Life Cycle Assessment and Life Cycle Cost Analysis of Repurposing Decommissioned Wind Turbine Blades as High-Voltage Transmission Poles

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Abstract: Wind energy is widely deployed and will likely grow in service of reducing the world's dependency on fossil fuels. The first generation of wind turbines are now coming to the end of their service lives, and there are limited options for the reuse or recycling of the composite materials they are made of. Current literature has verified that there is no existing recycling pathway (i.e., mechanical, chemical, thermal methods of recovery, etc.) for end-of-life materials in wind blades that can meet cost parity with landfilling in the US. However, to the authors' knowledge there is no study to date that uncovers the cost structures associated with repurposing wind turbine blades in the US. Repurposing could offer a cost-competitive advantage through displacement of higher-value products, rather than materials or chemical constituents alone. This study implements life cycle assessment (LCA) and life cycle cost analysis (LCC) to assess the environmental and financial implications at each stage of repurposing wind turbine blades as the primary load-carrying elements for high-voltage transmission line structures in the United States. This case study contribution to knowledge is based on the successful management of construction waste by analyzing an application for repurposing construction demolition waste. Specifically, this study presents an environmental and financial analysis of repurposing wind turbine blades as transmission line poles. Under this case study, our results show that BladePoles have lower greenhouse gas emissions than steel poles, and we anticipate BladePoles will be less costly than steel poles. Overall emissions are most sensitive to combustion emissions, driven primarily by transportation distance and hours of required crane operations during the installation process. Compared to other evaluated recycling methods, repurposing wind blades as BladePoles has the least overall global warming potential. **DOI: 10.1061/JCEMD4.COENG-13718.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

Practical Applications: As renewable energy production grows, managing infrastructure at its end-of-life is increasingly relevant—for example, wind turbine blades. This case study presents a financial and environmental analysis of repurposing decommissioned wind turbine blades as transmission poles, called BladePoles. This paper presents the cost and associated greenhouse gas emissions at each stage of the process. The case study also compares this reuse application to typical steel pole deployment, finding that for the same 60-year life span and 161 kV, 230 kV, and 345 kV transmission line poles, the BladePole cost is lower than the steel pole. Greenhouse gas emissions are most sensitive to transportation distance from the wind farm to the transmission project and the time of crane use for installation are key parameters in this case study and reducing them directly reduces the total greenhouse emissions overall.

Author keywords: BladePole; Construction; Transmission pole; Life cycle assessment (LCA); Life cycle costs (LCC); Repurposing; Wind turbine blades.

Introduction

Wind turbines have been powering renewable electricity production for a few decades now, and for the first time in US history, renewable electricity production surpassed coal electricity production in 2020 (BCSE 2021). In October 2023 YTD, the top 10 states with the highest net electricity generation in the United States per year were Texas, Iowa, Oklahoma, Kansas, Illinois, Colorado, California, New Mexico, Minnesota, and North Dakota with 101, 34, 31, 22, 17.5, 13, 12.8, 12.5, 11.8, and 11.8 terawatt hours produced respectively (USEIA 2023). Between 2021 and 2022, the United States had record-breaking wind turbine installations which increased the wind energy capacity by 30% to more than 135 GW (Conte 2022). While this is promising for the renewable energy industry, it has also increased the amount of nonbiodegradable blade waste. Cooperman et al. (2021) estimated in their sensitivity analysis that the projected decommissioned wind turbine blades total weight by 2050 will range from 1.53 to 2.75 million tons in the United States alone; however it should be noted that some in the

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industry project the actual values to be higher (Korey et al. 2023). Work by our team indicates the potential for even larger amounts of waste due to current trends in repowering of wind turbines (Bank et al. 2021). Therefore, it is imperative that current research focuses on finding the most cost effective and environmentally appropriate way of providing solutions for current and future wind turbine blades coming out of service. The remainder of the turbine is composed primarily of concrete, steel, and copper, and there are well-known processes for reusing and recycling these materials.

Repurposing the material in the wind turbine blades can preserve the highest possible value of the decommissioned blade. When a structural element reaches its end-of-life, there are three scales for reuse: element scale, aggregate scale, and molecular scale (Gentry et al. 2020). At the element scale, the wind blade is reused in its entirety or in large sections, and the nature of the continuous fiber-reinforced composites and the structure are preserved. At the aggregate scale, the composite materials are separated into centimeter size pieces or ground to milli- to micrometer sized particles and used as reinforcements or fillers in concrete or in other products (Yazdanbakhsh et al. 2018). At the molecular scale, the resins revert to monomers for use in new polymers, and the fibers are recovered in short strands. In general, energy inputs to recycle materials go up as the scale decreases.

There are several aggregate/molecular level recycling technologies that have been developed to handle these material streams, and some have been utilized to demonstrate circularity in the industry. These include mechanical recycling (Cruz Sanchez et al. 2020; Moreno et al. 2020; Zhang et al. 2021), thermal or thermochemical recycling (Anuar Sharuddin et al. 2016; Caltagirone et al. 2021; Coughlin et al. 2021; Stelzer et al. 2022; Xu et al. 2023), chemical or solvent recycling (Coates and Getzler 2020; Rahimi and García 2017; Zhao et al. 2023), and enzymatic recycling (Chen et al. 2020; Kaushal et al. 2021; Mohanan et al. 2020). The case of cement production from co-processing is a special case of the molecular scale, as the hydrocarbon-based resins are burned as fuel and the oxides of silicon, calcium and iron in the glass fibers are used in the production clinker for portland cement. While these technologies all exist to different degrees, not all are available at scales relevant for the wind energy industry and there are significant limitations to more wide-spread industrial adoption of these technologies in the US. The nature of the composite materials and the monocoque construction of wind blades makes it highly energy intensive to separate the materials and the parts for reuse. Due to this reason, and the low cost of landfilling in the US, most decommissioned wind blades are either landfilled or incinerated (Cooperman et al. 2021). Until recently, the cost structures associated with recycling have not been fully understood. Korey et al. (2023) and Sproul et al. (2023) have recently unpacked the costs and environmental impacts associated with each recycling application within the US market. Yet to date there has not been a robust analysis of the reuse at element scale repurposing technologies available for end-of-life wind turbine blades. Reuse at this element level could enable the highest-value recovery of a final product (i.e., bridges, sound barriers, transmission poles, etc.) rather than molecular constituents/precursors.

