Green Roof Team
Sustainably Green Solutions

Life Cycle Assessment of Small Wind Turbine Blades: Environmental Impact and Sustainability

Author: Tess Obuchowski

Table of Contents

I. Introduction

Wind turbines are one of the most widely used forms of clean energy as they are capable of generating high magnitudes of power for a relatively low cost. They produce 5 - 26 grams of emissions per kWh of energy generated, while traditional power plants produce 436 - 758 grams. Once installed, they produce zero carbon emissions and make back the energy used to manufacture them within 7 months of installation [1]. With a lifespan of 20-25 years, wind turbines are a critical aspect of reducing global carbon emissions and building a greener future.

Small wind turbines – frequently used in urban areas or for meeting individual energy needs – are expanding where we can take advantage of wind energy and making clean energy solutions more accessible to the public. However, new environmental concerns arise as more and more turbines reach their end of life. In 2018, U.S. blade waste totalled 50,000 tons, most of which ended up filling valuable landfill space. By 2050, that number could be between 200,000 and 370,000 tons per year [2]. Additionally, manufacturing and transportation produce emissions and use up raw materials. If wind turbines are going to help the climate crisis, steps must be taken to reduce emissions, increase longevity and improve end of life solutions.

II. Lifecycle Stages

The lifecycle of a wind turbine consists of four primary stages: production, construction, use, and end of life. Production encompasses all material processing and manufacturing of individual components, such as the blades, tower, and internal generator and other electrical machinery. By mass, turbines are 66-79% steel, 11-16% fiberglass or other composite, 5-17% iron and less than 1% of both copper and aluminum [3]. While these raw materials are all widely available, processing them creates the majority of carbon emissions associated with wind turbine production. Processing one ton of steel from raw materials emits approximately 1.4 tons of CO_2, and the global steel industry is responsible for 11% of all CO_2 emissions [4]. One ton of glass fiber has a carbon footprint of 1.7-2.2 tons [5].

Most emissions associated with construction arise from transportation costs. The larger the turbine, the more difficult it is to transport. During its use, wind turbines produce no excess emissions and require only a few extra materials for maintenance.

End of life presents the biggest environmental concern. Most turbines have a lifespan of 20-25 years, which can be marginally increased by replacing parts and constructing with durable materials. Eventually, the turbine will need to be decommissioned and replaced, and transporting the old turbines creates additional CO_2 emissions. Traditionally, turbine blades have been put into landfills at their end of life, taking up valuable space with waste that will not decompose. Regarding recycling solutions, fiberglass is a composite, a combination of thin glass fibers and an epoxy resin or similar plastic, and separating these two materials requires a lot of energy. Additionally, fiberglass's high strength – one of the reasons it's best suited for use in turbines – makes it difficult to break apart and repurpose. The recycling process is complex and not yet feasible on a large scale. Other alternatives to landfilling present their own challenges as well.

Over the course of a lifespan, wind turbines can create 1.2 million kilograms of CO_2 during material production, another 100,000 in the manufacturing of materials, and 10-15 thousand kilograms each for transportation, use and end of life [6]. Since transportation costs are difficult to eliminate, production and end of life are the two lifecycle stages with the flexibility for reducing environmental impact.

III. Environmental Impact Indicators

In order to conduct an informative lifecycle assessment, impact indicators are used to focus analysis and quantify environmental consequences. According to a handbook on analyzing existing environmental assessment methodologies, the primary impact indicators are "climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related) respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion" [7]. Since the necessary materials are found in abundance, resource depletion is not yet a major concern. Climate change is the most relevant indicator for wind turbines, and some land use issues can also arise.

Climate change is quantified by kg CO_2-eq, and indicates how a process contributes to global warming by greenhouse gas emission. The kg CO_2-eq unit accounts for emissions like methane that also contribute to climate change. Land use measures the impacts of occupying, reshaping and managing land, and can be measured using the hemeroby index, which indicates the magnitude of deviation from potential natural vegetation [8]. Avoiding turbine installation in wetlands and other sensitive ecological areas will eliminate land use concerns [9].

IV. Material Selection and Design Strategies

Table 1: Large turbine energy and CO_2 emissions for all life cycle stages, specifically comparing landfilling versus recycling metal components [6].

