glass cloth is wrapped around a form for the blade shape and the resin is rolled on, much like paint would be. During this process, foam or balsa blocks are added to areas requiring extra strength, such as the leading edge of the airfoil. Additional adhesive is used on most trailing edges to add extra support to the sharpest edge of the blade, where flexing can cause the most damage from deformation.

Due to the nature of fiberglass or carbon fiber composites, recycling and disposal is extremely difficult with existing technology. While glass fiber may be infinitely recyclable, and many of the resins used may have a secondary life, they must be separated prior to material recovery. The fiberglass construction process fully enrobes the glass fibers in resin with a chemical bond, which is both extremely strong and extremely hard to break down. Composites that have not been broken down with chemical or physical processes are not able to be recycled, but some limited reuse opportunities do exist. The majority of retired blades so far have been landfilled, as costs for recycling are too high to be recovered through recycled material sales.

Most manufacturers have determined their airfoils should last for roughly 20 years, and many of them offer equipment guarantees that reflect this.

TASK A: Feasibility, Costs, and Environmental Impacts of Disposal Methods

Introduction

There are over 1800 wind turbines in the State of Washington, mostly focused in the Columbia River Valley of Central Washington. Each of these generators have three turbine blades with lengths between and are generally constructed from fiberglass, balsa wood, carbon fiber, and epoxy. These have been constructed for commercial generation in Washington since 2001, when the Stateline Wind Project was created in Walla Walla County along the Washington/Oregon Border. Since then, over 1800 turbines have been constructed, with a total capacity of 3.4 Gigawatts of generation potential.

Wind turbines operate on a simple principle that's been exploited by humans for thousands of years- blowing wind makes blades, vanes or another wind catching surface move, often rotating around a hub like a wheel. The hub will then have rotational energy with which it can perform work. Historically, that work may have been turning a pump to raise water or a grindstone to make flour. Modern turbines use their rotational energy to turn a generator and make electricity. Advanced materials, computerized design, and lessons from the aerospace industry have all contributed to great improvements in efficiency, design, and operations, while turbines get larger and more powerful every year.

A modern wind turbine like you may find in Kittitas or Klickitat wind farms has a few major components with various levels of recyclability: the tower, nacelle, and blades, as well as gearboxes, generators, sensors, and actuators. The tower and nacelle are generally made of steel and aluminum, both infinitely recyclable materials with dedicated resale and processing markets. Gearboxes, hubs, shafts, and generators are also primarily metal components that have a market for easy recycling, and in limited scenarios they may be reconditioned and refurbished for further uses.

The entire assembly must sit on a concrete foundation, which may be reused for a subsequent generator or deconstructed as part of land restoration activities. Generally, utilities such as PSE have clauses in their land use agreements with local governments to restore the land back to the original state following the closure of the wind farm. Concrete has limited recyclability- aggregates may be crushed out, cleaned, and reused, but the cement is generally treated as waste and disposed of in a landfill. Additionally, chunks of concrete have reuse potential in planters, as a sub-base in road construction, and it can be processed into the "eco-block" jersey barrier for various civil engineering applications.

Finally, the most advanced component of a wind turbine is the blade, or the airfoil. These are the largest moving parts on a turbine and are typically arranged in groups of three on a central hub, set perpendicular to the ground and parallel to the main tower. Due to the physical demands put on the object- lots of varying force, near constant motion, large surface areas, and low tolerances for extra weight- their designs are nearly totally constructed from ultra-lightweight materials like Fiberglass and Carbon Fiber. When used with a plastic polymer resin, fiberglass and carbon fiber make a very strong material known as an FRP- Fiber Reinforced Polymer. Glass fibers are arranged into a woven mat-style fabric, laid around a form, and enrobed in the special polymer. The arrangement of fiber increases rigidity and reduces impacts of shear and compression forces, while the polymer binds the fibers together and allows for the fabric to take on a set shape. For most turbine airfoils, it is then baked in an autoclave to high temperatures, which cures the resin and creates a very strong, resilient bond between the resin and the fiber matrix inside. While each manufacturer has their own design and processes, many use balsa wood in certain areas for additional strength and rigidity, and each airfoil will have some sort of metal collar on the attachment end so it can be bolted to the turbine hub. These blades are shipped as single pieces to the site, often reaching hundreds of feet long and requiring specialized Schnabel-style carriers for truck and rail shipment.

Assumptions:

- Using a 14 m long, 2.59 m wide flatbed truck as transportation method
- Therefore, WB pieces are no longer than 14 m.
- Based on current Vestas models, the chord length or max 'depth' of blade is between 5% and 10% of the total blade length. In other words, if the blade is 50 meters long the chord length is estimated to be around 3.75 meters.
- The height of a flatbed truck is 5 ft. The allotted foot from the ground is around 13.6 feet so 8.5 feet of load for the height is allowed. While the max chord length is in the range of 2.5-5 meters this means that the base of the blades of some turbines will have to be cut length wise or taken through larger transportation.
- For now, the assumption is that the amount of space on a flatbed can be doubled to fit more than one 14-meter-long blade piece. This is explained more in depth in the transportation section of our estimated calculations.
- We assume based on Cooperman et al that the length of a wind turbine blade is half that of the rotor diameter.
- An estimated range of 100-200 (150 AVG) mile range is used to perform the transportation calculations.
- The dataset is the number of wind turbines assuming each blade has a lifetime of 20 years. (if a wind farm was commissioned and built in 2001, the retirement year being used is 2021)
- All EoL options from landfilling to chemical recycling will dismantle the turbine in the same way. E.g. cutting down to 14 meter long segments and transporting on a 48 foot flatbed truck.

End of Life Assessment

A turbine's end of life is dependent on a variety of factors. Most manufacturers offer a design life of about 20 years, however environmental or operational conditions may allow for longer service or early retirements. Turbine condition is continually assessed by maintenance staff with tools like drones, high speed cameras, and ultrasound devices. In the Northwest, there have been very few turbines that have hit their end of life according to the utilities that spoke with researchers.

A turbine is a complex array of machinery that experiences many different stresses over its lifetime. Constant motion and vibration stresses metals in gearboxes, bearings, and towers, and flutter and abrasives in the wind can cause chipping, delamination, and other issues in fiberglass. Typically, entities like PSE and Avista have noted gearboxes failing first, with bearings being the largest concern. They are generally replaced if the remainder of the turbine is in good condition. From interviews with operators, blade life is usually a secondary concern to other operational issues beyond safety- the formula for a turbine's end of life is mostly economic and similar to another complex piece of equipment, like a vehicle.