This paper aims to understand the logistics, environmental impacts, and cost structures of reuse at the element scale for the first time in the literature within the US market. If full material repurposing measures were set in place, we could divert over 1 million tons of global blade material waste annually (Bank et al. 2021). Because reuse and repurposing research is still in its initial stages of design and implementation, there are many supply-chain logistics and technical barriers that must be understood before adoption can begin, and this paper will uncover them. Since wind turbine blades present a more challenging recycling problem than other parts of the turbine, our case study provides the financial (LCC) and environmental (LCA) impacts of repurposing decommissioned wind turbine blades as high-voltage transmission poles. Prior work by the research team has demonstrated the structural feasibility of the concept for electrical transmission lines in the 69 kV to 345 kV range—with poles up to 40 m long (Alshannaq et al. 2021). This structure, called the BladePole [T. Al-Haddad, et al. "Systems and Methods for Repurposing Retired Wind Turbines as Electric Utility Line Poles," Patent No. WO/2021/026198 (2021)], fulfills the same functional requirements as traditional steel or spun concrete poles.

Literature Review

Electricity Grid Infrastructure

The energy system in the United States is transitioning from fossil fuels to renewable electricity generation and other zero or negative emission technologies to achieve carbon neutrality (Webster et al. 2020). According to the Williams et al. (2021) study on decarbonization pathways in the United States, electricity demand could more than double by 2050, in part due to beneficial electrification. One of the key tasks to achieve zero or negative CO_2 emissions from the electricity production system while keeping up with demand starts with more than tripling wind and solar electricity production by 2030 (Williams et al. 2021).

Additional challenges for the transition to renewable electricity generation are the high system costs necessary to achieve the maximum emission reduction and the need to increase electricity transmission infrastructure buildout (Cole et al. 2021). Many renewable energy projects are delayed or canceled due to the lack of transmission capacity in the existing electricity grid. Updated and new long-distance electricity transmission lines are required for grid expansion (Reed et al. 2021) and to reduce electricity costs (Brown and Botterud 2021). One of the main structural components of the electricity grid are the poles that support the power lines. Previous research has studied the environmental and economic impacts of utility poles (Bolin and Smith 2011; Lu and El Hanandeh 2017). When it comes to distribution poles, wood is the preferred material as it has a low-carbon, low-cost lifecycle, making it infeasible to compete with (AquAeTer, Inc. 2013; de Simone Souza et al. 2017). Current pole innovation for use in electricity transmission includes poles made of fiber glass for lightweight poles with reduced required maintenance (RS Poles 2022). Typically, transmission poles are made of concrete or steel due to their height ranging from 30 to 45 m (100 to 150 ft) tall for 161 kV, 230 kV, and 345 kV voltage capacity. The heights of transmission poles are consistent with the current lengths of wind blades coming out of service and could potentially provide demand for repurposing most of the blades.

To understand the US transmission pole market demand, we study the MISO and SPP regions which have most of the wind farms in the United States (Hoen et al. 2023). In MISO territory, 45% of the transmission infrastructure investment is going toward building new lines or upgrading them. In the next 10 years 2,116 circuit-miles of new transmission line are planned of which 39% are less than 230 kV and 61% are 345 kV or more (MISO 2022a). Additionally, the 2023 SPP Transmission Expansion Plan—the list of all transmission projects in SPP for the 20-year planning horizon—has upgrades approved for construction that include 805 miles of new 115 kV, 138 kV, and 345 kV lines expected to be built and 233 miles of existing 69 kV–345 kV lines to be rebuilt (SPP 2023). Therefore, more than 6,300 transmission poles are expected to be installed in the next 10–20 years in the Midwest region of the United States alone.

Wind Turbine Blade Circular Economy

Globally, it is expected that the wind energy market will grow 6.6% per year on average with an expected annual installation of more than 90 GW for onshore wind and 20 GW for offshore wind (Lee and Zhao 2022). Worldwide, wind installations, installed capacity, and rotor diameter keep increasing every year to reduce the cost of electricity production and expand feasible locations for wind farms (Enevoldsen and Xydis 2019). Assuming 20 years of operation, by 2050 around 84 GW from offshore and 1,220 GW from onshore wind are expected to be decommissioned globally (Bennet 2021), accounting for 13 million tons of waste assuming 10 t/MW (Albers et al. 2009).

The United States new onshore and offshore wind power capacity in 2021 was 12.7 GW (14%) of the global 93.6 GW. By 2021, the total capacity of onshore wind in the United States were 134.4 GW (17% of global onshore installations) second to China (Lee and Zhao 2022). Assuming 20 years of operation, by 2050 around 6 GW from offshore and 160 GW from onshore wind are expected to be decommissioned in the United States alone (Bennet 2021), for an estimated 1.7 million tons of waste assuming 10 t/MW (Albers et al. 2009). According to Bank et al. (2021), between now and 2050 the amount of blades coming out of service on average will range from 8,000 to 10,000 blades per year in the United States alone.

Because of the fast advancement in wind electricity production, stakeholders are deciding to replace wind turbines earlier (after 7–15 years) than their designed end-of-life (20–25 years) mainly to increase capacity and production efficiency, to keep stakeholders profitable, and to reduce energy production costs (del Río et al. 2011; Korey et al. 2023). This has increased the amount of decommissioned blades in the last decade as stakeholders choose to benefit from tax credits and improve the energy generation (del Río et al. 2011) than to extend the life of older blades. Because blades tend to be decommissioned earlier than their design life, there is structural capacity left in the decommissioned blades. It is important to note that research has shown that even after a complete design life of 20–25 years as a wind blade, there is structural capacity that can be deployed for repurposing applications (Alshannaq et al. 2021; Ruane et al. 2022).

Wind turbine blades are made of glass (or glass and carbon) fiber reinforced polymer (FRP), balsa wood, polyethylene, steel and copper wiring and separating these materials at the end-of-life is an extremely high energy intensity, polluting process (Cooperman et al. 2021). In a linear economy, end-of-life solutions focus on disposing of the material in incineration facilities or landfills (Cooperman et al. 2021). Some potential solutions for recycling FRP composites that have been studied to date include cement coprocessing, mechanical recycling, high-voltage fragmentation, thermal recycling (pyrolysis), and chemical recycling (hydrolysis and solvolysis) (Cooperman et al. 2021). It is important to note that these recycling processes often reduce the overall value of the recycled materials produced. Cement coprocessing is increasingly being implemented in the world as an end-of-life solution with thousands of blades getting shredded and sent to cement kilns. In the kilns, shredded material is burned and the resulting ash is mixed with other cementitious materials (Holger and Petroni 2022); however, there is minimal to no recycled product value in North America (EPRI 2020). Thermal recycling like pyrolysis has a high recycled product value, but it requires a higher investment compared to mechanical recycling and cement coprocessing (EPRI 2020).

