



Life-Cycle Assessment Considerations of **Offshore Wind Turbine Blades**

by Christopher Whitehead

A look at the design, composition, and sustainability of wind turbine blades.

It's been a busy few years for the offshore wind (OSW) industry in the United States. Since Block Island wind farm—a small pilot project off the coast of Rhode Island consisting of four turbines—became operational in 2016, the industry has seemingly taken leaps each year to now be close to exponential domestic growth. There are currently 16 OSW projects¹ in development along the U.S. Atlantic Coast, with further lease areas planned for the Gulf of Mexico, California, Oregon, and even perhaps the Great Lakes. These projects are a central focus of President Biden's recent push to decarbonize our domestic power sector, and each one holds the potential of removing thousands of tons of carbon dioxide equivalent (CO₂e) emissions from our domestic power matrix each year. These emission savings are generally calculated by using the Bureau of Ocean Energy Management's (BOEM) Emissions Estimating Tool.²

However, to fully understand the environmental impacts of this technology, we would have to perform a detailed life cycle analysis exploring things like raw material uses, transportation, and disposal. For the purpose of this article, we will focus on one of the most prominent symbols of the industry: turbine blades. What materials are they made from, how are they transported to and from installation points, and how are they disposed of once they have reached the end of their useful life? Many of the answers to these questions will come via Europe as the region has about a 30-year head start on the U.S. market and is actively addressing

logistical issues that we will not have to face for years. Let's learn from them.

Composition

It is important to understand what goes into these massive turbine blades. While each blade producer has their own proprietary materials blend, the lion's share (by mass) will be made up of various composites. As you will see in Figure 1, the blades are hollow yet rigid and often composed of aluminum, copper, carbon fibers and various epoxies and urethanes. Luckily, none of these materials are especially difficult to source, but they are difficult to recycle since they are composites. Due to their impressive size (~45–55 m) and gravitational and weather-related forces put on them, the blades each must be massive, strong, yet also flexible to a degree.

OSW projects are permitted for a useful life of between 25–30 years, and the blades can last 20 years, but are usually changed around 10 years, if not sooner, due to potential minor damage.³ Developers aim to minimize these replacements, but if they cannot, as you will see from Figure 2, the next steps down the blade waste management hierarchy include reuse, repurposing, recycling, recovery, and disposal. Major project developers commit to waste minimization processes based on this hierarchy and assume responsibility for their turbine components through the project lifespan and decommissioning.⁴