Decommissioning

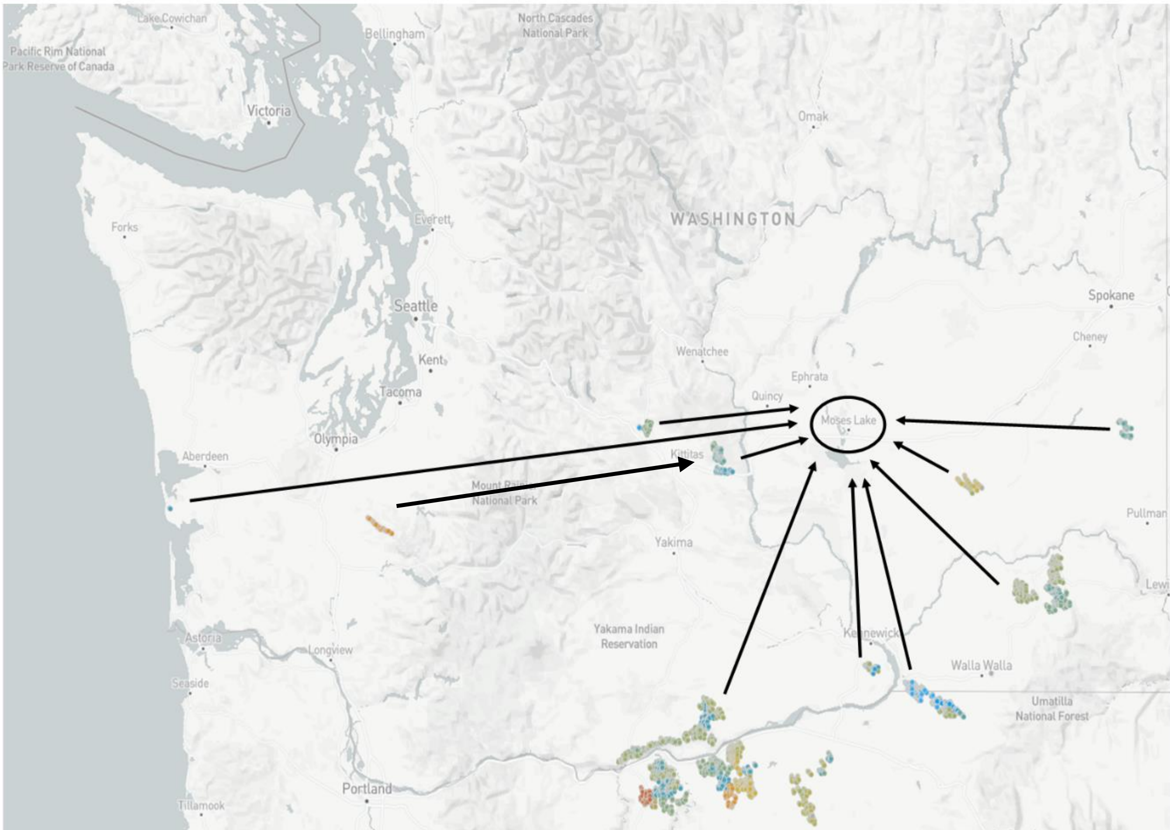
When a component of a wind turbine reaches the end of its life, it must be decommissioned. Because of the height of a wind turbine and the location of the wear components, often a crane must be utilized to remove or replace equipment. Airfoils, our primary focus, often require more than one crane due to the unwieldy size and windy conditions. Operators must unbolt the airfoil from the hub and lower it down to ground level. Should the turbine owner choose to repower the site, newer turbine blades and generator equipment may be installed at this time, utilizing the existing steel base, wiring, and foundations. Should the site owner choose to fully retire the site, the base and foundation must be deconstructed as well. Many operators of wind farms in the state have pledged to return their sites to original condition following the closure of a facility.

Once the airfoil has been taken down from the tower, it must be prepared for transportation to a processing facility. Often, it is not worth the expense and difficulty to transport a retired blade without sectioning into more manageable pieces. The blade is cut down into sections appropriate for road transport, often less than 40 feet to adhere to highway "oversize load" regulations. These cuts are performed on site utilizing standard power tools. Several airfoil waste management companies advertise environmental protections for this process, as cutting into a composite structure can generate dust and fine particulates containing plastic and glass fibers that can damage both worker health and the environment.

Disposal Location

The suggested location for a recycling facility based on our current research is within Grant County. The location is relatively close to the concentration of wind turbines in Washington (Columbia River) and therefore can reduce the cost and impact of transportation.

Below is a map identifying the proximity of Grant County to the locations of the Wind Turbines in Washington.



USGS Wind Turbine Database/WSU Energy Program

Electric Utility	Average $/year energy cost
Grant PUD	6247
Chelan PUD	5249
Clark PUD	10726
Avista	16460

Disposal Methods

Background context

A wind turbine blade is a composite made up of resin matrix binding materials such as fiberglass or carbon fiber for reinforcement and strength. When using materials such as epoxy resin as an adhesive, the term thermoset resin matrix is used. The term thermoset insinuates that the composite is extremely hard (virtually impossible) to reverse. This results in a very strong composite that cannot be separated out easily.

Despite this, Washington alone has nearly 1800 wind turbines, approximately 5400 blades that will approach or have approached the end of their life. By using one or more of the following processes, the epoxy resin can be decomposed or broken allowing for further usage of the fiberglass material.

Landfill
Landfilling is the baseline for decommissioning a wind turbine blade. Blades are transported in smaller segments to a designated landfill and covered in large plots of land.

However, due to the size of the wind turbine blades, the task is not small and is very logistical. There are a few transportation options for dismantling a wind turbine. One is shredding the blades to a coarse material to reduce the volume occupied. The second is to reduce the blades to segments of no longer than 14 meters. Each method has its benefits and limitations.

Shredding the blades into coarse material onsite can reduce the large volume that a wind turbine blade occupies. In Cooperman et al and EPRI 2020, the research finds that modeling shredding the material onsite to fibers between 1-3 cm brings a cost of $99.21 per metric ton. For comparison, the same studies show that cutting the turbine blades to a size no longer than 30 meters is closer to $27.56 per ton.

Shredding the blade allows for the blades to be charged by weight rather than by volume. Due to the size of the wind turbine blades, the cost could be significantly cheaper to shred the blades since the transportation cost is reduced. By reducing the volume of the blades, much more material can be transported in a single load and thus reducing the transportation cost as well as the landfill cost itself.

Based on the research conducted by Cooperman et al the cost of landfilling shredded material is near $60.63 / metric ton for shredded material and around $19 / cubic meter (note that the $19 valuation was taken from the Texas Commission on Environmental Quality within Cooperman et al research). When these values were transposed onto the data from the USGS Wind Turbine database, our estimates show that it is more than 10 times as expensive to landfill large segments rather than shredding the material (on average over 19 years).

There are further limitations with each of the processes. By shredding the blades onsite and potentially outside of a facility, there are harmful pollutants and particulate matter that would be released into the atmosphere. This could be harmful to the nearby communities as well as the laborers shredding the material. In the case of reducing the size of the blades to 14-meter segments that could be significantly reduced.

To reduce this potential pollutant in the air from cutting or shredding it is advised that the blades are reduced to the size of the flatbed truck that could be used to transport the pieces. The suggested size based on current studies that optimizes transportation space and reduces environmental pollution is around 14 meters, or the length of a 48 ft flatbed truck.

Transportation
Transportation will be one of the largest if not the largest considerations in this process. If recycling is the approach that Washington will take, keeping the integrity of the turbine blade will be extremely

important and therefore excludes shredding as a means of simpler logistics. Furthermore, wind turbine blades will need to be deconstructed using a crane rather than demolition or blasting as this can negatively affect the blade composition and quality.

Current estimates put the cost of bringing a crane to the site at $30,000 per day, according to officials with Avista, an operator of several thousand turbines around the western US. To estimate the amount that transportation plays into the cost of these different end of life approaches, certain assumptions and steps had to be taken.

Using the USGS Wind Turbine Database, all states and territories were filtered out except Washington leaving a datasheet with most information about each wind turbine and wind project.

Then, to understand the forecast of wind turbine lifetimes and inventory, an assumption was made that each turbine lives only 20 years. This estimate will have a margin of error since depending on location and quality of maintenance, some turbines experience fatigue. It is not uncommon for a turbine to be retired or decommissioned after 15 years nor is it uncommon for it to surpass 22 years.

From the Cooperman et al and Liu et Barlow research papers, the following table was used to estimate the wind turbine blade mass.

Turbine Rated Capacity (MW)	Total Blade Mass (kg/kW)
≤1	8.43
1–1.5	12.37
1.5–2	13.34
2–5	13.41
≥5	12.58

(Liu et Barlow/Cooperman et al)

After calculating the estimated wind turbine blade mass per turbine, it was then totaled up and converted into tons. This allowed for further calculations to be performed to estimate the cost of landfilling the turbine blades by mass.

To estimate the cost of landfilling the turbine blades by volume the following calculations were performed.

From the USGS Wind Turbine database, each wind turbine has an associated rotor diameter. Within the Cooperman et al research an equation was derived to estimate the volume of a wind turbine blade.

$$V_{blade} = 0.0016 \times (D_{rotor}/2)^3$$

Figure X Blade Volume Estimate from Cooperman et al

This equation, applied to the subset of data for Washington State allowed for the input of the rotor diameter. Then multiplying the whole calculation by 3 gave an approximate estimate of the volume of each wind turbine.

Simply summing the data gave a total ranging from 1716 cubic meters for 2023 to 125447 cubic meters in 2040. As a reminder, these numbers were calculated to show the expected retired blade mass on an annual basis assuming a 20-year lifetime per turbine.

The final calculation for the landfill by mass scenario uses the Cooperman et al research of landfill tipping fee by mass, transportation costs per mile/km, and the cost to shred the turbine blade. This results in an estimated average of $27,358 per year between 2021 and 2040.

The final cost of landfilling it by volume required the volume equation provided above by Cooperman et al to estimate the total volume. Then by using the approximate length, width, and height of a 48 foot flatbed truck, we were able to render an expected number of 14 meter segments per truck load. This allowed us to estimate how many truckloads were needed per year under the same 20 year lifetime expectation.