Previous literature has studied the life cycle environmental impact of the raw materials, production, transportation, operation, and maintenance of wind turbine blades for their intended use (Liu and Barlow 2016). After realizing the environmental impact that blades have at end-of-life, previous research has studied the benefits of recycling and repurposing wind blades instead of sending them to landfills to reduce blade waste filling up landfills and recycling some important material components in blades. Current research is focusing on the LCA of recycling (downcycling) applications for decommissioned wind turbine blades (Ghosh et al. 2022; Hanes et al. 2021; Rathore and Panwar 2022) such as mechanical and thermal recycling for material recovery (Cousins et al. 2019; Liu et al. 2022), disposal and life extension (Liu et al. 2022), and repurposing wind turbine blades as medium size elements by cutting the blade into usable pieces (Pronk 2022). However, few LCA studies have focused on re-using the entire blade (Nagle et al. 2022).

Motivated by the expected growth in wind turbine blades reaching end-of-life, coupled with an expectation that more electricity transmission will be built in the United States (Cole et al. 2021), this study uses a circular economy lens to evaluate the life cycle environmental and financial impacts of repurposing decommissioned wind turbine blades (WTBs) into high-voltage transmission poles. To support this analysis, we show the critical process steps in repurposing WTBs as transmission poles, then describe how these results can inform end-of-life decision making of WTBs and management required at critical construction stages. The next section will present the life cycle assessment (LCA) and life cycle cost (LCC) analysis implemented in this study with the respective environmental and financial results. We implement a sensitivity analysis of the results by varying different independent variables to measure their impact on the results.

Methodology

The goal of this study is to unpack the environmental impacts, costs, and logistical considerations for the reuse at the element level of a decommissioned wind turbine blade. This study focuses on the environmental (LCA) and financial (LCC) impact of repurposing one decommissioned wind turbine blade into a transmission pole, called the BladePole. This analysis is designed to support future comparison with conventional poles (made of concrete, steel, wood, or composite materials) with the same function. The LCA and LCC are based on the same functional unit and scope, described in detail as follows.

Some of the benefits of repurposing WTB as poles are their high residual structural capacity, low static loads required, and embedded lightning protection. Blades are decommissioned with sometimes more than 50% of their design life left. Wind blades are designed for dynamic loads, whereas for blade repurposing applications (e.g., electricity transmission lines) static or quasistatic loads are expected at a much reduced magnitude which are not nearly as high as the loads expected spinning on a turbine at a high speed (Alshannaq et al. 2021; Ruane et al. 2022). There is a need for good quality control for full blades, which have been decommissioned and remain in good condition, to ensure that they will perform well during reuse. Beyond the scope of this paper, we foresee a plan where nondestructive tests are performed with the blades on the ground followed by structural and material failure testing to ensure that blades have sufficient strength and stiffness for the intended structural application (Ruane et al. 2022).

Life Cycle Assessment

Scope Definition

Our study addresses decommissioned wind blades repurposed as 30 m (100 ft) high-voltage transmission poles with a 230 kV voltage class in the United States. Decommissioned blades are selected depending on a minimum of 37 m (120 ft) length.

Functional Unit

One 60-year life span, 30 m (100 ft) long transmission pole, matching the common length and life-span for 230 kV electricity transmission poles (Bolin and Smith 2011). This study assumes the performance characteristics of the BladePole and conventional pole are identical (Alshannaq et al. 2021), except for the former's lighter weight when compared with steel and concrete poles. Previous literature typically uses a measure of weight as a functional unit because the considered recycling applications involve WTB being cut into pieces, shredded and/or grounded to finer material (Li et al. 2016). For repurposing applications, a blade is likely more valuable as a single structural unit than as shredded and/or grounded material due to the costs/logistics of recycling and the reduced market value of the product generated from it (Cousins et al. 2019). Therefore, our functional unit is a single pole and blade instead of its final weight (or mass). For transportation purposes, typically the weight of the blade is not the key metric, but rather the shape and length to be transported.

System Boundary

This study addresses wind turbine blades that are fit for repurposing as BladePoles, with a supply chain that starts after the wind turbine blade is decommissioned, on the ground next to the turbine, and ends with the BladePole deconstruction after its end-of-life. See Henao et al. (2022) for additional details about the supply chain of repurposing wind turbine blades.

The boundary conditions follow a gate to end-of-life LCA from the Institution of Structural Engineers (Gibbons and Orr 2022) where the initial gate is considered as the decommissioned blade on the ground. Since several decommissioning methods exist that may or may not preserve the integrity of the blade, a deeper study is required to quantify the environmental and financial costs associated to this stage and the impact of repurposing applications. The product stage only involves remanufacturing/modifying the decommissioned blade and the end-of-life stage involves the deconstruction or dismantling of the BladePole but does not account for the waste management or transportation as it is assumed to be the same as if it had happened at the wind turbine. Using the code ISO 21931 (ISO 2019) LCA on infrastructure projects (A0 to D granularity), each phase is presented with its inputs and associated emissions in Fig. 1.

The process flow diagram (Fig. 1) presents the supply chain phases from the moment the blade is manufactured until its end-of-life. The impacts from the initial production and decommissioning of the WTB prior to evaluation for reuse (i.e., the stage before the WTB is on the ground next to the wind turbine after retirement) are not part of the BladePole system boundary, as repurposing blades is still a relatively novel application and is not part of the initial decision to create the blade. This process assumes that a conventional transmission pole foundation is required and already in place, and this part of the construction is also excluded from LCA calculations. Further along the process presented in Fig. 1, the end-of-life waste management of a BladePole could include reducing its size (cutting) on site, transporting and depositing it whole or shredded in landfill, but it can additionally serve as the first step for repurposing a decommissioned BladePole into another application, such as noise barriers, canopies, furniture and more (Bank et al. 2021; Nagle et al. 2022). Due to the many possibilities, this step of the supply chain is not included in this study.

