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ANALYZING RECYCLING OPTIONS FOR WIND TURBINE BLADE WASTE

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By

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Abstract

The purpose of this study was to conduct a systematic literature review to identify recycling options for wind turbine blade waste. Wind energy is a rapidly growing energy source due to its renewability and accessibility. However, the turbines that produce this energy have blades that must be replaced throughout the turbine's lifetime. The standard disposal method of decommissioned blades is the landfill. However, problems are arising within states as landfills are being overrun by the wind turbine blades once they reach their end-of-life. Conducting this study aims to provide a list of recycling options and provide an evaluation of each with suggestions on how to utilize them going forward. This study also aims to provide awareness on the issue of wind turbine blade waste. The results of this study concluded that cement co-processing was the best method for recycling wind turbine blade waste going forward because of its low environmental impact, cost, readiness, and quality. If this recycling method were to be implemented throughout the United States, a large amount of waste could be redirected from landfills.

Acknowledgments

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Introduction

Wind turbines are often seen on large plots of land across the United States, and they are also used all over the world including offshore where these machines are planted straight into the ocean. Wind turbines, as their name might suggest, harness the energy from the wind. The force of the wind spins the machines' massive blades which then rotates an internal generator and provides electricity (Martínez et al., 2009). With current global temperatures on the rise caused by rising carbon dioxide concentrations, this form of energy harvesting is becoming more popular since the energy form is renewable and has minimal carbon emissions. This means that the energy can be remade over and over with no worry of depletion. However, with so many wind turbines in the country, an important question comes up as to what happens after their time is up. The purpose of this study is to analyze the recycling options for wind turbine blade waste and identify the best options for the future.

The end-of-life of a wind turbine blade is important because of how rapidly this energy form is growing, and it is assumed not many people know the process after these blades are decommissioned, even though many drive by them throughout the year. It is not uncommon for drivers to see freight vehicles carrying blades for wind turbines and may have also seen piles of blades near cargo ports or sitting in fields. Although wind energy is proposed to be an environmentally friendly alternative to other energy sources like coal, there is still a large amount of waste from these machines, and transportation and installation of these blades use a lot of fossil fuels and carbon intensive energy (Martínez et al., 2009). The question becomes: Is the use of wind energy really green? Do we have the infrastructure to deal with all of this blade waste in the United States? It is important to not only answer these questions but also help the public gain an understanding of what happens at the end-of-life of a wind turbine. If more people were to know about the downsides of wind energy, we could then promote more sustainable ways for the end-of-life of these objects.

It is important to note that wind energy itself is not bad, and it is a better option than a lot of commonly used energy sources because of its renewability and the minimal pollution effects that it brings. Since nothing is being burned in this process, no significant air pollutants are being released into the atmosphere. However, wind turbines still produce carbon emissions through transportation, construction, and their waste. Carbon is a strong greenhouse gas, and when released into the air, traps the heat from the sun in a way that cannot be removed easily, and that contributes to higher global temperatures. Although the environmental impact surrounding wind turbines is notable, the energy payback time only takes a few months (Martínez et al., 2009). Wind energy also uses less water than fossil fuel energy which increases freshwater availability for the environment (Saidur et al., 2011). Additionally, wind turbines create 3.4 times the energy they consume (Alsaleh & Sattler, 2019). This allows for more growth opportunities in the communities surrounding these wind turbines and possibly lower energy costs for residents because of the abundance. It should also be noted that these machines last for many years which means that the good of wind turbines outweigh their bad by a significant amount. The average service life of many of these wind turbines is anywhere from 20-30 years (Crawford, 2009). However, many of the blades will need to be replaced and repaired throughout this time and with three blades each, this number of decommissioned blades adds up quickly. It is important to ask, what happens to these parts after their use.

One of the main places old wind turbine blades go is into the landfill and this is the common way of disposing of this kind of waste. Researchers sought to identify the end-of-life options for wind turbines, and specifically the landfill capacity in different areas. They were able to create a prediction for the amount of wind turbine waste there would be by the year 2050 with the aim to analyze and identify the best end-of-life options. They estimated that roughly 2.2 million tons of waste from wind turbines would be present in 2050. These researchers also analyzed the landfill capacity in different states and based on the current number of wind turbines there were already and the projected number to be built, they were able to determine if a state could handle that amount of waste. Many states will be able to handle this amount of waste within their landfills in 2050, but other states cannot. This would mean transportation of waste to different areas would be necessary (Cooperman et al., 2021). Additionally, new laws banning the burying of wind turbine blades have been talked about in various states like Wyoming and Nebraska where bills were proposed (H.B. 0217, 2020; NE - LB775, 2022). Figure 1 below shows an example of wind turbine blades in Gurley, NE. The use of landfills may be the most accepted place of rest for this kind of waste because it does not require that much excess energy or cost. However, if the landfills were to fill up and bans were to be put into place, where would this waste be able to go? Luckily, there are many recycling options available for these parts.