Note: The transportation calculation for the 14 meter segments is used across all recycling options.

Mechanical Grinding

Mechanical grinding is the process of taking composites and shredding them down to fine filler powder and short length fibers.

As with any of these processes, once the wind turbine has been disassembled, the blades are cut into 14 meter segments to be transported via flatbed truck. (Note that with mechanical recycling, it is possible to shred the material onsite to a size of 1-3 cm but this would release many harmful pollutants into the atmosphere.) Once at the facility, the segments are cut further into smaller pieces and fed into different possible grinding technologies including but not limited to milling, shredding, and grinding. It then gets separated into various categories based on size and density. Larger, more holistic fibers are sieved out allowing smaller composite fibers and powders to fall below. Once separated out, the finer residue is compacted to reduce space and can be made ready for transportation.

The resulting material is no longer than 1 centimeter. As shown in multiple studies (Liu et Barlow, Cooperman et al) the strength of the result is much lower than the virgin material and cannot be used in the same application as the reinforcing glass fibers are in a wind turbine blade.

Despite mechanical grinding showing a lower fiber yield and quality rate than other processes, it has been proven to work as a filler in cement materials, potentially reducing the environmental impact of concrete. In Glosser et al, the research points out that the structural integrity of glass fiber reinforced polymers could be used as a supplementary cementitious material.

A major consideration when evaluating recycling processes is the energy consumption and ratio of renewable to nonrenewable energy that is required. For example in mechanical grinding, according to research within Wei et al, 75% of the energy supply can come from renewable sources for electricity such as wind, solar, and hydroelectric power. The remaining 25% of the energy is expected to come from nonrenewable sources to support the compactor in the process.

Based on multiple studies such as Rani et al & Goncalves et al, the estimated quantity of energy needed is 3-5 MJ/kg for the higher estimates. This is considerably lower than the energy consumption of other processes explained later.

Pyrolysis

Pyrolysis is a thermal decomposition process commonly used in recycling glass fiber reinforced polymers (GFRP) like wind turbine blades (WTBs). This process involves exposing the materials to high temperatures, typically ranging from 300 to 800 degrees Celsius, within an environment devoid of oxygen. The main objective of pyrolysis is to effectively separate the composite materials into their constituent components, primarily the glass fiber and the resin matrix.

During the pyrolysis process, WTBs are carefully placed in a controlled environment where temperatures are elevated, and oxygen is kept out. In this environment, the WTB gradually breaks down into its individual components. The resin matrix, which binds the materials together, undergoes decomposition, resulting in the production of gases, while the valuable glass fibers are left behind.

The utility of pyrolysis in GFRP recycling is significant, as it is considered a promising method for effectively breaking down the polymer matrix and enabling the recovery of high-quality glass fiber. The resulting glass fibers obtained through pyrolysis tend to be longer and possess a higher tensile strength, making them suitable for various applications Ribeiro et al.

Pyrolysis offers several advantages in the recycling of GFRP materials. It can be designed to recover heat generated during the process, potentially leading to self-sustaining aspects as shown in Yang et al. Additionally, the process can yield larger glass fibers with a higher tensile strength, enhancing their usability in various applications.

However, there are certain disadvantages associated with pyrolysis. It can result in the formation of char on the fibers and epoxy residue, affecting the quality of the final product as shown in Xu et al. The removal of char can also lead to further quality degradation.

Furthermore, pyrolysis is more energy-intensive compared to some alternative recycling methods, such as mechanical grinding. The energy required for the high temperatures typically comes from non-renewable sources, like fossil fuels, which can impact its environmental footprint. It can potentially be powered by renewable energy sources such as solar, wind, biomass, or hydrogen as outlined by Wei et al. While these sustainable options align with environmental goals, challenges arise due to the intermittent nature of renewables, requiring solutions for energy storage or backup heating during periods of low generation.

Achieving and maintaining the high temperatures needed for pyrolysis using renewables can also be less energy-efficient compared to direct fossil fuel combustion. The choice between renewable and non-renewable energy sources for pyrolysis hinges on factors such as energy availability, system scale, and environmental objectives, with ongoing efforts aimed at enhancing the sustainability and efficiency of pyrolysis processes with renewables.

As shown below multiple resources have large ranges of the energy requirement for pyrolysis but the upper range is 25-30 MJ/kg Farooq et al.

In summary, pyrolysis is a valuable recycling technique for GFRP materials like wind turbine blades. It efficiently breaks down composite materials into their constituent parts, with the potential to yield high-quality glass fibers suitable for various applications, including concrete reinforcement. While it offers advantages such as heat recovery, larger fibers, and increased tensile strength, it also presents challenges such as char formation, energy intensity, and reliance on non-renewable energy sources.

Chemical Recycling

Solvolysis is a process that involves submerging wind turbine blades in a solvent in a supercritical state. The objective is to depolymerize the resin matrix, leaving behind high-quality fibers suitable for various applications. Solvolysis encompasses several techniques, including hydrolysis using water, glycolysis with glycol and other alcohols, and the use of solvents such as nitric acid to break down the matrix (Yang et al.

The resulting high-quality fibers obtained through chemical recycling offer versatility in potential applications. Industries that rely on high-quality fiberglass could particularly benefit from these recycled fibers.

Chemical recycling through solvolysis yields the highest quality fiber compared to other recycling options, ensuring the suitability of the recycled material for various demanding applications.

This recycling method tends to be expensive due to its high energy demand. It relies on nonrenewable energy sources, primarily because of the elevated pressure and temperature requirements. Based on Farooq et al it could be as high as 90 MJ/kg, where other resources estimate it at 20-23 MJ/kg Cooperman et al.

The process is time-consuming, taking upwards of 16 hours for full decomposition, in contrast to pyrolysis, which can be completed in as little as an hour in some applications or mechanical grinding, which takes under an hour. Depending on the specific chemical recycling option chosen, volatile chemicals may be involved as explained in Wei et al. The current lack of scalability is due to the need for advanced equipment and substantial energy capacity.

In summary, solvolysis, a chemical recycling technique, offers a method to reclaim high-quality fibers from wind turbine blades. While it provides advantages in terms of material quality, it is associated with high costs, energy demands, and time requirements, hindering its scalability and environmental sustainability, particularly due to its reliance on nonrenewable energy sources and potential generation of waste liquids.

Comparison of Recycling Methods:

Table 1.
GF recyclate value.

Glass fibre	Fibre yield rate	Virgin fibre value per t	% virgin performance conserved in recyclate	Filler yield rate	Virgin filler value per tonne	% virgin performance conserved in recyclate	Feedstock fibre content	Resin yield rate	Virgin resin value per tonne	% virgin performance conserved in recyclate	Feedstock resin content	Overall process yield	Years extended	Recyclate value/$ per tonne
Landfill	Nothing													$0.0
Incineration	Energy recovered only		–	–	–	–	–	–	–	–	–	–		$58.7
Mechanical	58.3%[1]	$1300.0	78.0%[1]	41.7%	$310.00	100.0%	60%	0%	$0.0	0%	40%	95%		$410.6
Fluidised-Bed	44.0%[2]	$1300.0	50.0%[2]	7.6%	$310.0	100.0%	60%	0%	$0.0	0%	40%	95%		$176.4
Pyrolysis	56.0%[3]	$1300.0	52.0%[3]	14.0%	$310.0	100.0%	60%	0%	$0.0	0%	40%	95%		$240.5
MAP	56.0%[4]	$1300.0	52.0%[4]	14.0%	$310.0	100.0%	60%	0%	$0.0	0%	40%	95%		$240.5
Chemical	100.0%[5]	$1300.0	58.0%[5]	0.0%	$310.0	100.0%	60%	100%	$5571.0	50%	40%	95%		$1488.3
HVF	90.0%[6]	$1300.0	88.0%[6]	0.0%	$310.0	100.0%	60%	0%	$0.00	0%	40%	95%		$586.9
Life extension 5 years	–	$1641.8	–	–	–	–	60%	–	$5571.0	–	40%	–	5	$803.4

References: 1 (Palmer et al., 2009), 2 (Pickering et al., 2000a), 3 (Cunliffe et al., 2003), 4 assumption made in this study, 5 (Keith et al., 2016a), 6 (Rouholamin et al., 2014).