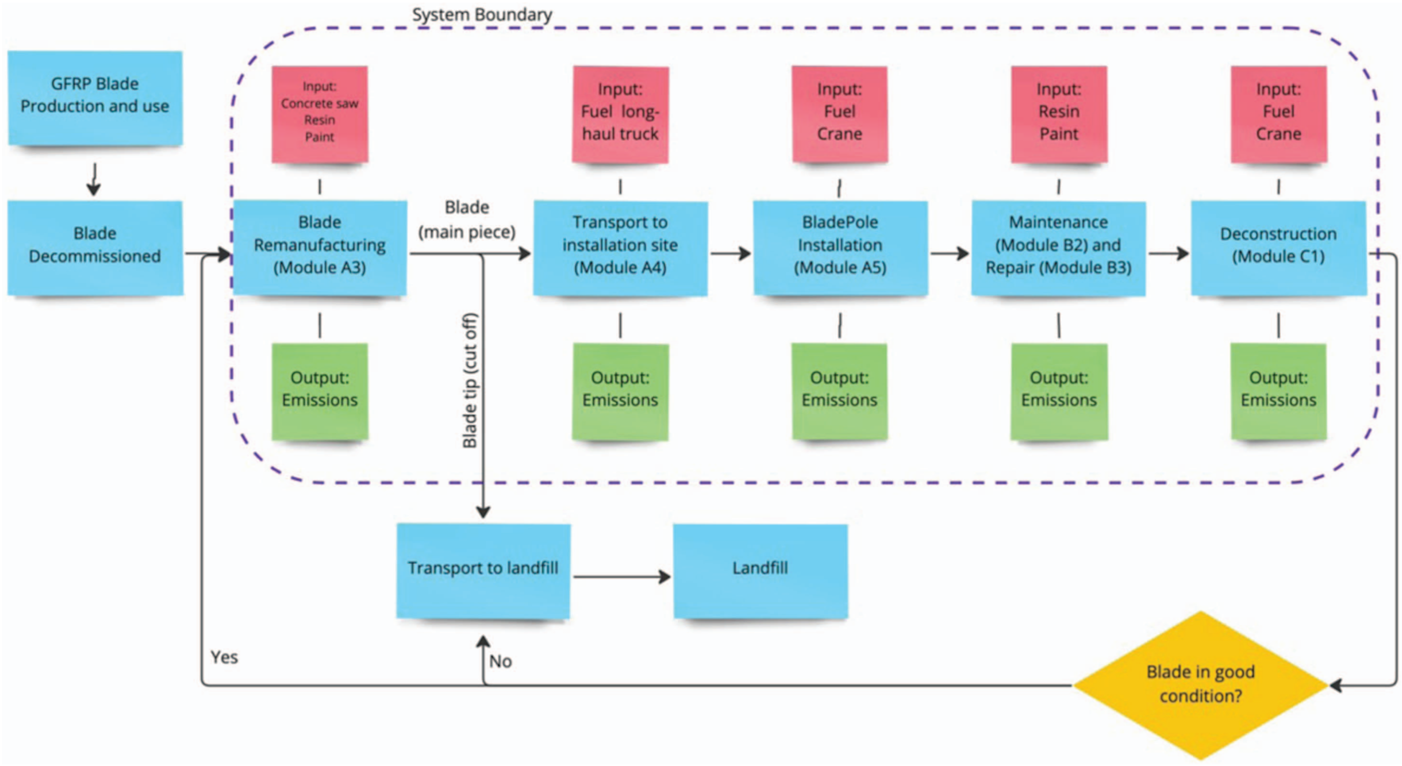


Fig. 1. (Color) Process flow diagram: Life cycle stages and system boundary.

Energy and Environmental Impact Assessment

This study focuses on quantifying the fossil fuel depletion in MJ and environmental impacts at every stage of the BladePole supply chain. The environmental impacts considered in this study include global warming potential (GWP) in kg CO_2 eq, eutrophication potential (EP) in kg NO_x eq, acidification potential (AP) in kg SO_2 eq, and particulate matter formation (PM) in kg $PM_{2.5}$ eq. The impact assessment method used is TRACI 2.11 with a normalization and weighting set for US 2008. The LCA is performed using OpenLCA version 1.11 (OpenLCA 2022).

Life Cycle Costing

This study considers three cost scenarios. The Scenario 1 accounts for a BladePole used as an angled deadend structure, which is designed for full terminal loads (the highest loads) with a double circuit (supporting power lines on both sides of the pole). The Scenario 2 considers a double circuit running angle structure which are designed for a change in the transmission line angle. For Scenario 3, a BladePole is used as a single circuit tangent structure, which is most commonly used in a continuous straight transmission line alignment and designed to carry the lowest loads among the different types of poles. All scenarios are developed for a 60-year BladePole life span as this is the expected life span of high-voltage transmission poles. Our life span assumption is based on the reduced load intensity required from a wind turbine dynamic load to a transmission pole static load, as described previously. All cost results are provided in 2022 US dollars.

Life Cycle Inventory Data

Emission rates data were collected and calculated for remanufacturing, maintenance and repair, transportation, installation, and deconstruction. Remanufacture, maintenance and repair data was obtained from Agribalyse (France) in partnership with Ecoinvent database and the Integrated Decision Support Tool (iDST) Life Cycle Costing Module for Distributed Stormwater Control Measures (SCMs) inventory data (Grubert and Krieger 2020). For transportation, MOVES3 and the EPA technical report "Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES3" was used to obtained emission rates and further calculations were performed to obtain the CO_2 emissions rate. For installation, the EPA technical report "Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES3.0.2" was used to calculate the 150-ton crane emission rates. The inventory data from the iDST was used for additional tools, vehicles, and materials used in the modification and installation of BladePoles.

Summary of Data Model

Life Cycle Assessment

Following is a summary of the assumptions stipulated for each stage, Table 1 presents the summary of the data model input required for the lifecycle assessment. Section "Life Cycle Stages" will provide details and the sources about these costs.