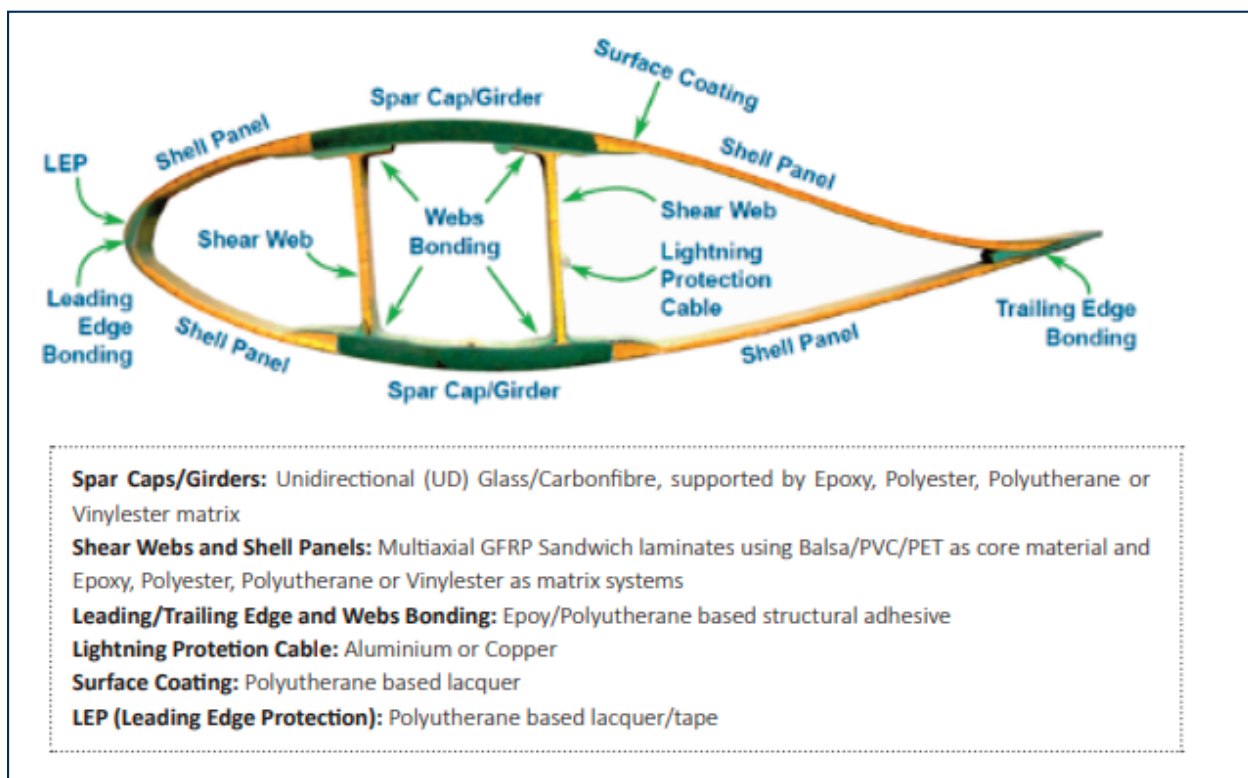
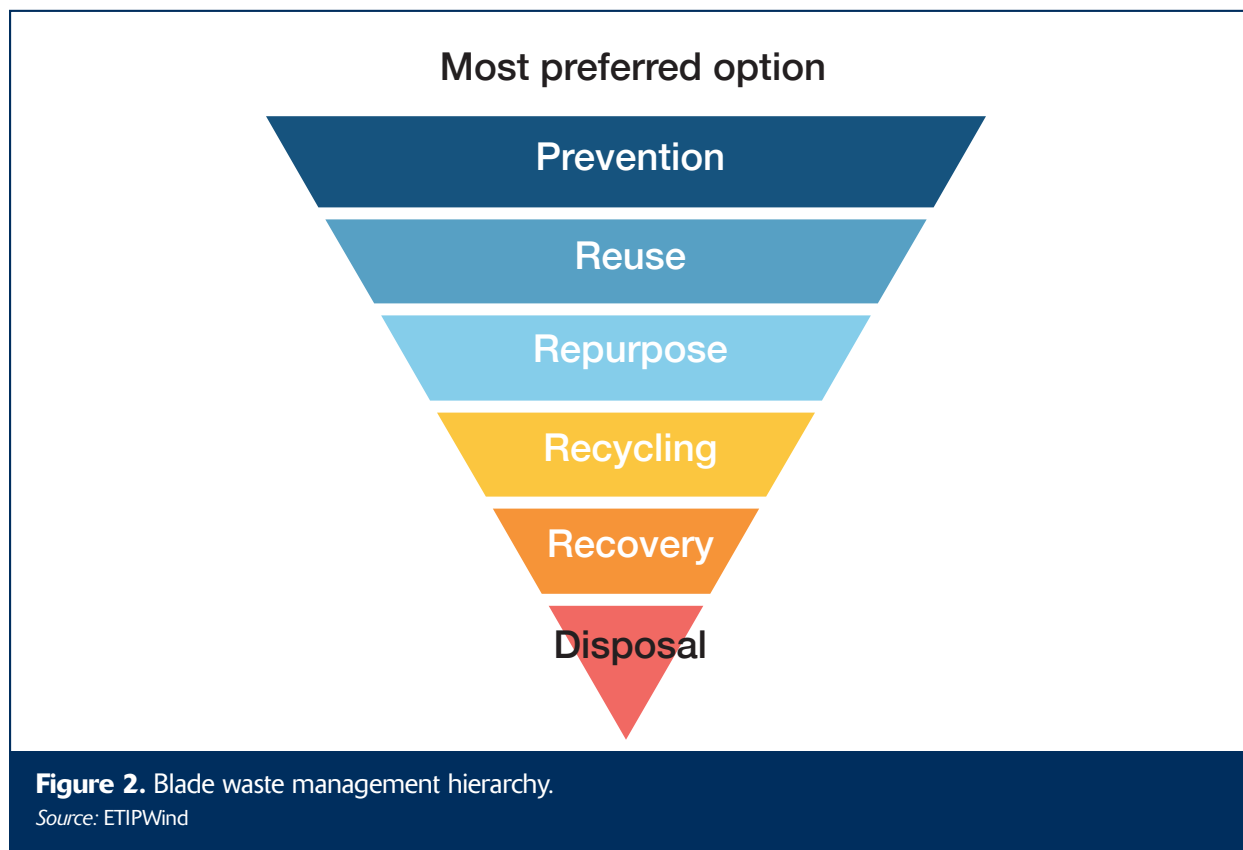


Figure 1. Typical composite cross section of a wind turbine blade.