Figure 1. Used wind turbine blades stockpiled in Gurley, NE June 12, 2022

In order to determine what end-of-life options are the most beneficial for the blade waste, their composition must be analyzed. The most common way of manufacturing wind turbine blades is by placing a composite into a mold and then bonding those materials together by pouring resin into the mold and letting it cure. There are a variety of composites that can be used to make these blades and they each have their benefits. Examples of fiber composites are glass and carbon fibers, aramid and basalt fibers, and natural fibers. Some examples of matrix composites are thermosets, thermoplastics, and nanoengineered polymers and composites (Mishnaevsky et al., 2017). The reason why there are so many different choices is that they all have different benefits and functions. However, the most important aspect to analyze between these composites is what will provide the lowest weight with the highest strength (Thomas & Ramachandra, 2018).

Most recycling options require the blades to be shredded before any recycling is to be done with wind turbine blade waste. This takes time and energy which is undesirable. One method of recycling these blades is through mechanical recycling. This kind of method is beneficial to recover glass fibers and other fine materials, however, 49% of the waste still needs to be disposed of either by landfill or by an incinerator (Heng et al., 2021). Although this method diverts a majority of the waste from going into the landfill, it is still not optimal as almost half needs to be disposed of in an unclean way. A second method of recycling is thermal recycling. This process is when the materials are heated at a high temperature in an effort to separate the glass fibers from the rest of the materials. However, this process weakens the glass fibers by around 50% and makes it more difficult to find other uses for the material since it cannot last as long. A third recycling option is chemical recycling which is a process where solvents are used to break polymer bonds in the blade material. This method seems to be a great option for recycling these blades, but it is not done on a large scale yet and more research needs to be done for this option to be viable. Other methods of recycling such as repurposing, shown in Figure 2, and reusing are also landfill alternatives as some companies use the blades as benches in parks or even as art (Cooperman et al., 2021). Unfortunately, all these recycling methods have their downsides, and more research needs to be done to prove them as beneficial options.

Figure 2. Example of wind turbine blades being repurposed. These blades were reused as materials for a playground constructed in 2009 in the Netherlands (Mishnaevsky et al., 2017).

The kind of study that I have conducted is a systematic literature review. One of the research questions that will be addressed within the study is what recycling options there are for wind turbine blades when they reach the end of their lives? By addressing this question, alternative methods for disposing of blades in the landfill can be identified. With recycling options available, there will be less landfills running out of space needed for more important needs. The second question to be addressed is what is the best recycling option for wind turbine blades? Once the options for recycling are identified, an analysis of each of the options will be conducted to find the best one for recycling this type of waste. The factors that will determine the best option will be dependent on the environment, cost, readiness, and quality. This study will provide a list of recycling options along with an evaluation of each including suggestions on how to utilize them going forward.

Methods

The research conducted will maintain an evaluative type of approach. An evaluative approach aims to identify the pros and cons of a topic. I will use this type of approach to identify what end-of-life options will be the best for wind turbine blade waste in terms of the environment, cost, readiness, and quality. The criteria of the ‘environment’ is related to the pollution and hazards presented during the recycling process. ‘Cost’ will be determined by the amount of money needed to put the recycling method into production. The criteria for ‘readiness’ will refer to the level of production a recycling method is currently in. For example, a method could be at a laboratory or commercial scale. Finally, ‘quality’ will be determined by the strength of the fibers recovered after each recycling method.

To conduct my research, I will use a systematic literature review. This kind of review will be used to analyze text sources in an unbiased form by collecting documents, analyzing them, and pulling out the necessary information. In this way of analysis, my collected data can be easily found by another researcher (Pati & Lorusso, 2018). It is also important to use this type of analysis so that my data stays unbiased, and my report is not swayed heavily to one opinion. I will be using the following search term groups to find my resources: ("Mechanical recycling" "wind turbine" "fiberglass"), ("thermal recycling" "pyrolysis" "fiberglass" "wind turbine"), ("chemical recycling" "wind turbine" "fiberglass”), ("cement co-processing"), ("high voltage fragmentation" recycling fiberglass) (repurposing wind turbine blades). All the search terms also include the parameters of being peer reviewed articles and dated 2018-2022. My primary tools for collecting this data will be in the form of internet resources. These sources will be online search engines such as Google and Google Scholar. They will be used to find scholarly articles, government documents, and other peer-reviewed documents.

Once I have collected my sources, I will extract and organize relevant information according to blade waste impacts on the environment, cost, readiness, and quality. This information will be further evaluated in terms of the pros and cons of each method of recycling blade waste.