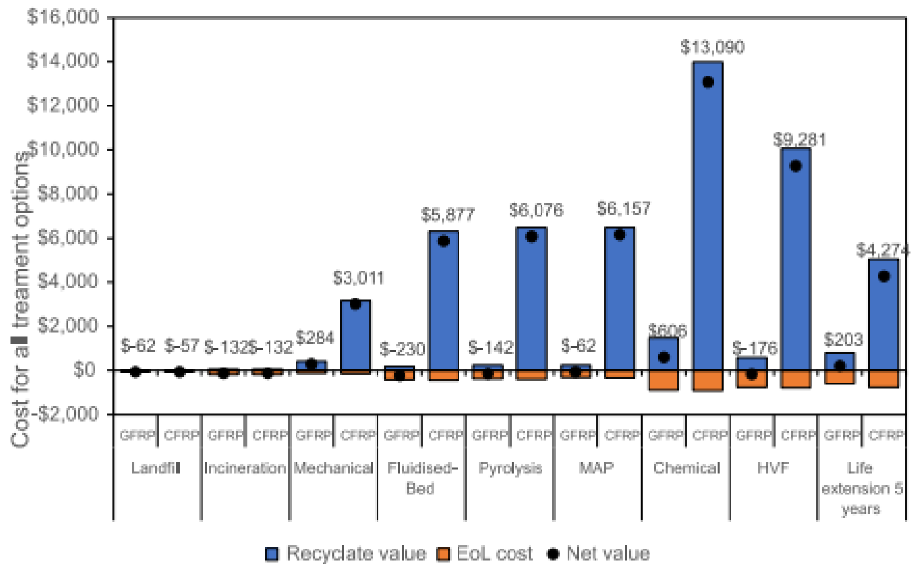


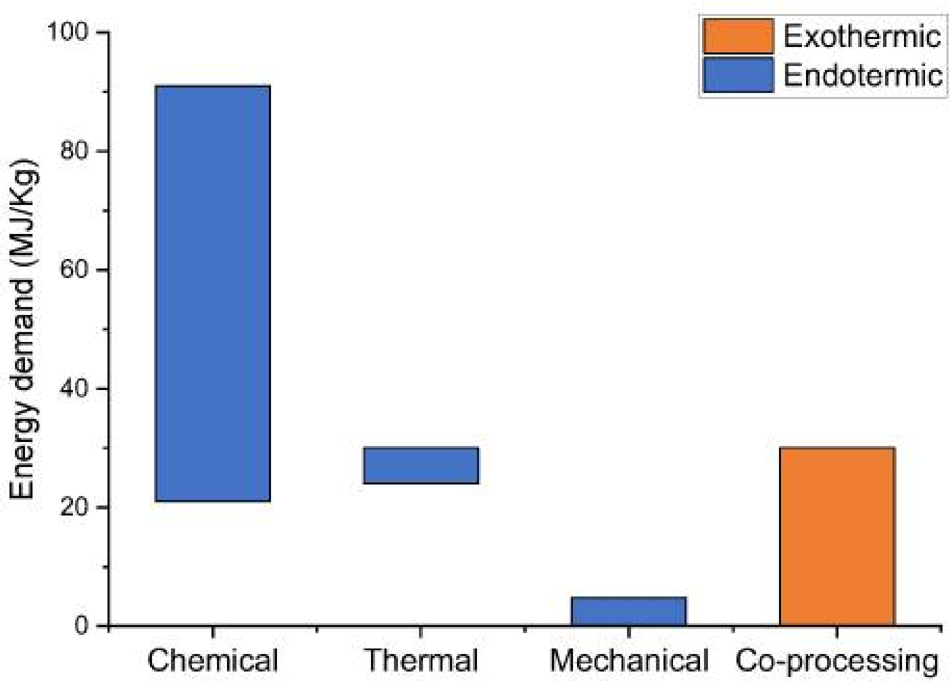
Fig. 2.. Comparison of cost, recyclate value and net profit for EoL options for GFRP and CFRP waste from wind turbine blades.

Liu et Barlow

Table 1
Comparison of EOL processes.

EOL Process	Circular Economy Strategy	Energy Requirement (MJ/kg) (Liu et al., 2019)	Technology Readiness Level (WindEurope 2020)
Landfill		0.3	9
Incineration	R9 – Recover	−4.2	9
Cement Coprocessing	R8 – Recycle	−4.2	9 (GFRP)
Mechanical Recycling	R8 – Recycle	0.3	9 (GFRP) 6/7 (CFRP)
Fluidized Bed	R8 – Recycle	22.2 (GFRP) 9.0 (CFRP)	5/6
Pyrolysis	R8 – Recycle	21.2	6/7 (GFRP) 9 (CFRP)
Microwave-Assisted Pyrolysis	R8 – Recycle	10.0	4/5
Chemical Recycling	R8 – Recycle	19.2	5/6
High-Voltage Fragmentation	R8 – Recycle	16.2	6
Life Extension 5 Years	R4 - Repair	1.4 (GFRP) 3.5 (CFRP)	9
Design for Circularity	R1 - Rethink	Varies by process	3/4

Cooperman et al



Farooq et al

Conclusions

Problems:

The problem we are continuously seeing with each of these different processes is the lack of a recycled market for materials such as fiberglass. While there are many different applications for materials such as glass fibers, whether mechanically grinded or chemically dissolved, the reality is that virgin fibers are extremely cost effective.

What places like Washington need are strict umbrella type policies outlining the prevention of landfilling wind turbines and pushing owners and operators of wind turbine farms to seek out other options.

There is also a need for incentives and subsidies for recycling companies to balance out the cost of the recycling process. For both pyrolysis and chemical depolymerization, the lack of scalability due to high energy costs and low demand of recycled fibers means a lower benefit to cost ratio.

There is also the problem of consistency in decommissioned wind turbine blades. In a big picture aspect as more wind turbine manufacturers push towards thermoplastic matrix designs, they reduce the need for recycling facility such that would include pyrolysis and chemical depolymerization. But the existing wind turbines are evident that there will be thousands of tons of waste (in Washington) from GFRP between now and the next 25-30 years.

From the smaller picture though, there needs to be an organization of the timeline of the wind turbine blades that are being decommissioned so that they follow the rate at which recycling plants can operate with. Some report having done 2000 tons a year and pushing for 50000 tons a year. These facilities would need a consistent flow of GFRP waste to be operational throughout the year.

This brings us to the next problem, the transportation costs and needs using Washington as a focus. The majority of the wind turbines in Washington State can be found along the Columbia River Gorge in the south central part of the state between the border of Washington and Oregon.

One of the potential models our organization sees is using the Columbia River barge system to ship and transport the wind turbine blades. If a recycling facility was placed in southwestern Washington further down the river, a barge could transport smaller pieces of the wind blades reducing the cost of advanced trucking for wind blades.

Transporting fully constructed wind blades is a challenging process as wind turbine blades can surpass 120 ft. in length. The trucks transporting the blades tend to do 1 at a time due to their immense size. But when being decommissioned, WTBs can be cut into smaller segments around a ton reducing the need for advanced trucking options and rather bulk shipping.

The process would also have to include labor and construction to deconstruct the turbine as blasting the wind turbine often prevents recycling facilities from accepting the blade segments

After deconstruction and splitting of the turbine into chunks, the turbine would have to be shipped to industrial ports along the Columbia and loaded onto a barge to be shipped further down the river or transported via trucks to said recycling facility.

There will be a need for trucks assuming the recycling facility is not immediately on an accessible port but rather further inland.

TASK B: Blade Processing and Availability

Introduction

Washington Recycling Facilities and Corporations

The investigative team took results from the previous survey and focused on facilities both in and immediately accessible to Washington. There are at least two companies in Washington that either operate or are developing facilities capable of processing GFRP products, Global Fiberglass Solutions of Bothell and Conrad Industries of Chehalis.

Global Fiberglass Solutions only has the main office located in Washington, but has two facilities in the American Midwest to store and process blades, where they produce a shredded product that can be used in plastics manufacturing. GFS also operates a RFID-based blade tracking system and has a good systemic understanding of end of life processes for blades, including specific materials and designs from the OEM.