Life Cycle Cost Analysis

Using the profit Eqs. (1)–(3), we present the cost results in Table 2 using the summary LCC data model input for each scenario at each supply chain stage. A detailed explanation of the calculated costs presented in Table 2 is provided in the section "Life Cycle Stages"

$$P = R - C \tag{1}$$

Table 1. Summary of BladePole LCA data model input

Process stage	Flow	Amount	Unit
A3 remanufacturing	Concrete circular saw	4	h
	Alkyd paint	7	kg
	Glass fiber	0.25	kg
	Polymer resin	0.5	kg
	Quantity for remanufacturing	1	Item
A4 transportation	Heavy heavy-duty combination truck (miles traveled)	1,610	km
A5 installation	Crane 150 MT (process duration)	5	h
B2 maintenance	Alkyd paint	1.75	kg
B3 repair	Glass fiber	0.06	kg
	Polymer resin	0.125	kg
	Quantity for maintenance and repair	3.00	Item
C1 deconstruction	Crane 150 MT (process duration)	5	h

Table 2. Summary of BladePole LCC data model input results

Scenario	Scenario 1	Scenario 2	Scenario 3
Pole type	Angled deadend structure	Running angle structure	Tangent structure
Circuit type	Double	Double	Single
Initial cost per blade	USD 0	−USD 5,000	−USD 10,000
Remanufacture	USD 2,230	USD 1,672	USD 1,115
Transportation (1,610 km)	USD 17,797	USD 13,608	USD 9,418
Additional transportation costs	USD 24,400	USD 21,400	USD 18,400
Foundation	USD 64,906	USD 45,858	USD 18,343
Installation	USD 75,544	USD 43,420	USD 19,592
Hardware	USD 28,116	USD 14,075	USD 7,229
Additional BladePole hardware	USD 2,960	USD 2,960	USD 2,960
Repair and maintenance cost (every 20 years)	USD 6,000	USD 4,500	USD 3,000
Deconstruction	USD 75,544	USD 43,420	USD 19,592

Sources: Data from Pronk (2022); Al-Haddad et al. (2022); Mishnaevsky and Thomsen (2020); USEPA (2020, 2021); MISO (2022b).

where

$$C = C_{\text{rem}} + C_{\text{trans}} + C_{\text{found}} + C_{\text{inst}} + C_{\text{har}} + C_{\text{maint}} + C_{\text{decon}} \quad (2)$$

$$R = C_{\text{pole}} \quad (3)$$

where P = profit; R = revenue; and C = cost.

Life Cycle Stages: Description and Environmental and Cost Assumptions

The life cycle stages follow a "gate to end-of-life" LCA from the Institution of Structural Engineers (Gibbons and Orr 2022) per Fig. 1.

Stage: Product and Use

The blade is assumed to be available after decommissioning, with no embodied environmental impacts allocated to the BladePole. We assume that potential WTB repurposers would be paid [C_{pole} = USD 0, USD 5,000, USD 10,000] (Scenarios 1, 2, and 3 respectively) (refer to Table 2) to take the blade, based on a blade weight of 6.5 tons. Previous studies have shown the budget for disposing of blades ranges from €400 to €900 per ton (Pronk 2022). Scenario 1 assumes no initial pay for taking the blades while Scenarios 2 and 3 conservatively assume Pronk's (2022) low and high budget range values for disposing of blades plus inflation.

Module A3 Remanufacturing

After decommissioning, blades need to be modified (remanufactured) to comply with specifications of repurposing applications. For BladePoles, on site decommissioned blades are cut in two sections: the main section that includes the root of the blade (size depends on the height of pole required) and the tip section of the blade (leftover). From our work with blades (Al-Haddad et al. 2022), we have found that using a wet concrete saw is a fast and safe way to perform clean and precise cuts on a blade. For our study, we assume that this process step takes half a labor day (4 h), involves two laborers and one wet concrete saw to make one cut. This assumption is conservatively high for both time and cost. In our experience, performing 10 cuts on a 37 m (120 ft) blade took a day and a half, excluding mobilization time (Al-Haddad et al. 2022). Our assumption that costs scale linearly with number of blades results is a conservatively high case estimate because mobilization costs are likely to be shared over multiple blades.

Based on the team's experience in Atlanta, GA in 2021, it cost USD 115 per cut including labor, but this price depends on the quantity of cuts performed. To be conservatively high, USD 115 is used as our lowest cost per cut for Scenario 3. A base and higher costs per cut are assumed to be 50% and 100% more than the lowest cost, at USD 172.5 and USD 230 for Scenarios 2 and 1 respectively. Our assumptions are in line with the literature: for a 10 ton member being cut over 4 h by two people, literature suggests USD 10–70/t for the cut (USD 100–700/cut) (Liu and Barlow 2016), or USD 7.2–25.1/h for the saw (USD 28.8–100.4/cut) (Grubert and Krieger 2020), plus USD 11.28–31.53/h for each laborer (USD 90.2–252.2/cut) (Grubert and Krieger 2020), for a total of USD 119–352, aligned with our Scenarios 3, 2, and 1 estimate of [USD 115, USD 172.5, USD 230] respectively. Aesthetic repair (see section "Module B2 Maintenance, and B3 Repair") is also added to the remanufacturing cost (refer to Table 2). For repurposing solutions, it is required that blades are kept in the best condition and specialized cuts are performed to the blade length required for the application.

After the blade has been cut, any small non-structural damage on the blade is restored with resin and glass fiber material if required. As seen in Table 1, we assume that up to a 0.5 kg (1.1 lbs) of resin and 0.25 kg (0.55 lbs) of glass fiber material are required on average to restore a blade (Al-Haddad et al. 2022). Lastly, a coat of paint is applied for the protection of glass fiber composite and to reduce damage from UV rays. The area of coverage is approximately $2(30\text{ m})(1.8\text{ m}) = 112\text{ m}^2$ (1,200 sq.ft. approx.). For a coverage rate of 37 m^2 (400 sq.ft.) per gallon, this process will require approximately 3 gallons (7 kg) of paint.

Module B2 Maintenance, and B3 Repair

We assume that the amount of material required for maintenance and repair (resin, glass fiber, and paint) is a quarter of that required for remanufacturing (refer to Table 1). This assumption is based on the exhaustive initial assessment performed when selecting the blades in the best condition. We assume a 60-year lifespan and 20-year maintenance intervals, so maintenance is performed three times over the lifetime of the BladePole.