End of Life – Landfill

Phase	Energy (J)	CO2 (kg)
Material	1.7594E+013	1.2546E+006
Manufacture	1.3593E+012	107669.7209
Transport	2.4336E+011	17278.6954
Use	1.6778E+011	11912.5577
End of life	2.1826E+011	13095.7080
Total	**1.9583E+013**	**1.4045E+006**

End of Life – Recycling

Phase	Energy (J)	CO2 (kg)
Material	1.7594E+013	1.2546E+006
Manufacture	1.3593E+012	107669.7209
Transport	2.4336E+011	17278.6954
Use	1.6778E+011	11912.5577
End of life	-6.8512E+012	-495917.2797
Total	**1.2513E+013**	**895503.8906**

Sustainable material design requires both environmentally conscious sourcing and disposal. 85% of turbines are recyclable metal, leaving a wide window of opportunity for saving energy [10]. Steel, which accounts for the majority of the turbine by mass, is one of the most recycled materials, with 69% of waste recycled annually [11]. Shown in Table 1, recycling the metal components of turbines at their end of life saves roughly 36% of the energy and CO_2 emissions. Steel, along with the other metals used in turbines, can be continuously recycled without damaging its properties, and recycled steel saves roughly 75% of the energy needed to produce it from raw materials [11]. Using recycled materials for the construction of wind turbines and recycling those same materials again at the end of life creates a circular economy, saving energy, money and the environment.

The fiberglass composite used in the blade shells presents more of a challenge. While there are many benefits to fiberglass – low energy cost, lightweight, easy to transport, abundant and long-lasting – it trades durability for recyclability [12]. There are multiple methods of recycling and repurposing, which will be elaborated on in the following section, but none offer a fully viable solution to the growing blade waste. Though fiberglass is used in roughly 80% of turbines, carbon fiber is a common alternative. It increases blade stiffness, and has a higher strength-to-weight ratio, though it is significantly more expensive and equally difficult to recycle [13]. Rather than replace the fiber, changing the type of resin could also improve recyclability. Thermoplastic resins are able to be reheated and remolded after curing, unlike the commonly used thermoset resins, and can make it easier to separate the resin and raw fibers for recycling [14].

Another alternative to fiberglass is natural fiber composites, which consist of any natural fiber that can be woven into thin filaments, including hemp and flax. Compared to fiberglass, certain natural fibers achieve equal or superior mechanical properties and are biodegradable [15]. Regarding emissions, natural fibers have a carbon footprint of 0.5 - 0.7 tons CO_2-eq per ton of fiber, roughly a quarter of the emissions of glass fibers [5]. Natural fibers do present a few challenges with availability and compatibility with current manufacturing practices, so implementing natural fibers on a large scale would require investment and adaptation [16]. However, for small scale wind turbines, they can help limit carbon emissions related to material process and reduce nonbiodegradable waste.