Transportation

Next, let's discuss transportation. These blades are quite large and heavy. Due to these fundamental characteristics blade manufacturing is ideally performed close to potential need. While there is some established domestic blade manufacturing capability,⁵ most OSW blades are currently produced outside the United States. The U.S. Department of Energy (DOE) is trying to change that.⁶ This fabrication process can be very costly and labor-intensive, but a partnership between DOE, Sandia National Laboratories, TPI Composites, and Iowa State University helped establish advanced techniques that reduce the time it takes to produce a single blade by approximately 37% (from 38 to 24 hours). DOE is also investigating the 3D printing of blade molds, which could save time and money during the blade development process.⁷ Turbine blades must be able to maintain their strength and aerodynamic structure during virtually non-stop operations for over 20 years. Closed-loop recycling of end-of-life wind turbines could supply a maximum of between 3% and 12% of total material demand for offshore wind energy from 2020 to 2030, and 2030 to 2040, respectively.⁸

If being transported from overseas, it will mean the utilization of specialized transport vessels that are Jones Act-endorsed;⁹ many believe that this is a likely bottleneck area as there is a finite number of capable and available vessels working on the same pool of ongoing projects. From an air emissions perspective, this is problematic as older vessel

models are more likely to consume heavy fuel oil (HFO; compared to marine gas oils [MGO] or marine diesel oils [MDO] for newer vessels), which has elevated emissions of oxides of nitrogen, particulates, and sulfur dioxide.¹⁰ Transport via land routes would be minimized for offshore wind projects through the use of marshaling ports and whenever possible direct transport to turbine installation sites.

Similarly, any domestic manufacturing of turbine components will likely take place in close proximity to major ports, as we have seen in the EEW monopile manufacturing facility recently built in Southern New Jersey to coincide with operations at the New Jersey Wind Port in Salem County.¹¹ Maintenance operations are expected to be ongoing through the life of each project and involve crew transfer vessels (CTVs) and various barges to move turbine components to and from installation sites, which average approximately 15–25 nautical miles from the continental United States and are stationed on various points across the outer continental shelf. Current CTVs usually consume distillates, which have lower emissions profiles, but collectively are still quite impactful throughout the maintenance lifespan of these turbine blades.

Sustainability

Finally, despite being challenging to recycle due to their composition and immense size, there are numerous examples of innovative solutions that have the potential to keep the blades from being landfilled. As an example, there are firms in Denmark¹² that shred the used blades into fist-sized

End-of-Life Approach: Composite Recycling Technologies of Existing Blades

1. Provide funding for research study comparing the economic viability of new recycling technologies, including market barriers associated with different end users.
2. Set up large-scale demonstration facilities to industrialize and scale-up new recycling solutions for wind turbine blades.
3. Provide funding to support new manufacturing processes using recycled materials from blades in other sectors.
4. Establish a cross-section platform (including the building, transportation, and energy sectors) to share best practices in recycling composites.
5. Promote reinforcement of value chain for recycling of composite waste from all sectors.

Design Approach: Development of New Materials for Future Blades

1. Earmark funding for the development of new high-performance materials that are more easily recyclable.
2. Support demonstration facilities to test and integrate newly developed sustainable materials in next-generation wind turbine blades.
3. Fund research into “smart” materials that enable better blade design. In addition, embed sensors in turbine blades to enable material health monitoring and forecasting capabilities.
4. Establish a full-scale demonstration of next-generation wind turbine technology using “smart” materials that help optimize maintenance and increase lifetime.
5. Encourage blade designers to consider recycling technologies and reuse options during design and development.

Figure 3. Blade design options.

Source: Accelerating Wind Turbine Blade Circularity (May 2020). Wind Europe.

chunks that are later used as aggregate for cement, reducing carbon dioxide emissions by 27% and water consumption 13% compared to traditional cement production. Other processes have been developed through pyrolysis to decompose composite resins into hydrocarbon gasses and liquids and glass fibers, all of which hold resale value.¹² However, there is considerable material loss through this process, as well as fiber degradation due to the intense heat involved in the process, above 300 °C.