For a repurposing application like the BladePole, blades can be aesthetically repaired as long as they do not have any structural damage. To structurally repair a blade on site, one study estimates the costs to be 4,800 EUR (Mishnaevsky and Thomsen 2020); however, for the purpose of this study, only minor repairs are assumed to be required. Minor repairs typically cost less than 1,000 EUR (Mishnaevsky and Thomsen 2020) and we assume the cost of one minor repair (C_{maint}) to be USD 1,000 for Scenario 3 (refer to Table 2). For Scenarios 2 and 1, this cost is increased by 50% and 100%, respectively.

Stage: Construction Process

Module: A4 Transportation (LCA)

We assume decommissioned blades are transported 1,610 km (1,000 mi) from the wind farm location to the installation site. This distance provides access to over half of the continental United States from the Midwest, where the greatest wind resources are located and where many decommissioned blades are likely to originate. This assumption is likely conservatively high in practice given the anticipated distribution of both wind farms and electricity transmission upgrades. Blades are light weight, but high volume: the typical blade length is longer than the US standard 15 m (50 ft) flat-bed truck and blades have asymmetrical cross sections, so typically only one blade can be transported per truck. A heavy-duty long-haul truck is required for the size of the blades, which we model as a heavy-duty truck with gross vehicle weight rating (GVWR) > 33,000 lb. This vehicle is large enough to transport a high volume which is the parameter that controls the blade transportation requirements. Truck emissions rates are derived from MOVES3 using 2019 data and the EPA "Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES3" technical report 2020 (USEPA 2020) (see Table 3), which are further compared

Table 3. Transportation environmental emissions per mile from EPA "Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES3" technical report

A4 transportation	Emissions	Unit
Energy	18.55	MJ
Carbon dioxide	1.625	kg
Dinitrogen monoxide	0.0006	g
Methane	0.0045	g
Nitrogen oxides	1.8	g
Pm 2.5	0.0025	g
Sulfur dioxide	0.0004	g

Source: Data from USEPA (2020).

for accuracy with data for similar vehicles in OpenConcrete (Kim et al. 2022) and the iDST SCMs inventory data (Grubert and Krieger 2020). National representative heavy-duty long-haul truck emissions from EPA technical report 2020 are applied in the final LCA model in OpenLCA. We assume all vehicles use diesel fuel because most of the emissions from the heavy-duty sector come from diesel vehicles (USEPA 2020).

Module: A4 Transportation (LCC)

Objects with an unusual shape and size tend to be costly to transport due to the increased logistics required by a nonconventional sized truck. Data for the cost associated to transporting different blade sizes were collected from six different heavy transportation companies and used only when validated with a sales order or a quote. Additional data was provided by the historical transportation model provided in cost ranges by company 7. The transportation cost data is presented in Table S1.

Table S2 presents in ascending order the cost of transporting one blade over the distance traveled for different blade lengths. We provide the cost of transportation per km and per mile for blade lengths that range from 12 to 72 m (40–235 ft). One outlier in the data is the highest cost per distance traveled that occurs when a blade is transported for a very short distance. Moving large objects for a very short distance is not economically effective per mile because the mobilization cost associated with truck and transportation are distributed between less distance transported. For comparison, our data is similar to previous literature of USD 14–USD 22 per mile for 40–45 m (130–150 ft) blade lengths (Walzberg et al. 2022).

Fig. 2 provides graphical representation of the transportation cost depending on blade length and the data points are clustered per distance traveled.

The multilinear regression analysis (see Supplemental Materials for regression analysis details and assumptions) provides a cost estimate of transporting one blade with the following estimated regression equation for blade lengths of 12 to 45 m and distance traveled of 16 to 3,219 km:

$$C_{\mathrm{trans}} = 6(d) + 438(b) - 9{,}581 \tag{4}$$

where d = distance traveled (km); and b = blade length (m).

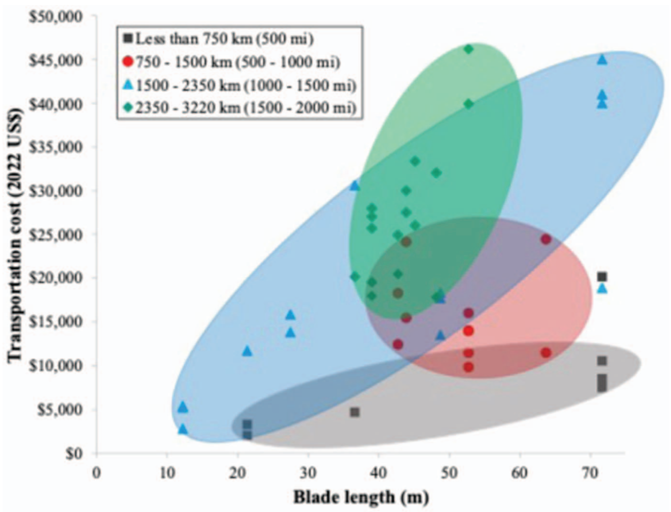


Fig. 2. (Color) Transportation costs per blade length, clustered per distance traveled.

The average distance that the observed values fall from the regression line (standard error) is USD 4,189.

Based on Eq. (4) and average variability, we obtain the cost to transport a 30 m blade for 1,609 km (1,000 mi) is USD 13,608 for Scenario 2 and ± USD 4,189 for the Scenarios 1 and 3 respectively (refer to Table 2).

Additional Transportation Costs

The previous sections focused on the transportation of the blades once they are on the truck. However, there are other activities required before and after the blades are transported. These activities include loading and unloading of blades at pick up and drop off locations, any special transportation fixtures required, and police escorts (if required) (refer to Table S3). No environmental impacts are calculated from this section as it is assumed that involves mostly labor.

Stages: Construction Process, End-of-Life (Deconstruction)

Module: A5 Construction Installation Process and C1 Deconstruction (LCA). The construction and installation process stage of a BladePole compared to a conventional transmission pole follows the construction steps presented in Al-Haddad et al. (2022) with the exception that the installation of BladePoles would take significantly less time than a conventional steel pole. This difference in installation time is mainly because steel poles are installed in 3–5 sections which takes several hours to lift and attach each piece to the next while BladePoles are installed in one piece. For the BladePole installation, we assume a 150 MT crane is required on site due to boom length capacity requirements. Once the blade and the crane are on site, the crane picks up the blade from the opposite side of the root, using the attached universal connector (Al-Haddad et al. 2022), and positions the root on the foundation. The total time that the crane takes to pick up, move, install anchor bolts, go back to its initial position, and move to the next pole is assumed to be 5 h. This time assumption is based on the reduced field work required for a BladePole compared to steel and composite pole assembly and installation (RS Poles 2022). Installation costs include the cost to transport, assemble, and install the structure, insulators, and grounding assemblies, including access to the structure location, and restoration. Equipment mobilization costs and emissions are ignored. Although this choice departs from the general assumption of linear impacts, it would be very atypical to install only one or even a small number of poles per project. Future work can investigate whether these costs and emissions are negligible per pole.