V. End-of-Life Considerations

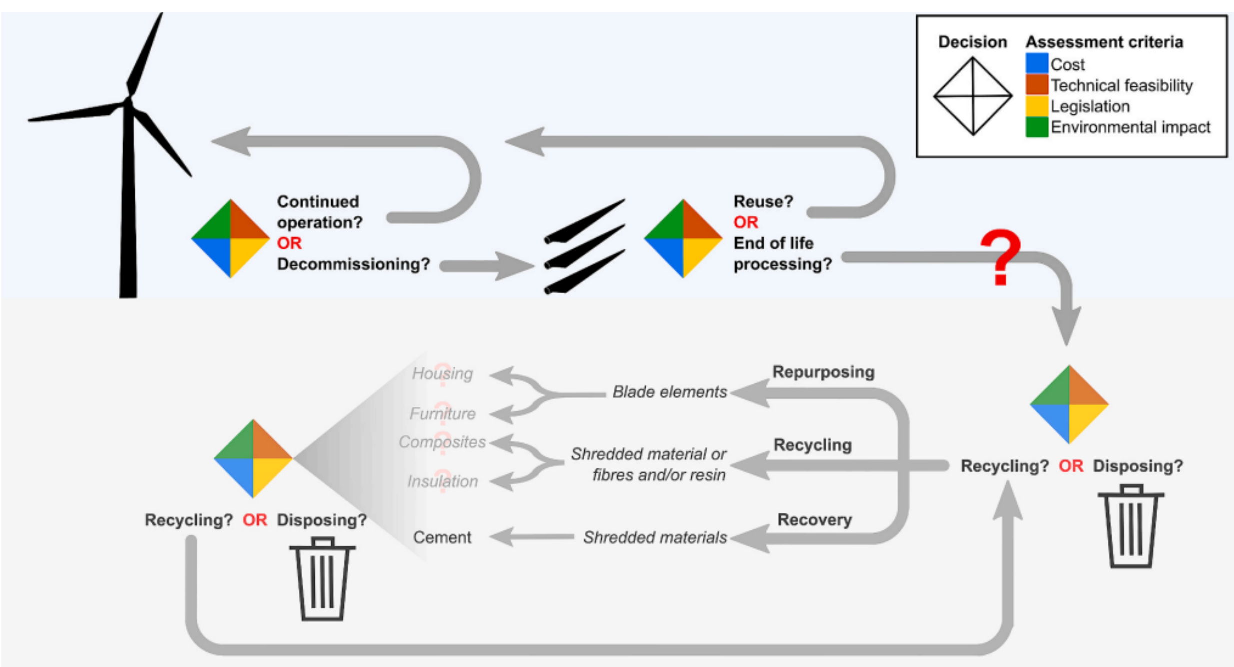

Figure 1: Flow chart illustrating end of life decision making for wind turbine blades [17]

Decisions	Economic	Technical feasibility	Legislation	Environmental impacts
Decommissioning OR continued operations?	Is it profitable to continue operating the turbine?	What is the damage state of the wind turbine blades?	Can the turbine continue its operations where it is installed?	What are the environmental impacts of continuing the operations vs decommissioning?
Reuse OR end-of-life processing?	Can the blade be sold as spare parts?	What is the damage state of the wind turbine blades?	Are there legislation preventing reuse (second hand market)?	What are the potential environmental impacts of extending the lifetime of the blade by reusing it?
Recycling OR disposing?	What is the landfill tax? What is the value of the materials in the wind turbine blades and the recycled ones?	Is it possible to recover materials with properties and quality valuable to any applications?	Are there legislation preventing landfill? Are there legislation on the use of recycled wind turbine blade materials for targeted applications?	What are the potential environmental benefits and impacts of recycling the blades *vs.* disposing them?

Figure 2: Overview of assessment criteria used for Figure 1 and related questions [17]

As illustrated by Figures 1 and 2, there are many paths the fiberglass components of wind turbines can take at their end of life. If, for example, a turbine was decommissioned due to upgrading technology and the blades are still functional, they can be sold and reused in other locations. If the turbine was decommissioned due to damage or quality issues, however, it goes into end-of-life processing, in which it can be landfilled, repurposed, recycled, or recovered [17].

Landfills are the most common destination for end-of-life blades, though, as mentioned previously, they take up valuable space and do not decompose. To increase sustainability, alternatives must be considered and improved. Repurposing encompasses any second life use of the structures, including building playgrounds, benches, or affordable housing [14]. It often requires the least amount of processing, and therefore offers the most environmental gain, especially since blades can potentially see third or fourth lives before being recycled further or disposed [18]. However, blade waste outweighs the demand for repurposed structures, making repurposing only part of a solution.

Another method of repurposing fiberglass waste is cement co-processing. The waste is shredded and burned in a cement kiln, effectively reducing the need for raw materials, both as fuel and in the cement itself, as the leftover fibers and ash replace sand and chalk [19]. The materials and energy are recovered, but some economic value is lost [14]. A life cycle assessment on decommissioned wind blades determined coprocessing to be the most immediately environmentally beneficial [18]. Recovery of energy by using waste as fuel is integrated into coprocessing, though it can also be a separate method of recycling. It reduces the volume of waste and helps save landfill space, although harmful byproducts are released in the process [14]. In terms of reducing CO_2 emissions and saving energy, recovery and co-processing are more advantageous than landfilling, as they make use of the energy stored in the blade waste.