Conrad Industries is currently developing a plastics pyrolysis process utilizing modular equipment that can be easily transported and deployed. Their headquarters and research facility is located in Chehalis, Washington, where they have prototyped their equipment and performed small demonstrations with more standard consumer plastics. The pyrolysis processes they are developing transforms plastic into a synthetic fuel, similar to a "dirty diesel fuel" that can be burned for heat and power, as well as a carbonized residue, through heating and pressure. The residue may be discarded or used as a filler in asphalt or concrete, and the synfuel can be used to power the pyrolysis process or in other combined heat and power operations. Conrad Industries did not have any public information on the environmental impacts or carbon intensity of their process, however comparable pyrolysis processes generate significant emissions that must be contained and treated, and fuels created have more soot, NOx, and other pollutants than standard fossil fuels. One beneficial byproduct of the process is gray hydrogen, which may be used in hydrogen fuel cells for transportation fuels, however it should be noted that the source of hydrogen in this case is nonrenewable and primary sources of hydrogen should be electrolyzers separating water molecules powered by renewable resources such as wind and solar.

The process used by Conrad Industries may successfully be applied to GFRP materials from wind turbine airfoils. The company indicated a high pressure, elevated temperature process running at a minimum of 1200 degrees Fahrenheit, consistent with pyrolysis processes for FRPs investigated by several peer-reviewed papers considered by this study. One concern noted by the authors is the inability to recover glass and carbon fibers, as well as the unfamiliarity of the company with FRP products. Fibers in this process would be irreparably damaged and unsalvageable, becoming comingled with the carbon residue. In this state, there is no end use beyond as a construction filler, and the recovered product is of exceptionally low value on the market. While mechanical grinding will be a necessity for the retired blade to fit in the machine, there's little likelihood that the glass or carbon fibers could be separated from the resin prior to processing in the pyrolizer.

The process and components used by Conrad are extremely attractive for deployment, however. The development team is focused on a modular, easily deployable solution that they can replicate at multiple sites, mostly in pursuit of the larger goal of eliminating consumer plastics from landfills.

Additionally, the use of ground up product for feedstock may be beneficial for transportation of retired blades and other larger FRP items. A pyrolysis facility may be located further away while a facility conducting sectioning and shredding may be located nearer to wind farms, and low carbon transportation options such as freight rail may be utilized to move shredded materials to their final processing location.

While these two companies operate development activities, they have yet to have a commercial process available in the state of Washington, especially for wind turbine blades. A full service recycling partner located in Washington would be in the best interest of the state, allowing for enhanced regulation and tracking, as well as the ability to funnel in waste streams from other industries like aerospace and recreational boating.

National Recycling Facilities

With very little GFRP processing immediately available in the state of Washington, the research team looked outward to national processing facilities. As this is a developing industry that is mostly in the conceptual stage, there are very few operational recycling facilities for turbine blades, if any. There are, however, a few companies and organizations that have demonstrated viable technologies and currently scaling their processes.

Global Fiberglass Solutions, whose corporate office is located in metropolitan Seattle, has several facilities in the Midwest, where there are a higher concentration of wind turbines with older vintages. The company also operates a variety of offsite services adjacent to recycling wind turbines, including sectioning, transportation, and tracking. GFS's primary facility is in Sweetwater, Texas, among the many wind farms that dot the western part of the state. Here, they process blades with a shredder, making a product that can be used in plastic injection molds to make a variety of products, including structural sections, manhole covers, and many other solutions. Conversations with Don Lilly, CEO of GFS indicated a strong demand for the filler product, as plastics manufacturers are looking to increase the amount of recycled content in their products. The open market costs are, however, not cost competitive with virgin materials such as calcium carbonate (which is a direct replacement), nor do they cover costs for recycling, storage, and transportation. Lilly also indicated an eventual plant capacity of 5000 blades per year, however, this may or may not be totally accurate.

GFS also operates storage yards, which have become a point of community and industry contention. Here, they store blades waiting to be processed, often after they are sectioned to 40-foot lengths at the wind farm and trucked in. The volume of acquisition has been much higher than the rate of processing, with several storage yards in Iowa and Sweetwater, Texas filling up to the point of community complaints and lawsuits. Lilly did not have a direct answer to questions about these facilities, but recent reports indicated a possible sale of their Iowa facilities to General Electric. Lilly similarly did not comment on other recent developments at GFS, including strained relations with the City of Sweetwater, the depublication of the corporate website and contact information, and possible agreements with utilities and manufacturers. Community experiences with GFS indicate the need for Washington to consider regulation of recyclers, either by requiring a certain throughput or maximum storage yard size.

GFS has several innovations that may be valuable to the FRP recycling industry, and specifically blades. They have developed a complex tracking system, allowing them to track blades from the moment they come off of a turbine to the moment they go into a shredder. They have also developed a full service transportation and disposal service, taking formal ownership of the retired blades from the original owner, sectioning them on site using specialized tools, and trucking the shortened blades to storage and processing from the farm. These innovations may be used for a similar tracking system operated by the state, allowing for government certainty of proper procedures being followed.

Another company making significant headway in developing a solution to recycling FRP products is Carbon Rivers, a Tennessee-based firm specializing in solvolysis. The process developed by Carbon Rivers allows for the recovery of glass and carbon fibers after processing, greatly increasing the value of recovered products and bringing recycling closer to economic viability. At latest publication, the company had achieved recovery of over 99.9% of glass fibers from a blade, creating a nearly pure fiberglass that can be mixed into virgin glass and reused in composites of various types. This is a revolutionary step, moving the industry closer to the materials circularity that’s already present in the metal recovery industry. The company had recently publicized several successful demonstrations and was selected to receive an RD&D grant from the US Department of Energy to further their development. The current processing rate is fairly small, in the handful of blades per year territory, but is expected to multiply to nearly 50,000 metric tons per year of capacity in the near future (for reference, a blade from a 1.5 MW turbine is estimated at roughly 11 tons). The initial facility will be located in Knoxville, TN, near to their research center, and mostly out of reach for Washington turbine owners to utilize. Should their pilot plant be successful, it may be in the state’s best interest to court a similar recycler for siting in the state.

Another company with significant promise in the area is Veolia NA, an environmental technology firm that has partnered with General Electric to provide end of life services for their turbines. Veolia’s primary developments have been in the field of Cement Co-Processing, where they sell shredded FRP material to cement kilns. The kilns then burn the shredded FRP with coal and other solid fuels, reducing coal consumption by the kiln and lowering the carbon intensity of concrete production, currently one of the leading contributors of carbon pollution. Additionally, the process allows the silica from the glass fiber to be reused in cement without separation. This solution is far from a circular model, as the old FRP cannot be reprocessed after combustion, but does divert waste from landfills and reduces other fossil fuel usages. It should however, be noted that the combustible qualities of the blades come from hydrocarbons used in the binding polymer, causing carbon and other emissions during combustion. Veolia NA’s main blade processing facility is located in Louisiana, Missouri, however, the underlying technologies are simple enough that a plant should be easily replicable nearly anywhere, and there are concrete plants around the state and nation that can utilize shredded material as a fuel without significant modifications or upgrades.

There are several other companies in the United States that repurpose and reuse wind turbine blades in novel applications. A company in Florida, Eco-Wolf, Inc. can shred blade material and use it as a plastic filler for thermoformed plastic yard products, industrial components, and marine equipment like boat bumpers.

Existing Agreements

As of October 2023, several wind manufacturers have signed agreements with recyclers to provide end of life services in the US and Europe. GE Renewable Energy has had a formal agreement with Veolia NA since December 2020 to recycle all onshore turbine blades at Veolia facilities. Post-recycling products from the Veolia partnership are at this time destined for cement co-processing, where they claim a "reuse" rate above 90%. It should be noted that "reuse" in this manner would not allow further circularity of materials; hydrocarbons in the polymers would be burned off as fuel and glass fibers would be used in place of sand and clay as raw materials, trapping it in concrete. Positive benefits indicated by the companies are a more than 27% reduction in emissions from concrete with this feedstock as well as landfill diversion for turbine blades.

The other major manufacturer of turbines in the US, Vestas, is also working on blade recyclability, but does not have a full end of life program in effect for American customers at this point in time. The company has been working closely with researchers at European universities and recycling firms for several years to improve solvolysis processes, increasing the usable products and simplifying processes for speedier deployment.