Environmental data inputs include EPA "Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES3.0.2" technical report 2021 (USEPA 2021) which has MOVES 2014a data and MOVES3 (2019 data) and provide crane emission rates that were validated by comparing to values in the iDST SCMs inventory data (Grubert and Krieger 2020) which were similar.

Foundation construction is not considered in this study because this study considers the unique processes that are required to repurpose a blade from the moment it is decommissioned until end-of-life. The foundation design for a BladePole is assumed to be the same as a conventional steel pole because both a traditional and a BladePole would carry the same loads when holding the power lines. Additionally, blade roots are designed as a perfect circle with multiple anchor bolts embedded and therefore, the foundation attachment would be the same for a BladePole and a conventional circular pole.

Module: A5 Construction Installation Process (LCC). MISO (Midcontinent Independent System Operator) is an independent, not-for-profit, organization that manages the electricity grid of 15 US states and one Canadian province, and each year it publishes the MTEP (MISO Transmission Expansion Plan) that contains data about the cost of building electric infrastructure including monopoles. According to MTEP22, the cost of installing a conventional 230 kV steel pole ranges from USD 40,000–USD 150,000 depending on the type of pole (tangent, angle, or deadend) and the circuit type (single or double) (Refer to MISO 2022 for definitions). The installation costs (C_{inst}) provided in MTEP22 include the cost to haul, assemble, and install the steel pole, insulators (hardware), and grounding assemblies. This cost includes access to the structure location, and restoration.

A conventional steel pole is transported in 3–5 sections that fit a standard 50 ft truck and it is installed by picking up each section, fitting it on the foundation and on top of each section thereafter. After each section is fitted on top of the next, 3–4 laborers are required to bolt the sections together. Since installing a BladePole only requires one piece to be lifted and bolted to the foundation, we assume that the BladePole installation costs are half of the steel pole installation costs (Refer to Table 2). Before installation can be performed, the foundation needs to be in place and the hardware required manufactured, transported, and attached to the pole before erecting:

Foundation. The foundation design and load requirements do not change for a BladePole because this application is designed to support the same loads a conventional steel pole supports. From MTEP22, we assume the same foundation size for tangent, running angle, and angled deadend poles which are 13, 32.5, and 46 cubic yard and cost approximately C_{found} = USD 18,500, USD 46,000, and USD 65,000 respectively (refer to Table 2).

Hardware. After installing the transmission pole, insulators that hold the power lines, shield wires and grounding assemblies are required to be installed. From MTEP22, we obtain the cost of the hardware (C_{har}) required for a 230kV electricity transmission pole. This cost ranges approximately from USD 7,000–USD 28,000 and it includes material cost for manufacturing insulator, line hardware and grounding assemblies (refer to Table 2).

Additional BladePole Hardware. It is important to note that even though the same hardware used in conventional poles can be used on a BladePole, it will require a universal connector to attach off-the-shelf hardware to the blade. From the team's field work, additional special BladePole hardware include four universal connectors (UC) per pole (USD 500 cost per UC) and six BlindBolts per UC to connect to the blade (USD 40 per BlindBolt) (Al-Haddad et al. 2022) (refer to Table 2). This assembly is the same for both double and single circuits designs. Additional details about the UC are specified in Al-Haddad et al. (2022).

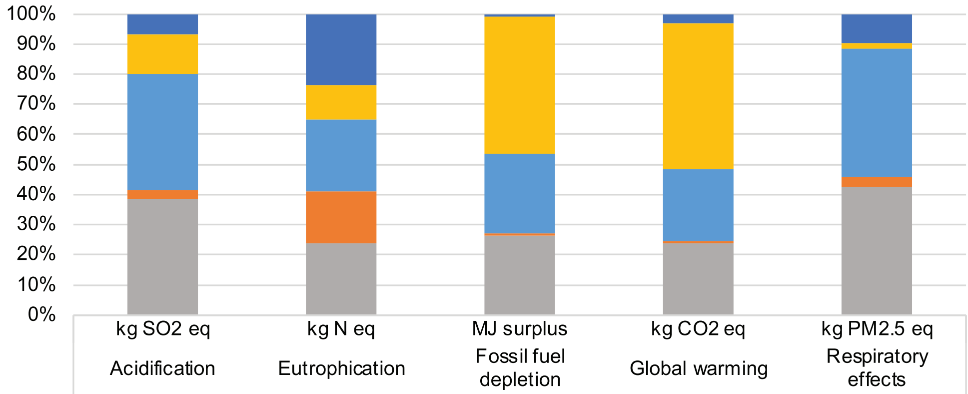
Module: C1 Deconstruction (LCC). In this study, we assume BladePoles are deconstructed at end-of-life. Deconstruction is a term used in construction where contractors disassemble existing elements in a way that preserves the highest value possible to improve its reusability (as opposed to demolition). Therefore in this study, we assume the deconstruction process has the same methods (cost and time) involved in the installation stage ($C_{\mathrm{decon}} = C_{\mathrm{inst}}$) and is applied at the end-of-life of the BladePole. Similar to installation, deconstruction requires one crane and 3–4 laborers to unbolt the BladePole from the foundation and place the pole on the ground.

Results and Discussion

Life Cycle Assessment Results

The results of our environmental LCA are presented in Fig. 3, which presents the emissions for each impact category, and in Table 4, which presents the percent allocated to each stage of the supply chain.