Literature Review

Mechanical Recycling

Most recycling methods require the mechanical process to take place before production so that the waste can be converted into a manageable size (Paulsen & Enevoldsen, 2021). This method works best for composites that are glass fiber reinforced (Olabi et al., 2021; Rani et al., 2021). In mechanical recycling, the composite is sent through multiple grinding sessions. Mechanical recycling uses pulverization, hydro cyclones, and a variety of sieves to reduce composite to a usable size. In this process, the composite is separated and shredded into 50-100mm pieces initially, and then a second grinding process takes place in which the material is ground into 50 μm to 10 mm pieces (Bernatas et al., 2021; Delvere et al., 2019; Giorgini et al., 2020; Zhang et al., 2020). Mechanical recycling takes 0.27–2.03 MJ of energy for the production of 1kg of carbon fiber composite (Xue et al., 2022). Furthermore, the energy consumption can change depending on the rate at which the composite is processed (Bernatas et al., 2021). Additionally, the cost of mechanical recycling is roughly $150 to $300 per ton (Delvere et al., 2019; Krauklis et al., 2021). This recycling method can be performed at room temperature and is non-toxic. The main health concern with mechanical recycling is the inhalation of the dust that is produced (Beauson et al., 2022). However, this can be mitigated with proper ventilation and personal protective equipment (Julian et al., 2022; Zhang et al., 2020).

Once the composites are ground up, the thermoplastic can be reheated and remolded into various products. The thermoset composites are shredded into tinier pieces and used as raw materials. Mechanical recycling is a low-end recycling method because it decreases fiber length and strength. However, this processed material is still able to be used as fillers in new materials such as filament for 3-D printing or construction materials like concrete (Julian et al., 2022; Martinez-Marquez et al., 2022; Xue et al., 2022). One method for secondary use is to only grind the composite into large flakes and then melt it together with a virgin matrix to create something new, and these results showed similar quality to other long fiber thermoplastics on the market (Montagna et al., 2022; Pegoretti, 2021). Overall, mechanical recycling provides material that can be used in an extensive range of applications (Senavirathna et al., 2022)

This method shown in Figure 3 below is simple but energy intensive and it does not result in good fiber quality as only 50-65% of the tensile strength is preserved using this method (Bernatas et al., 2021; Chen et al., 2019; Olabi et al., 2021; Zhang et al., 2020). This is partly because the base material becomes fragmented after going through this process leaving the fibers to be weaker and shorter with this method (Gonçalves et al., 2022). Mechanical recycling shortens the fibers and fibers that are too short cannot be used in creating new polymers since they could be pulled out from the matrix when under stressful conditions (Martinez-Marquez et al., 2022; Pegoretti, 2021). The matrix binding capabilities are low, but the internal bonds remain strong after using this method (Woo & Whale, 2022). However, the price of the recycled material obtains is low which makes this method unprofitable (Mulvaney et al., 2021; Yang et al., 2022). Nevertheless, this method is environmentally friendly as it does not give off large amounts of greenhouse gas emissions (Gonçalves et al., 2022; Khalid et al., 2022). Additionally, this method is low cost as it only requires simple grinding methods. Because of this, it is able to be used on a commercial scale (Xue et al., 2022).

Figure 3. Diagram of mechanical recycling using composite material (Khalid et al., 2022).

Cement Coprocessing

Cement co-processing is a large-scale industrial method for disposing of wind turbine waste (Mendoza et al., 2022). It is also a frequent form of recycling for composite material since it is low cost, low energy, and efficient. In this process, shown in Figure 4, the fillers and glass fibers within the composite material replace some of the raw materials of the cement production (Majewski et al., 2022). Within this method, 67% of the raw materials are recovered and 37% of the energy is. The organic polymer matrix within the blades is used as a replacement for fossil fuels once extracted. This means that 100% of the material can be recovered through materials and energy (Krauklis et al., 2021). It was also determined that cement co-processing causes no adverse effects on the quality of the cement. And lowers greenhouse gas emissions since it replaces fossil fuels (Ghosh et al., 2022). An example of this would be in Europe where cement co-processing is the main form of disposal for wind turbine blade waste. One study found that when the organic part within the material is burned as a fuel replacement, it lowered the CO_2 emissions in the area by 16% (Rhodes, 2019). Germany is another country that has implemented cement co-processing, and at one of its plants, 10,000 tons of its composite waste comes from wind turbine blades (Krauklis et al., 2021). Cement co-processing done in China was estimated to be $167.2 per cubic meter. This cost includes transportation, excavation, and incidental expenditure (Liang et al., 2022). Researchers believe cement co-processing is a suitable method for disposal due to its efficiency, cost, and ability to recover 100% of the materials (Ghosh et al., 2022; Krauklis et al., 2021; Majewski et al., 2022; Mulvaney et al., 2021; Rhodes, 2019). However, the article by Mendoza et al. in 2022 states that it is not a suitable method for disposal as the composition of blade waste has too much variation within different models. They also note that carbon fiber reinforced polymer should not be disposed of in this manner and some wind turbine models use this kind of material.