At the same time, Vestas has been working with researchers in India to develop a different epoxy to make new blades. The principal issue with the current epoxies used in blade manufacturing is the high temperatures needed to melt them at the end of life- often over 1200 degrees F. The high temperatures will inherently damage the glass fibers in the epoxy, reducing their strength, length, and usability in future processes. Additionally, contaminants from epoxy residue may complicate recasting the glass before using for other purposes. Researchers are seeing processing temperatures decrease by more than half with the new epoxies, improving the quality of the reclaimed product, reducing energy inputs and emissions, and increasing safety and reducing volatile airborne chemicals.

These new processes would likely see impacts on Vestas product lines before the end of the decade. Vestas and the RecomBlades partnership announced their advancements over the past 3 years and are well on their way to developing commercialized processes for advanced solvolysis. Similarly, integration of new polymers into the manufacturing chain will take some time, but Vestas has been hard at work commercializing the new technology alongside the development.

Conclusions

Analysis of known commercial processing facilities capable of more than sectioning a blade indicated a lack of nearby services for many wind producing regions of the United States. The two major facilities in the US at this time are Veolia NA's facility in Missouri, and GFS's facility in Sweetwater, TX. There are no known facilities on the western side of the Rocky Mountains, while approximately 16% of all registered US wind facilities are in Alaska, Arizona, California, Idaho, Hawaii, Oregon, Utah, and Washington, with a rated capacity of just over 16 GW. 14% of the nationwide total is just in Washington, Oregon, and California, with that number definitely increasing soon.

Assuming a locus of wind production (the geographic center of all facilities) in Washington is roughly in the Tri Cities, it is nearly 1,700 miles of road travel to Sweetwater and over 1800 miles to the Veolia facility in Louisiana, Missouri. This distance expands to 2000 miles when considering our furthest-flung turbines in Grays Harbor. These distances are extremely cost prohibitive utilizing nearly any transportation method, especially when preprocessing activities are limited. Under a best-case scenario, without any additional facilities, the most efficient method of moving retired blades would be on a railcar, sectioned to fit car lengths and loading gauges. Trucking would be untenable for any volume, as you can fit only one or two blades per truck before a multiday drive, likely with minimal opportunity for a return load.

It's in Washington's best interest to work with recycling facilities to site a facility that either preprocesses or fully processes blades within or very close to its borders. More localized siting offers a range of benefits from reduced expenses and carbon emissions in transportation to increased regulatory capability to follow-on benefits for complimentary industries like aerospace and pleasure boating. Even if a full processing facility cannot be sited in Washington due to economic or environmental reasons, a preprocessing facility capable of shredding GFRP blades would be advantageous to the transportation equation. By shredding, you can greatly increase the capacity of transportation vehicles, fitting dozens of blades into the space formerly occupied by one. Utilizing equipment used to transport and store plastic pellets may be a way to reduce chances of environmental impacts from loose fibers and resin dust.

Task C: Supporting Incentives

Introduction

Most methods for recycling airfoils from the wind industry are lacking in economic competitiveness.

Incentive Design- Facility Construction

One option for increasing the economic competitiveness of a recycling facility, as well as demonstrating our state's commitment to the environment, would be to incentivize the construction of a facility directly.

1. **Wind Turbine Blade Recycling Regulation:**
    a. Generator and Blade Registration
        i. Every wind turbine generating electricity with a minimum nameplate rating of 100 kW[1] must be registered with the Department[2] and receive a unique identification number.
        ii. Each registration application must include information on location, including Coordinates, City, County, and, if applicable, Wind Project name.
        iii. Each registration must include information on physical attributes, including nameplate rating, hub height, blade length, blade composition, installation date, manufacturer, and model. Serial numbers for all major components must be listed. A manufacturer's specification sheet for the model and/or components may be provided as a supplement to the registration.
        iv. Each registration must include the owner and operator
        v. Each registration must include a Federal Aviation Administration registration number and an Energy Facility Siting Evaluation Council registration, if applicable.
        vi. Each unique identification number shall have sub designations indicating unique blades. The naming conventions shall be consistent with methods used by the manufacturer or operator[3].
            1. This identification number must be affixed to the inside of the respective blade at the hub collar upon commissioning for every qualifying turbine and blade after July 1, 2025[4]. This may, in addition, be marked on the outside of the qualifying blade in a manner that does not interfere with operations or safety.
            2. For qualifying turbines constructed and commissioned before July 1, 2025, the identification number must be affixed to the outside of the blade at the time of decommissioning. Blade Identification numbers must be kept on file by the owner and operator after registration.

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[1] Relatively arbitrary number, but will capture every commercial facility and is consistent with an unrelated net metering cap in other legislation.

[2] Could be the Department of Ecology, but just using general Department until we find a good home for the program.

[3] To be determined, probably during stakeholder work. This would be a WAC anyway, not the RCW.

[4] Arbitrary date for model legislation.

vii. A preregistration process is to be operated by the Department to provide identification numbers to operators prior to commissioning. A preregistration applicant may apply up to 180 days prior to commissioning. The Department shall process an application within 30 days of receipt.
viii. Any qualifying turbine that is not registered with the Department may not export electricity to Washington State Utilities.
ix. The Department may collect a fee at the time of registration or preregistration to cover associated costs.

b. Registration Changes
   i. The Department shall be notified by the registrant within thirty (30) days if:
      1. Contact information for the owner or operator changes.
      2. Ownership of the facility changes, or company name changes
      3. Components included in registration are altered or removed.
      4. The generator is decommissioned.
      5. Other alterations to the registration information are required.

c. Registration Recertification
   i. Every five (5) years following registration, the Registrant must certify that registration information is current. The Department may provide a consolidated list of registered

d. Decommissioning Notification
   i. The Registrant shall notify the department upon decommissioning a qualifying turbine or component.
      1. The notification shall include affected registration numbers, date of decommissioning, method of disposal, and qualified disposal firm.
      2. The Registrant shall provide invoice, receipt, or other documentation including serial number, Unique Registration Number, and disposal firm, of transfer, sale, or qualifying disposal of a qualified turbine.
   ii. The Department shall confirm receipt by qualifying disposal firm.
   iii. Qualifying Disposal Firm[5] shall report final disposition of component to the Department within 180 days of transaction, including Serial and Unique Registration Numbers.

2. Extended Producer Responsibility (EPR) Program:

a. The Wind Turbine Disposal account is created in the custody of the state treasurer. All payments, fees, fines and other contributions or money transferred, appropriated or directed to this account and the rules and regulations adopted under this act must be deposited into the account. Expenditures from the account may only be used for the purposes of enforcing this chapter. Only the Department or their designer may

[5] Build out a proof-of-work concept for recyclers. We need to head off the Texas and Iowa controversies before that even starts.

authorize expenditures from the account. The account is subject to allotment procedures under chapter 43.88 RCW, but no appropriation is required for expenditures.

   i. The Department is authorized to collect deposits to the Wind Turbine Disposal Account. Deposits are collected from companies engaged in end-user power sales on an annual basis and based on the amount of wind power sold at a rate of X per kilowatt hour of wind energy sold. Wind energy sales are calculated in a manner consistent with RCW [*wind power definition for clean energy*]. Electricity sellers may include end user costs in customer billing and identify them as associated with the account.

b. The Department is authorized to collect deposits to the Wind Turbine Disposal Account. Each Facility must remit costs equivalent to those required to

   The Department is authorize to disburse payments in the amount incurred by a Registered Blade owner while following procedures outlined under Section 4[6]. The Registered Blade Owner may only receive payment following notifying the Department of Decommissioning using procedures under Section 1 of this act. A registered blade owner is disqualified from payments if a disposal firm other than a Qualified Recycler is used.

   Expenses eligible for repayment include transportation from installation site to recycling facility, materials processing fees, and administrative fees. Total cost incurred by the state is not to exceed $X per linear foot of blade recycled.

   The Recycling Program must undergo a biennial review of costs to best align incentives with market conditions. These reviews should factor in changes in costs associated with labor, transportation, recycling processes, or end product markets that may cause realized costs to be incongruent with incentive payments.

Recycling Certification and Standards

Due to previously outlined incidents of bad actors in the recycling industry, it may be prudent and simplest for the State to consider a certified recycling program that regulates disposal activities and ensures program funds are used in their original intention. This program may be housed in the Department of Ecology, which already includes a robust recycling program and a strong understanding of waste management. Under assumed market conditions and volumes, the number of processing facilities would be minimal for the foreseeable future and thus easy to regulate without burdensome resource demands on the Department.