Existing recycling methods for fiberglass have yet to be perfected. One method is mechanical recycling, where composite is crushed or ground into granulate-like materials in order to be incorporated into other composites. It requires a lot of processing steps, and the materials lose many of their advantageous properties along the way [18]. However, it doesn't require separation of the resin and fibers, and the recycled powder is well suited for products with less specific material demands, like plastic lumber or sound-absorbing panels [14]. Thermal recycling, or pyrolysis, involves heating the composite to separate the fibers from the resin matrix. The primary benefit of pyrolysis is that the fibers are able to be recovered with up to 70% of their original strength, though they are more expensive than virgin fibers [18]. Chemical recycling has similar benefits, using a solvent to break the matrix bonds and recover both the fiber and polymer. Similar to pyrolysis, the materials suffer in quality after recovery and are limited in application. Additionally, large volumes of chemicals are required, making it difficult and expensive to scale-up. If these hurdles are overcome, and large enough markets are found for the recycled materials, chemical recycling could reduce environmental impacts up to 44% compared to landfilling [14].

Ultimately, extending the lifespans of existing turbines by replacing worn parts is the best way of reducing waste and environmental impact. Though older blades require more maintenance, extending blade life by 5 years creates enough energy that life cycle impacts are reduced by 24% [14]. Small wind turbines face another hurdle for end of life, which is consolidating waste for recycling. All end of life options become increasingly inefficient the more transportation is required. Small turbines have less waste, and are spread out over larger distances compared to traditional wind farms. Until small wind turbines become commonplace in urban areas, it will be difficult to implement feasible recycling systems.

VI. Case Studies

Figure 3: Images of horizontal axis wind turbine (left) and vertical axis wind turbine (right).

Small wind turbines have great potential for urban areas as they minimize energy lost to transmission. A 2017 study at Clark University compared the power output of horizontal (HAWT) and vertical (VAWT) axis turbines, two rivaling designs for small turbines shown in Figure 3. HAWTs are more commonly used, as they are more efficient at generating power. The study confirmed that the HAWT generated roughly 55% more energy, but claimed VAWTs may be better for urban environments. They are better at tracking wind changes, capable of generating energy from lower wind speeds and display greater durability [20]. VAWTs are generally seen as a good design for low power demands, urban applications, and the decentralization of energy generation [21], while large HAWTs are best for generating large quantities of energy in rural environments.

A case study in Prishtina, Kosovo looked at the benefits of urban wind turbines, and whether they generate enough power to make a substantial impact. A 300W HAWT was installed, and produced 189 kWh over 2019 with negligible emissions. Due to low wind speeds, it only produced electricity around 30% of the time, which could be improved with the use of VAWTs. With electricity demands of 5000 GWh for the nation of Kosovo, all of which is generated by two power plants, lots more turbines would be required to make a significant impact. However, the case study presents energy transmission as one of Kosovo's primary problems, and states that installing 100 similar wind turbines to power lighting for parks and streets could reduce CO_2 emissions by 44000 kg per year [22].

The type of generator used in a wind turbine greatly affects the sustainability of the design. One case study compared direct-drive permanent magnet synchronous generators (PMSG) with doubly-fed induction generators (DFIG) [23]. DFIGs are the most common type of generator, while PMSGs are more compact, have a lower maintenance cost and higher energy efficiency at low speeds. However, PMSGs have magnets that require rare earth elements, which can be challenging and unethical to source. The study compared the different generators at each lifecycle stage, and ultimately determined DFIGs to have a more positive sustainability impact, despite the higher efficiency and reliability of PMSGs.

Several different methods of fiberglass recycling are already being tested and implemented throughout the globe. The company Carbon Rivers recently found success in scaling up the pyrolysis process [24]. The recycled fibers are 99.9% pure and show minimal degradation in their properties, so they can either be mixed into new composites or remelted and used to make new fibers. Carbon Rivers is currently capable of recycling over 50,000 tons of fiberglass waste per year. Germany has been implementing cement co-processing for decommissioned wind turbine blades since 2005 [19]. By replacing coal as fuel and substituting raw materials with waste glass fibers, the CO_2 output of the cement process has been reduced by 16%. One company, Veolia, is capable of processing 30,000 tons of glass fiber annually.

New material alternatives are also showing promising developments. At UC Davis, professor Valeria La Saponara is constructing turbine blades using bamboo and mycelium, which are both fast-growing and compostable organic materials [25]. The design is still in the testing stages, but it has the potential to combat growing blade waste, reduce emissions associated with manufacturing, and make material sourcing simpler.