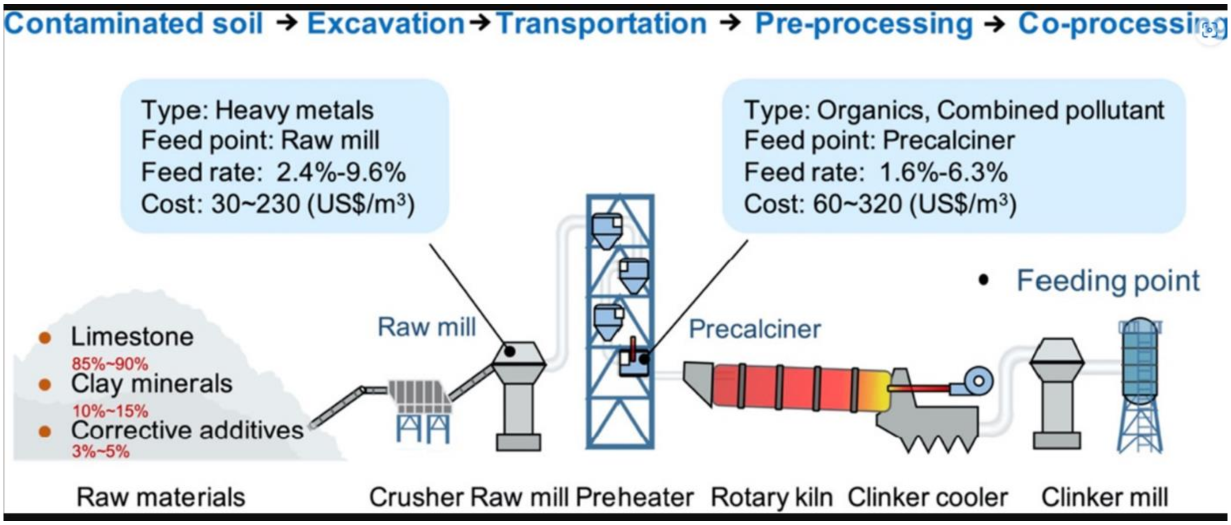

Figure 4. Diagram of cement co-processing using contaminated soils (Liang et al., 2022).

Chemical Recycling

Chemical recycling is a laboratory procedure that uses chemical solvents to recover both carbon and glass fibers from the waste composite (Beauson et al., 2022; Jani et al., 2022; Julian et al., 2022; Woo & Whale, 2022). The composite waste is typically ground before going through the recycling process (Giorgini et al., 2020; Krauklis et al., 2021). From there, this method depolymerizes the cross link bonds used in thermoset composites using solvents containing catalysts as seen in figure 5 (Khalid et al., 2022). These solvents could be in the form of ketones, glycols, alcohols, or water and they work in combination with pressure and temperature to separate the resin from the fibers which can lead to the recovery of both (Paulsen & Enevoldsen, 2021; Zhang et al., 2020). However, glass fibers will need to be processed at temperatures under 200°C to maintain quality, but at this temperature range, corrosive solvents will need to be used to separate the fibers (Bernatas et al., 2021; Gharde & Kandasubramanian, 2019; Paulsen & Enevoldsen, 2021; Xue et al., 2022). Additionally, lower temperatures allow for greater control of the chemical reactions, but it takes longer than using higher temperatures (Rosales et al., 2020). Carbon fibers can be processed at high temperatures over 200°C, and using this temperature range is more environmentally friendly as alcohol or water can be used as a solvent (Gonçalves et al., 2022; Martinez-Marquez et al., 2022; Paulsen & Enevoldsen, 2021). Before going through one of those processes, pretreatment is required to accelerate the process of the chemical reactions, and without it, about 15 hours are required for this method (Delvere et al., 2019). After the process, the fibers are then washed to remove any residue. The result is long clean fibers that maintain high structural integrity (Giorgini et al., 2020; Krauklis et al., 2021). Studies have shown that about 90-98% of the tensile strength is recovered with this method (Khalid et al., 2022; Rani et al., 2021; Xue et al., 2022). This means that fibers recovered from chemical recycling can be used in an array of applications (Chen et al., 2019). The energy consumption for chemical recycling is 63–91 MJ/kg which is high compared to other recycling methods (Jani et al., 2022).