Regulatory Certification should include a process component and a product component. Recyclers should submit information on the intended process, including scientific models, methods, and expected

[6] References qualifying disposal

end products. Additionally, a recycler should track and report volumes of incentive-eligible blades processed. End products, including glass fiber and resin byproducts, should be reported to

As many residents of Sweetwater, Texas and Ellsworth, Iowa can attest, no community will tolerate the eyesore and misuse of land that comes with mass used blade storage. Every effort should be made by a certified recycling firm to process a blade within a reasonable time and keep stored blades to a minimum. There are few noted concerns with environmental impacts from blades waiting to be processed, however the large footprint of an unprocessed blade or blade section leads to storage yards that can cover dozens of acres. These sites are often graded, bare dirt or otherwise minimally surfaced and may cause runoff issues, dust storms, or other environmental impacts. Several of these storage yards are subject to pending or recent judgements regarding their community impacts. One way to limit the potential of this being an unintentional byproduct of a recycling facility and/or program in Washington could be to limit the time a recycler has to process a blade before imposing penalties. A 180-day period from decommissioning and used blade receipt should be a reasonable amount of time for processing, as most processes will require mechanical shredding as an initial step, which will significantly reduce the space required for the remaining steps. This length of time should additionally account for any supply chain or operational irregularities that impede regular operations at a recycler.

Recycling Market Development

The GFRP recycling market is not limited to only retired wind turbine airfoils. Washington has two other industries that generate a significant amount of glass and carbon-fiber product and waste- airplane manufacturing and boat construction.

Boeing is the largest American manufacturer of commercial jets and has numerous facilities in the state, where they manufacture products like the 767, KC-46, 737Max, and 777 jetliners. These planes have been shifting in design over recent decades to include a significant number of fiber-reinforced polymers, which now make up over 60% of the components in a 737Max and 777. Boeing generates thousands of tons of FRP waste per year from the construction of aircraft, not including end of life operations in places such as Mojave Air and Space Port, Kingman Airport, and Victorville Field in the American Southwest. Additionally, there are several smaller manufacturers of planes and related components outside of the Boeing sphere. Glasair Aviation of Arlington makes planes nearly entirely from composite components. Similarly, Eviation of Arlington is developing a battery electric passenger airliner in Moses Lake and plans expanded manufacturing at the Grant County International Airport. There are no known commercial aircraft disposal operations in Washington, however a functional FRP recycling program may attract investment from businesses seeking to responsibly retire old aircraft.

An additional contributor to a successful FRP recycling program in Washington may come from the maritime industry. Most pleasure boats, and most boats under 50’, are constructed from Fiberglass and have been for the better part of half a century. These boats line marinas along the shores of the Puget Sound, Columbia River, and many other bodies of water. According to boatinfoworld.com, which tracks boat registrations across the nation, there are over 15,000 registered recreation boats in Washington, (Washington Boat Owners by City, 2023) and 5,000 other vessels registered with the Department of Licensing. The state operates a derelict boat recovery program to remove problem vessels, but otherwise does not have active fiberglass boat recycling policies.

Reporting and Compliance

Mandatory reporting and other compliance activities would be key to ensuring that program funds are properly assessed, collected, and spent, and that the legislative intention behind the regulation was achieved by the program. Utilities already have a wide variety of compliance and reporting activities they perform at the local, state, and federal level, handling everything from the generation methods used to end-user costs to safety.

Landfill Disincentives

Landfill bans for retired wind turbine blades seem to be an attractive, easy method for ensuring blades do not end up as another piece of trash. Some states are thinking about it, such as Wyoming and Iowa. However, just banning landfilling in Washington may have follow-on effects for other communities. While the Legislature may have control over our state, State Government cannot regulate interstate commerce or actions that may be taken in other states. There's significant risk of just diverting the issue to other states or nations with a landfill band, as we've seen with refuse like consumer plastics that receive similar regulations. Many of our "recyclable" products are shipped internationally for processing, where they may not be recycled to the standard intended. They may also be

- Local Job Creation: Promote job creation in Grant County through blade recycling operations. Provide grants or tax incentives for recycling facilities employing local residents.
- Adjusted Recycling Targets: To account for the higher transportation costs in Grant County, allow wind farms in the county to have slightly lower recycling targets compared to those in regions with closer recycling facilities.

Task D: Potential Mechanisms for Establishing Recycling Requirements and Recycled Content Standards

Introduction

Wind Turbine blade and other GFRP product recycling technology is an evolving field, with improvements in both product creation and recycling. While the viability of post-consumer content in turbine blades has not been proven, efforts should be made to encourage manufacturers to develop more recycling.

Utilizing the Stewardship Organization model used by the battery and solar industries, exact recycling requirements can be set by industrial partners with expertise and experience in the realities of the industry. While this process may require additional time and expense, manufacturers are more likely to honor agreements that they create themselves. The Department of Ecology has a history of conducting these workgroups with industrial partners and should continue in this role; both solar and battery programs operate through their Recycling department. The Department should report on processing volumes on a biennial basis, allowing the Legislature to analyze and understand the work performed and recommend improvements to better fit policy goals.

Every 3-5 years following agreement on program rules, the Stewardship Organization should review available technologies and manufacturer recommendations to develop approved paths for retired turbine blades, as well as communicate approximate volumes to contracted processing services.

There are some turbines that may be too small to qualify for this program- these may be seen in agricultural scenarios such as vineyards, where they power irrigation equipment and other remote electric devices. Generally, they are products with similar GFRP blades to larger utility turbines, but orders of magnitude smaller and generally generating a few kilowatt hours per day. Most of them are owned by farmers, not utilities. While it would be good from an environmental perspective to require tracking and recycling, it may be too expensive and administratively burdensome for a small volume of GFRP to be included in a full program. At this time, there is little academic research.

Task E: Considerations Options for a State-Managed Product Stewardship Program

Introduction

Washington State does have some existing producer responsibility legislation that has application to wind turbines. The recent battery recycling bill, while not a direct model, has several key provisions that may offer guideposts for a Wind Blade-GFRP focused program. The battery program was crafted through an extensive legislative process, utilizing stakeholder meetings with industry and environmental leaders to craft a solution to battery waste. Because of the large impacts of the battery program affecting the vast majority of consumers, the structure of the program had significant input during development, giving significant weight to definitions and programmatic concepts outlines in the legislation.

The Battery Recycling Program establishes a clearly defined recycling regiment and funding mechanism to ensure that certain battery products are properly disposed of, with the explicit direction to avoid landfilling and perform the highest-feasible level of recycling. The program is funded through "Battery Stewardship Organizations," ostensibly a single industry association made up of manufacturers, sellers, and other industry entities. This organization is required to pay for cost incurred by cities providing recycling operations as well as fund additional pickup and recycling operations, distributing the costs among the manufacturers. It additionally tasks the organization with educational activities for the public, improving recyclability of products, and collaborating with state government in setting further recycling goals.

There are several definitions in the enabling legislation for the Battery Recycling Program that have relevance to a turbine blade recycling program. Section 2 (2) describes the "Battery Management Hierarchy," for these products, prescribing the prioritization of waste prevention and reuse before recycling, which is defined separately, and requiring other end of life management techniques are only used after demonstrating the infeasibility of reducing, reusing, or recycling. Section 2 (17) gives a broad definition of recycling activities that transform waste materials into a usable material, allowing for flexibility in technology while restricting certain uses such as incineration or fuel production. Section 2 (8) describes "Environmentally Sound Management Practices" to protect workers and the environment, as well as requires full documentation of covered materials up to their "Final Disposition," further defined in Section 2 (9) as a fully recycled, ready for reuse end product with residues and Non processed materials handled appropriately.

The regulatory process outlined by the Battery Recycling Program also offers a model for a further Turbine Recycling program. Battery producers must form a stewardship organization(s), which has been described by the Department of Ecology as practically being a singular entity with all covered entities enrolled. . This entity proposes and operates the program in consultation with the Department, which provides oversight and reporting mechanisms. The flexibility in the program is intended to allow for producers and recyclers to continue existing agreements that already meet the requirements while bringing more producers into compliance.

While some of the exact definitions and processes may have to be tweaked to apply to the correct technology, the robust stakeholder process that drove the Battery Recycling Program's enabling legislation lends credence to the practicality of the model to be applied to other industries, such as Wind.