VII. Policy and Regulations

In the U.S., waste management falls under the jurisdiction of the Environmental Protection Agency (EPA). Under the existing guidelines, reduction and reuse of waste is prioritized, followed by recycling, recovery, then disposal. There is a landfill tax to discourage blades from being disposed of, but no official landfill ban. Currently, the cost of recycling is still higher than landfilling, meaning there is little incentive for companies to look for recycling solutions [17].

Despite technological advancements, the future of wind energy ultimately rests in government legislation and investment. For blade waste management, extended producer responsibility can help mitigate any financial loss from recycling. Extended producer responsibility allows the government to shift the responsibility of disposal and waste management from the consumer to the manufacturer, legally ensuring products get recycled at end of life [17]. Governments are also capable of offering financial incentives for building more recyclable blades, pushing companies towards more sustainable solutions.

Another major legislative concern for wind turbines is zoning. Since small turbines operate in more urban environments, safety, sound level, aesthetics, and communal interest all affect whether a location is suitable for a wind turbine [26]. Local zoning codes for personal turbines can be difficult to navigate for individual families and greatly restrict where turbines can be built. Rooftop turbines in populated areas are greatly restricted by public opinion, as many view them as eyesores for their community. Without the encouragement and support of both government legislation and the public, turbines will be difficult to implement on a large scale and even more difficult to recycle at end-of-life.

VIII. Conclusion

Although wind turbines show great potential in producing carbon-neutral energy, they produce emissions during manufacturing and are difficult to handle at end of life. By taking advantage of the continuous recyclability of metals, continuing to develop and scale-up composite recycling, and encouraging investment through legislation, it is possible to reduce wasted materials and energy, stave off future environmental concerns, and make the most of a turbine's lifespan. Existing and emerging technologies, like natural fibers and co-processing, will continue to improve an already beneficial technology, and installing small wind turbines in both urban and rural areas will reduce transmission costs and improve energy accessibility. With further developments to improve sustainability and efficiency, wind turbines will be ready to meet growing demand for clean energy.

References

1. https://yaleclimateconnections.org/2021/06/whats-the-carbon-footprint-of-a-wind-turbine/
2. https://windexchange.energy.gov/end-of-service-guide#:~:text=The%20average%20rate%20of%20retirements,lives%20(see%20Figure%2013)
3. https://www.usgs.gov/faqs/what-materials-are-used-make-wind-turbines
4. https://www.sustainable-ships.org/stories/2022/carbon-footprint-steel#:~:text=Steel%20carbon%20footprint&text=The%20IEA%20estimates%20that%20direct,of%20CO2%20per%20ton%20steel
5. https://library.wur.nl/WebQuery/titel/2100133#:~:text=The%20production%20of%201%20tonne,excluding%20transport%20to%20the%20customer
6. https://www.researchgate.net/publication/221926189_Life_Cycle_Analysis_of_Wind_Turbine
7. https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf
8. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Hemeroby_index#:~:text=The%20hemeroby%20index%20measures%20the,increase%20of%20the%20human%20influence
9. https://www.windustry.org/land_considerations
10. https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling/
11. https://www.rubicon.com/blog/steel-recycling/
12. https://citizensustainable.com/fiberglass/
13. https://www.energy.gov/sites/prod/files/2019/12/f69/SAND2019-14173-Optimized.pdf
14. https://www.sciencedirect.com/science/article/abs/pii/S092134492100046X
15. https://www.sciencedirect.com/science/article/abs/pii/S2214785317322757
16. https://www.compositesworld.com/articles/natural-fiber-composites-whats-holding-them-back
17. https://www.sciencedirect.com/science/article/pii/S136403212101114X
18. https://www.sciencedirect.com/science/article/pii/S0301479721020569
19. https://cementassociation.ir/library/Co-ProcessingMagazine/202101.pdf
20. https://commons.clarku.edu/idce_masters_papers/127/
21. https://www.sciencedirect.com/science/article/pii/S1364032118301254
22. http://www.rericjournal.ait.ac.th/index.php/reric/article/view/2736/pdf
23. https://www.sciencedirect.com/science/article/pii/S0195925522002098
24. https://www.energy.gov/eere/wind/articles/carbon-rivers-makes-wind-turbine-blade-recycling-and-upcycling-reality-support
25. https://engineering.ucdavis.edu/news/project-mushrooming
26. https://windexchange.energy.gov/small-wind-guidebook#practical