Green solvents, such as supercritical water, can be used to effectively separate fibers from the composite. Supercritical water refers to when the water is at its critical point for both temperature and pressure which are 374°C and 22.1 MPa. At this point, the supercritical water can go through reactions that are free radical, ion, or polar non-ion, as well as acid catalyst and base catalyst capabilities. Other solvents commonly used in solvolysis can cause pollution and damage the fibers (Gagliardi et al., 2021; Xue et al., 2022).

A drawback of this method is that there's a need for expensive equipment that can withstand the corrosive solvents used which can be costly on a large scale (Bernatas et al., 2021). Additionally, chemical recycling produces a large amount of chemical residue that would be troublesome if production was moved to a commercial level as there would be a need to have post process acidic or caustic waste flows so the contaminants don't end up in the water stream (Julian et al., 2022; Kazemi et al., 2021; Senavirathna et al., 2022). This method also depends on the composition of the composite used as not all solvents will work for all materials and the same goes for temperature and pressure levels (Paulsen & Enevoldsen, 2021; Pegoretti, 2021; Woo & Whale, 2022). This means that the properties of the blade waste will need to be closely monitored which is a challenge since the composition of these blades is always changing (Bernatas et al., 2021; Delvere et al., 2019; Olabi et al., 2021). Chemical recycling is a costly, complex process that would be a challenge to move to a commercial scale (Paulsen & Enevoldsen, 2021).

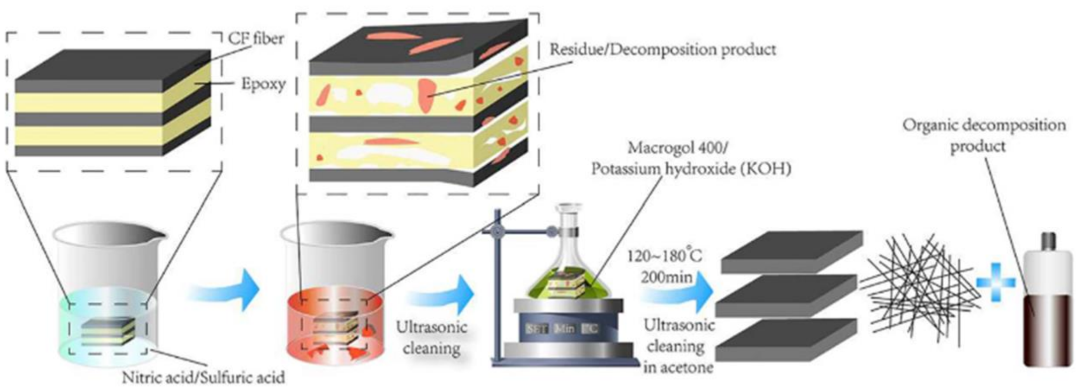

Figure 5. Diagram of the decomposition of carbon fiber composite using chemical recycling (Xue et al., 2022).

Thermal Recycling

There are three main types of thermal recycling: pyrolysis, microwave pyrolysis, and fluidized-bed combustion. However, the underlying principle stays the same for all processes. That is, high temperatures are used to degrade the polymer matrix and leave behind the fibers which can then be used again in later applications (Giorgini et al., 2020). Thermal recycling works for both thermoplastics and thermosets (Pegoretti, 2021). These processes also produce byproducts that can be used in other areas (Rani et al., 2021). However, thermal recycling cannot work on its own as the blades need to be shredded into small pieces to start the process. This multi-step process makes thermal recycling energy intensive (Beauson et al., 2022). Within this form of recycling, energy consumption can be anywhere from 20-90 MJ/kg (Gonçalves et al., 2022) However, some of that energy consumed can be recovered in the recycling processes (Xue et al., 2022). Yet, if thermal recycling is used solely for energy recovery, the materials are lost, and it produces polluting emissions and ash which can only be disposed of by the landfill. (Giorgini et al., 2020; Julian et al., 2022).

Pyrolysis is an industrial scale operation in which the composite is heated with no oxygen to 300-1000°C. A char product is formed after, and the fibers are recovered from within. (Delvere et al., 2019; Julian et al., 2022; Martinez-Marquez et al., 2022; Olabi et al., 2021; Zhang et al., 2020). In order to gain clean fibers for after use, a post-pyrolysis of the material is required to remove the char residue (Zhang et al., 2020). The temperature and time within this process need to be monitored and controlled so as to not damage the fibers further (Woo & Whale, 2022). The temperature of pyrolysis depends on the composition of the composite. Polyester resin decomposes at temperatures between 400 and 450°C, whereas epoxy resin decomposes at higher temperatures between 500 and 550°C. The higher the temperature- the more the fibers will degrade. 500-550°C was found to be optimal to separate the fibers and maintain strength. However, only 50% of the strength of the fibers remained, and this process requires high costs for proper infrastructure (Delvere et al., 2019; Korniejenko et al., 2021; Paulsen & Enevoldsen, 2021). The organic material is diminished into gases or pyrolysis oils (Julian et al., 2022; Senavirathna et al., 2022). The gas by-products can be used as fuel for combustion engines and other by-products like charcoal can be used in other applications such as for fertilizer (Woo & Whale, 2022)