On a micro scale, we have also seen companies repurpose spent OSW blades into shelters. However, despite these promising minor reuse options, and the fact that between 85–95% of raw materials in the blades can be recycled, there is not yet scalability and the vast majority of spent turbine blades used to date have ended up in landfills.¹³ This is problematic for many reasons not the least of which is that useful space inside landfills is a valuable commodity. Many around the world are nearing capacity and potential new space only becomes available as older biodegradable wastes

decay, letting off CO₂, methane, nitrogen, ammonia, sulfides, and other gases.

Looking to Europe

The European markets have been taking the lead on many of these issues and are further along in solution development since their OSW industry has been growing for decades. As Figure 3 details, there are two main thought centers on these topics, an end-of life approach that recycles existing blade materials, and a design approach that develops new materials for future blades. Initial funding considerations went to the former but as recycling challenges became more apparent, funding also began to flow toward the latter, and the implementation of less material intensive blade constructions.¹⁴

Optimistic projections have the bulk of commercial scale OSW projects currently in development in the United States coming online toward the end of this decade, sometime around 2026 or 2027. By that time, it is reasonable to

assume there will be progress on the blade recycling and repurposing issue as industry recognizes the need and is investing⁴ and the federal government has increased investment in green energy projects through the Inflation Reduction Act

and Bipartisan Infrastructure Law.¹⁵ Some people see bottlenecks, some see potential opportunities, but perhaps most importantly each provides a chance for innovation toward the development of less environmentally impactful processes. **em**

Christopher Whitehead, QEP, CESM, is an Air Practice Leader in Environmental Consultation and Remediation with Enviro-Sciences (ESI), certified SBE in New Jersey, and a member of *EM's* Editorial Advisory Committee.
Email: cwhitehead@esienv.com.

References

1. Bureau of Ocean Energy Management. Lease and Grant Information; <https://www.boem.gov/renewable-energy/lease-and-grant-information>.
2. Bureau of Ocean Energy Management. Offshore Wind Energy Facilities Emission Estimating Tool, Version 2.0; <https://www.boem.gov/sites/default/files/documents/about-boem/BOEM-Wind-Power-User-Guide-V2.pdf>.
3. Nielsen, J.S.; Sørensen, J.D. Bayesian estimation of remaining useful life for wind turbine blades; *Energies* 2017, 10 (5), 664.
4. Ørsted. Ørsted commits to sustainable recycling of wind turbine blades; Ørsted, Denmark, 2021; <https://orsted.com/en/media/newsroom/news/2021/06/702084352457649>.
5. Lenett, R. Wind Turbine Blade Manufacturers in USA; MicrogridMedia.com (August 5, 2022); <http://microgridmedia.com/wind-turbine-blade-usa/>.
6. Wind Manufacturing and Supply Chain; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; <https://www.energy.gov/eere/wind/wind-manufacturing-and-supply-chain>.
7. Transforming Wind Turbine Blade Mold Manufacturing with 3D; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; <https://www.energy.gov/eere/wind/videos/transforming-wind-turbine-blade-mold-manufacturing-3d-printing>.
8. Li, C.; Mogollón, J.M.; Tukker, A.; Dong, J.; von Terzi, D.; Zhang, C.; Steubing, B. Future material requirements for global sustainable offshore wind energy development; *Renewable and Sustainable Energy Reviews* 2022, 164, 112603; <https://doi.org/10.1016/j.rser.2022.112603>.
9. Customs Issues Comprehensive Offshore Wind Jones Act Ruling, 2022; Winston and Strawn LLP; <https://www.winston.com/en/maritime-fedwatch/customs-issues-comprehensive-offshore-wind-jones-act-ruling.html>.
10. Bunker fuel (Marine Gas Oil) Explained – An easy guide; Crown Oil Fuels and Lubricants; <https://www.crownoil.co.uk/guides/bunker-fuel-guide/>.
11. EEW American Offshore Structures; <https://eew-group.com/locations/eew-aos/>.
12. Jacoby, M. How can companies recycle wind turbine blades?; *Chemical & Engineering News* 2022, 100 (27); <https://cen.acs.org/environment/recycling/companies-recycle-wind-turbine-blades/100/i27>.
13. Cooperman, A.; Eberle, A.; Lantz, E. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options; *Resources, Conservation, and Recycling* 2021, 168, 105439.
14. Wind Europe. Accelerating Wind Turbine Blade Circularity (May 2020)
15. Production Tax Credit and Investment Tax Credit for Wind Energy; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; <https://windexchange.energy.gov/projects/tax-credits>.



In Next Month's Issue... Transportation Emissions

The July issue will focus on transportation emissions: How recent U.S. federal, state, and local legislation and regulations can reduce emissions to improve air quality and public health, and the potential climate trade-offs.