The State of Washington has also required producer responsibility and stewardship programs for the solar industry. Passed in 2017, the Photovoltaic Module Stewardship and Takeback Program requires similar actions by manufacturers, distributors, and installers. This effort is in the final stages of stewardship program development with installers, manufacturers, and distributors.

Wind Manufacturing Stewardship Organization-managed program

Utilizing the Stewardship Organization model developed and implemented by the battery and solar stewardship programs, all manufacturers of turbines above a certain size threshold should form a stewardship organization in collaboration with operators and utilities. This program should be monitored by the Department of Ecology, which is already the agency in charge of most recycling efforts. This stewardship organization shall develop forecasts of the volume of retiring wind turbines every biennium and ensure that each covered turbine is retired according to a waste management plan. The stewardship organization should also work with recycling partners to ensure reasonable access to facilities.

The Stewardship organization must also keep a list of all active, qualifying wind turbines, with information on make, model, size, ownership, installation date, location, FAA #, and geographic coordinates and have it freely accessible to the public. The Stewardship organization must also list the final disposition of the materials from processed turbines. Direct tracking of blades will be performed from decommissioning to final disposition and reported out annually.

Due to the long distances to existing facilities, it may be in the stewardship organization's best interest to establish an intermediate processing facility, and any enabling legislation should include the ability for this to occur. Intermediate processing can include basic activities such as shredding to reduce shipping volume and costs, as well as offer an opportunity for intermodal transport to the destination. Industrial shredders can be readily acquired for a low cost, and siting a facility with access to the cargo rail network can reduce transportation costs and carbon emissions. While a single, unsanctioned blade travelling over road can require 4 employees, 3 vehicles, and many labor hours, a single railcar can fit several dozen shredded blades and be moved for a fraction of the price with a fraction of the staff. Additionally, each facility interviewed has cargo rail access. It may also be appropriate to process other GFPR products such as old fiberglass boats and aerospace components at these intermediate facilities, as they would be recycled in the same manner as GFRP wind blades.

Funds for these activities should be assessed on members of the Stewardship Organization based on the volume of retiring equipment per year. Eligible activities should be limited to processing-decommissioning should be at the expense of the owner. Existing agreements, such as the GE-Veolia deal, should be honored and excluded from funding obligations. There should also be limited funds for outreach and technical assistance, as well as regular meetings to establish the most acceptable recycling options for organization members.

The Stewardship organization should work with selected recycling partners to ensure that the process followed allows for the most complete recycling possible, using similar definitions to the Battery Recycling program on hierarchical dispositions. One key difference between the programs may be an allowance for the combustion of GFRP products under the hierarchy, which is disallowed by the battery recycling policy. The most practical end-of-life processing for GFRP products is co-processing with cement production, which combusts the hydrocarbons as a fuel and uses the glass fiber as a borosilicate replacement. This process reduces emissions in cement production by up to 20%, mostly through the substitution of fossil fuels. Also, the next most practical management solution is pyrolysis, which also implies combustive activities from fuel production. Due to recent advancements in blade composition including more readily reprocessible resins, the Stewardship organization should regularly review options for recycling GFRP blades and update requirements for members.

Conclusions

While a vital component of a circular economy, at this time, there are many barriers to a functional recycling system for GFRP wind turbine blades and similar materials. The only effective solution that has been deployed at scale in the United States is co-processing with cement- which, while it may reduce carbon emissions, is not an effective economic use. The primary material recovered in this scenario is a replacement for borosilicate, one of the most abundant mineral materials on earth. Other methods utilizing mechanical grinding may be acceptable in the near future, such as those services offered by Global Fiberglass Solutions. It should be noted that Global Fiberglass has yet to commercialize their system, and materials recovered from their process would replace some types of plastics in a one-time reuse scenario. The most effective ways of breaking down wind turbine blades of today, solvolysis, are several years away from commercialization of any significant form, and likely even further away from practical deployment in the Northwest United States. Other methods of disposal, including structural reuse, does not have enough demand for materials to keep pace with the understood retirement phasing.

There are several opportunities to improve blades into the future, including the efforts Vestas has made to reduce the amount of heat needed to break down the polymer binders and recover additional, better preserved, glass fibers for reuse. While this improvement is still in development, it promises to offer a better solution for GFRP recycling as the industry matures.

In the interim, and keeping in mind complex agreements between manufacturers, operators, and disposal organizations, it would be best to pull together an advisory group of stakeholders from utilities, manufacturers, and recyclers like efforts made by the Department of Ecology in determining rules for battery and solar panel recycling. This allows for a more realistic look into expected retirements, a better understanding of existing processes and agreements, and a more holistic, industry-centered way of ensuring recycling wind turbine blades is done in the most environmentally friendly, energy-efficient, and responsible manner.

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Appendix A

Calculations

Transportation of 14-meter segments:

$$\frac{\left[Rotor\ Diameter * \frac{1}{2}(blade\ length\ is\ half\ of\ RD) * 3(number\ of\ blades\ per\ turbine)\right]}{14}$$
$$= number\ of\ blades\ in\ 14\ m\ pieces\ per\ wind\ turbine$$

$$\frac{Rotor\ diameter}{2}(blade\ length) * 0.075 = average\ \max chord\ length$$

$$\frac{2.59\ meters\ width\ of\ truck}{Width\ (using\ chord\ length)} * 2(vertical\ side\ by\ side\ or\ horizontal\ on\ top\ of\ each\ other) =$$
$\#\ of\ 14\ meter\ blade\ segments$ per truck

$$\frac{\#\ of\ 14\ meter\ blade\ segments\ per\ turbine}{\#\ of\ 14m\ blade\ segments/truck} = number\ of\ truckloads\ per\ turbine$$
$$SUM(number\ of\ truck\ loads\ per\ turbine\ per\ year) = total\ number\ of\ truckloads\ per\ year$$

$$\#\ of\ truckloads * 150\ miles\ to\ grant\ county * \frac{1}{7}\left(\frac{gallons}{mile}\ \ with\ load\right) * \left(\frac{\$5.3}{gal}diesel\right)$$
$$= cost\ driving\ to\ grant\ county\ 1\ way$$

$$\#\ of\ truckloads * 150\ miles\ to\ grant\ county * \frac{1}{10}\left(\frac{gallons}{mile}\ \ without\ load\right) * \left(\frac{\$5.3}{gal}diesel\right)$$
$$= cost\ driving\ back\ to\ windfarm\ 1\ way$$

$$\frac{\$2.9(truck\ labor\ cost)}{mile} * \frac{total\ miles\ driven}{year} = Labor\ cost$$
$Labor\ cost + Fuel\ cost += Transportation\ costs$ for 14-meter segments

Note: The transportation costs above do not include the cost of cutting the wind turbine blade to 14-meter-long segments.

Landfill:

Mass:

$$Capacity\ in\ kW * \frac{kg}{kW} = Mass\ (kg) \rightarrow * 1000 = Mass\ (tons)$$

$$\frac{\$\ (Shred\ cost\ for\ landfill)}{ton} * Mass\ (tons) = Shredding\ Process\ Cost$$

$$\frac{\$\ (landfill\ tipping\ fee)}{ton} * Mass\ (tons) = Landfill\ Tip\ fee\ total$$

$$Shredding\ Process\ cost + Landfill\ Tip\ fee\ total = total\ cost\ of\ Landfill\ process$$

Volume:

$$\left(0.0016 * \left(\frac{Rotor\ diameter}{2}\right)^3\right) * (3\ blades) = \frac{Total\ Blade\ volume}{turbine}$$

$$SUM(Blade\ Volume\ per\ turbine\ for\ expected\ retirement\ year) = Total\ blade\ volume\ for\ retirement\ year\ in\ cubic\ meters$$

$$\frac{\$}{Cubic\ meter\ (cooperman\ et\ al)} * Total\ Blade\ volume\ (cubic\ meters) = landfill\ tipping\ fee\ cost\ for\ volume$$

$$\frac{\$\ pre\ cutting\ cost}{ton} * \frac{tons}{year} = pre\ cutting\ cost\ total\ per\ retirement\ year$$

$$Landfill\ tipping\ fee\ cost\ by\ volume + Recycling\ transportation\ cost\ (14\ meter\ segments) + precutting\ cost = Total\ landfill\ cost\ by\ volume\ per\ year$$