Microwave pyrolysis is a similar process to pyrolysis, but instead, microwaves are used to separate the fibers (Delvere et al., 2019; Martinez-Marquez et al., 2022; Paulsen & Enevoldsen, 2021). Microwaves lie between infrared and radio frequencies (Zhang et al., 2020). This process occurs in a nitrogen atmosphere chamber and is carried out at temperatures between 300 and 600°C. The advantage of this process is that the material can be heated at the same temperature throughout. (Delvere et al., 2019; Paulsen & Enevoldsen, 2021). Additionally, the tensile strength for microwave pyrolysis is 75% which is higher than pyrolysis (Zhang et al., 2020). However, microwave pyrolysis is at a pilot scale and has limited ability (Julian et al., 2022).

Fluidized-bed combustion is a process in which the blade composite is converted into 20-30mm sized pellets. These pellets are then placed on a silica sand bed and heated to temperatures of 550°C in a fluid-bed reactor in the absence of oxygen (Delvere et al., 2019; Martinez-Marquez et al., 2022; Olabi et al., 2021; Zhang et al., 2020). The heat comes from a stream of hot air blown at a velocity of 0.4–1.0 m/s. The material is volatilized which separates the fibers from the filler. The particles are then suspended in a gas stream outside of the fluidized bed (Zhang et al., 2020). The shortened fibers are then collected from the hot gas upstream by a cyclone (Julian et al., 2022; Senavirathna et al., 2022; Zhang et al., 2020). The fibers are then transfer into another combustion chamber where it is fully oxidized (Zhang et al., 2020). However, this gas could be hazardous within this process (Gharde & Kandasubramanian, 2019; Korniejenko et al., 2021; Zhang et al., 2020). The quality of the fibers using this method is low, but it can obtain cleaner fibers than pyrolysis which is better for applications (Xue et al., 2022). Furthermore, the fluidized bed method also consumes lower energy amounts than pyrolysis (Krauklis et al., 2021) (Julian et al., 2022). This method can be used on mixed and contaminated materials which eliminate the need for extensive cleaning or sorting (Woo & Whale, 2022). Figure 6 below shows the different thermal recycling processes using composite material.

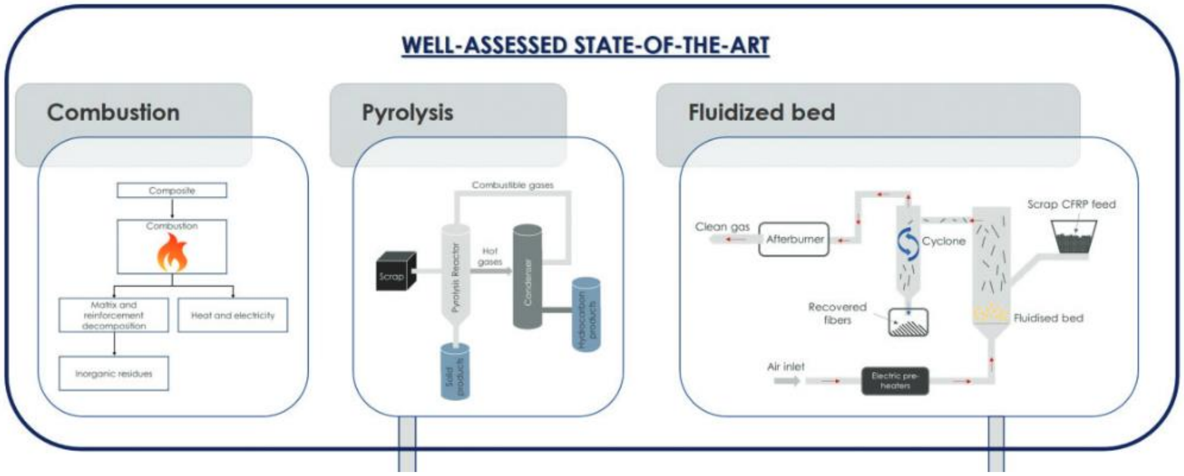

Figure 6. Diagrams of different thermal recycling processes using composite material (Gagliardi et al., 2021)

High-voltage fragmentation

High-voltage fragmentation was originally used to separate minerals from rocks, but researchers have since found that it can be used for the decomposition of composite material (Bernatas et al., 2021; May et al., 2021). High-voltage fragmentation occurs when 160kV are sent through two electrodes at a rapid pace in a vessel containing deionized water (Isa et al., 2022; Karuppannan Gopalraj & Kärki, 2020; Kharlov, 2022). This process, shown in Figure 7, occurs in temperatures above 104K and pressure between 109–1010 Pa to help lead to disintegration (Utekar et al., 2021). This procedure breaks down the fiber-reinforced polymers when the electric pulses are above 1μs (Maurice et al., 2021). The degree of fragmentation of the residual resin amount is based on the number and intensity of the pulses (May et al., 2021; Utekar et al., 2021). Glass fibers can be separated from the polymer matrix through this electromagnetic process (Majewski et al., 2022).

The energy consumption of high-voltage fragmentation is 2.6 times higher than mechanical recycling and 75-80% of the energy that is consumed during the process goes straight into the vessel containing the waste material versus the waste itself (Utekar et al., 2021; Zhang et al., 2020). Additionally, this recycling method is immature and needs more research to improve it (Gagliardi et al., 2021; Khalid et al., 2022). High-voltage fragmentation results in long clean fibers that can be reused. However, this method has low cost competitiveness and results in long clean fibers with low resin content and a strength retention rate of about 90% (Bernatas et al., 2021; Krauklis et al., 2021; Martinez-Marquez et al., 2022; Zhang et al., 2020). High-voltage fragmentation is also environmentally friendly as it does not emit many carbon emissions (Colombo et al., 2022). A challenge is finding applications for the fibers after processing, but it has been found useful as a concrete additive or as a base filament for 3-D printing (Korniejenko et al., 2021).

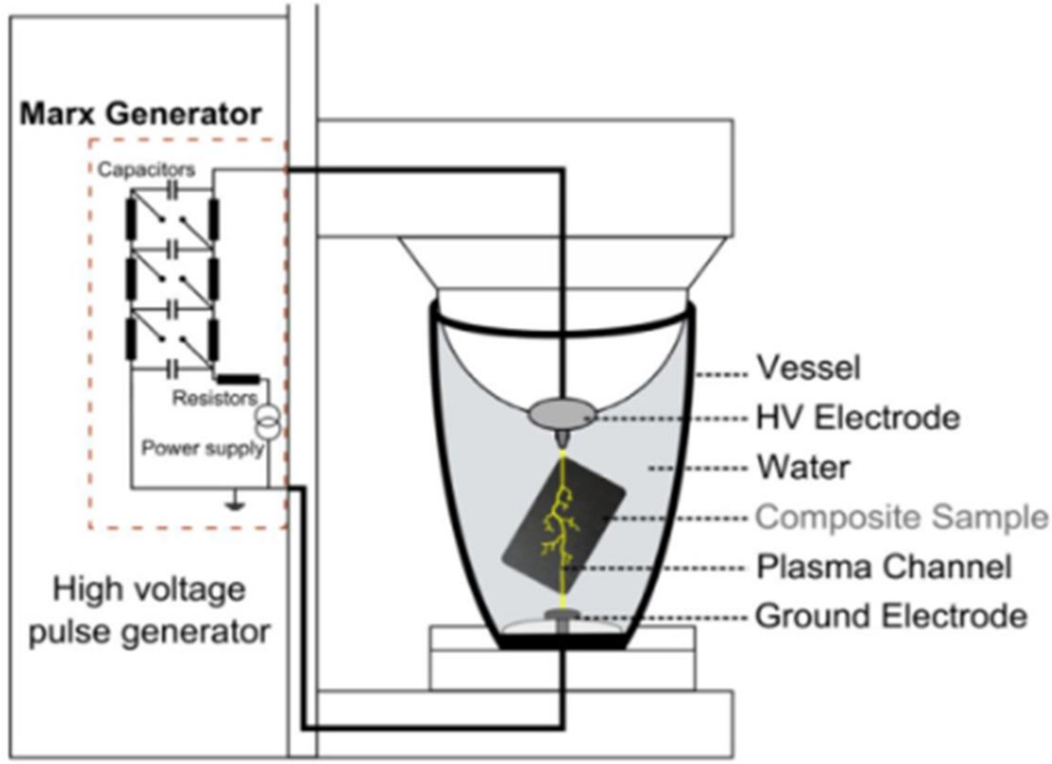

Figure 7. Diagram of the high-voltage electro fragmentation process at a laboratory scale (Bernatas et al., 2021).

Repurposing

Repurposing is a form of recycling in which the wind turbine blades can be used in other applications without having to be completely broken down. In Ireland, a bridge was constructed using two wind turbine blades. The bridge, shown in Figure 8, used the blades as a replacement for traditional railing and was placed over a 16-foot wide stream (Brandon, 2022). In Aalborg, Denmark, blades were transformed into bike sheds to protect bikes from the elements (designboom, 2021). This can be seen in Figure 9. Furthermore, researchers are identifying the plausibility of using wind turbine blades as utility poles, shown in Figure 10, as part of the BladePole project at Enel Green Power's Smoky Hills Wind Farm in Kansas, and a study done in 2018 identified a possibility of using decommissioned blades to create affordable housing (Bank et al., 2018; Gallucci, 2022). This is shown in Figure 11.

Figure 8. Wind turbine blades being used for the construction of a bridge in Ireland (Brandon, 2022).

Figure 9. Wind turbine blades being used as a bike shed in Aalborg, Denmark (designboom, 2021).

Figure 10. Rendering of wind turbine blades being used as utility poles as part of the BladePole project in Kansas (Gallucci, 2022).

Figure 11. Rendering of affordable housing built using parts of wind turbine blades (Bank et al., 2018).

Discussion

Table 1. Pros and cons of each recycling method.

Recycling Method	Pros	Cons
Mechanical	• Inexpensive • Environmentally friendly • Commercial Scale	• Shortened fibers • ≈ 50-65% strength retention
Cement Co-Processing	• Industrial scale • 100% material recovery • Environmentally Friendly • Inexpensive	• Not suitable for all composition types
Thermal: Pyrolysis	• Industrial Scale • Useful by-products	• Energy intensive • ≈ 50% strength retention • Costly
Thermal: Microwave Pyrolysis	• ≈ 75% strength retention	• Energy intensive • Laboratory Scale

	• Heated at the same temperature throughout	• Costly
Thermal: Fluidized Bed Combustion	• Clean fibers • mixed/contaminated materials	• Energy intensive • Environmentally hazardous gas product • Costly
Chemical	• Both resin and fibers can be recovered • ≈ 90-95% strength retention • High quality material	• Hazardous materials used • Costly • Complex process • Laboratory scale
High-Voltage Fragmentation	• Longer & cleaner fiber recovery • ≈ 90% strength retention	• Laboratory scale • Energy intensive
Repurposing	• Innovative	• Mainly Concepts • Doesn't account for large amounts of waste

The literature was able to identify many recycling options for wind turbine blade waste. However, there are pros and cons to each method. Mechanical recycling is an environmentally friendly option with the only concern being the inhalation of particulate matter that can easily be mitigated. To add, this process is inexpensive and is already being performed on an industrial scale. The downside of mechanical recycling is that it shortens the fibers that are recovered and only provides 50-65% tensile strength retention. Thermal recycling by pyrolysis could be industrial scale and create useful by-products, but it is energy intensive, costly, and the fibers only maintain 50% of their original strength. Thermal recycling through microwave pyrolysis has the ability to retain 75% of the strength within the fibers, but it is also energy intensive and costly. Furthermore, the method is currently only at a laboratory scale. Thermal recycling by fluidized bed combustion results in cleaner fibers and uses less energy over pyrolysis. Nevertheless, it is still costly in money and in energy resources. Plus, the process gives off an environmentally hazardous gas product. Chemical recycling is the best option for maintaining high quality as 90-95% of strength is retained and both resin and fibers can be recovered, Despite that, this method would be a challenge to turn into an industrial scale production. This is because of the hazardous materials that are used and the complex process of identifying which chemicals to use based on the composition of the wind turbine blade. High-voltage fragmentation is also a good method for maintaining quality as it maintains the original strength by 90% and results in long and clean fibers. Yet, this method is only laboratory scale and is extremely energy intensive as it would require 2.6 times more energy than mechanical recycling. Repurposing wind turbine blades brings a lot of new innovative ideas, and it would help bring practices like recycling to the public eye. However, many of these ideas are only concepts with further research needed to be implemented, and it doesn't account for the large amount of waste that these wind turbines are providing.

Based on comparison, cement co-processing is the best method for recycling wind turbine blade waste when it reaches its end-of-life. This is because of its ability to recover 100% of the material within the composite of the blade. Additionally, since some of the organic material within the makeup can be used as a fossil fuel alternative, cement co-processing can aid in decreasing carbon emissions. Furthermore, this method is inexpensive and doesn’t require a lot of additional energy. This is because cement processing plants are already placed throughout the United States so adding a couple of extra processing steps to these plants should not require a ton of infrastructure to do so, unlike other methods.

Conclusion

The aim of this study was to conduct a systematic literature review using specific search parameters to identify recycling options for wind turbine blade waste. I was able to find that there were multiple options for landfill diversion. Of those options, cement co-processing was found to be the best recycling option for decommissioned blades. Implementing this method throughout the United States would significantly help decrease the amount of waste going to landfills or being incinerated. For future studies, I would recommend that the search terms used be defined more, as I found that many articles did not apply to the study I was conducting. Additionally, further research could be done on the economic feasibility of each option as the literature analyzed did not go in-depth about this topic, and I believe that it is a main factor in determining the implementation of these recycling methods.

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