These initial results show that more than 45% of the fossil fuel depletion and global warming emissions are attributed to transporting the blades, and therefore, the transportation stage should be evaluated further. This further evaluation is particularly important in a real setting as this analysis uses an assumption of 1,610 km (1,000 mi) transport and does not specifically include potential short trips between sites (e.g., wind turbine site to remanufacturing facility), which might have higher impacts due to start/stop conditions. When it comes to energy consumption, transporting the blades has a higher consumption than the installation process itself. In comparison, the use of a crane in the installation and deconstruction stages has the highest impact on acidification, and respiratory effects, and tied with remanufacturing for eutrophication impacts. Decarbonization of heavy transportation and machinery would reduce these impacts but might not be significant during the initial



	kg SO2 eq Acidification	kg N eq Eutrophication	MJ surplus Fossil fuel depletion	kg CO2 eq Global warming	kg PM2.5 eq Respiratory effects
■ Remanufacturing	0.674	0.168	52	108	0.0880
■ Transportation	1.260	0.080	2671	1625	0.0155
■ Installation	3.760	0.167	1547	796	0.3781
■ Maintenance	0.271	0.122	39	31	0.0324
■ Deconstruction	3.760	0.167	1547	796	0.3781

Fig. 3. (Color) Life cycle assessment results for case study analyzed.

Table 4. Allocation by life cycle stage

Impact category	Total	Reference unit	Remanufacture (%)	Transportation (%)	Installation (%)	Maintenance (%)	Deconstruction (%)
Acidification	9.73	kg SO_2 eq	6.9	13.0	38.7	2.8	38.7
Eutrophication	0.704	kg N eq	23.8	11.3	23.8	17.3	23.8
Fossil fuel depletion	5,856	MJ surplus	0.9	45.6	26.4	0.7	26.4
Global warming	3,355	kg CO_2 eq	3.2	48.4	23.7	0.9	23.7
Respiratory effects	0.892	kg $PM_{2.5}$ eq	9.9	1.7	42.4	3.6	42.4

Table 5. Steel production emissions

		Steel production emissions (AISC 2022)	30 m (100 ft) steel pole weight (Meyer 2020)	Steel production emissions
Impact category	Reference unit	Per metric ton	Metric ton	Reference unit
Acidification	kg SO_2 eq	4.35	3.251	14.1
Eutrophication	kg N eq	0.235	3.251	0.764
Fossil fuel depletion	MJ surplus	1,780	3.251	5,787
Global warming	kg CO_2 eq	1,990	3.251	6,469

period of transmission buildout when many BladePole repurposing actions would be expected.

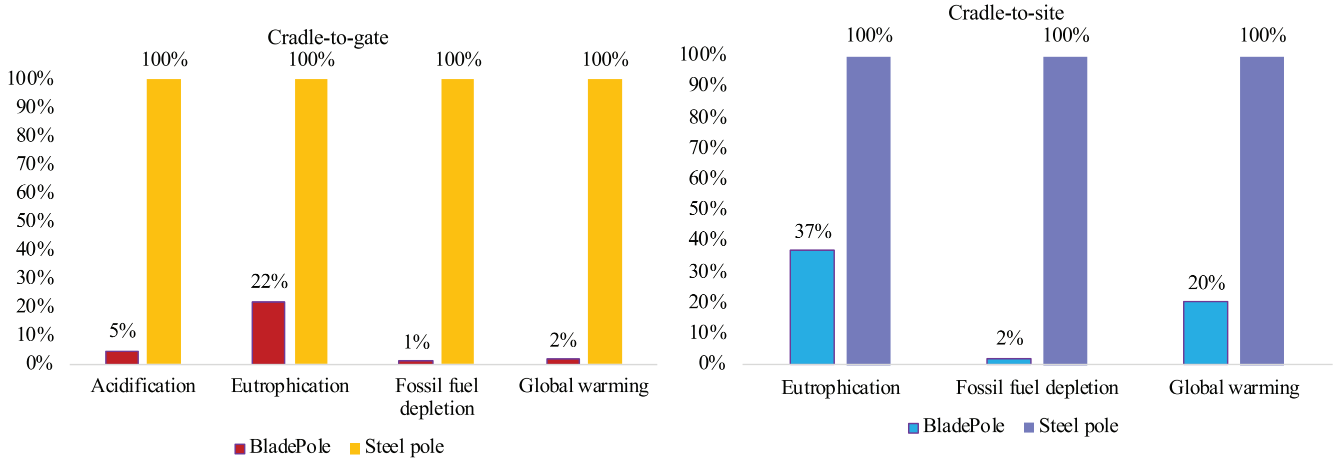
Comparative LCA between BladePoles and Steel Poles

For comparison between the BladePole and steel pole, we calculate the steel production emissions per Table 5. The environmental product declaration for fabricated hollow structural steel sections provide the emissions per metric ton at the product stage (cradle to gate) for raw material supply (including the net scrap input), transport, and manufacturing in the United States (AISC 2022) for each impact category which is then multiplied by the pole weight of a 30 m (100 ft) 12-sided LD12 steel pole (Meyer 2020).

In Fig. 4(a), we compare the steel production emissions (Table 5) with the BladePole remanufacturing emissions [Fig. 4(a), cradle-to-gate]. We find that the cradle-to-gate comparison is in the order of 1:20, 1:5, 1:100, and 1:50 for acidification, eutrophication, fossil fuel depletion, and global warming emissions respectively. Beyond cradle-to-gate, we compare steel pole manufacturing plus delivery (Bolin and Smith 2011) with BladePole remanufacturing plus transportation to the installation site [Fig. 4(b), cradle-to-site]. See the Supplemental Materials for details about the steel pole cradle-to site calculation. Per cradle-to-site our results, when adding blade transportation for 1,610 km (1,000 mi) the comparative emissions with steel are in the order of 1:3, 1:50, and 1:5 for eutrophication, fossil fuel depletion, and global warming emissions respectively.

Comparative LCA between BladePole and Other Decommissioned Blade End-of-Life Alternatives

Current solutions for decommissioned blades focus on recovering material from the blades by reducing the blade size to an aggregate and molecular scale. The lifecycle analysis of these wind blade end-of-life alternatives typically include the emissions associated with decommissioning, on-site size reduction, transportation, and recycling practices (LCA product stage, module A1 only). Then a carbon credit from producing recycled materials is subtracted from the total emissions (Sproul et al. 2023). For comparison, the BladePole cradle-to-gate approach is used (LCA product stage A1, A2, and A3) which includes dismantling of blades (Sproul et al. 2023) plus remanufacturing of the blade before transportation to site plus 20% of the landfilling emissions calculated by Sproul et al. (2023) (less than 20% of the blade is assumed to be cut and send to landfill). In our study, the carbon credit associated with using BladePoles for high-voltage transmission poles is the substitution of producing



(a) (b)

Fig. 4. (Color) Comparative LCA between BladePole and steel pole: (a) cradle-to-gate; and (b) cradle-to-site.

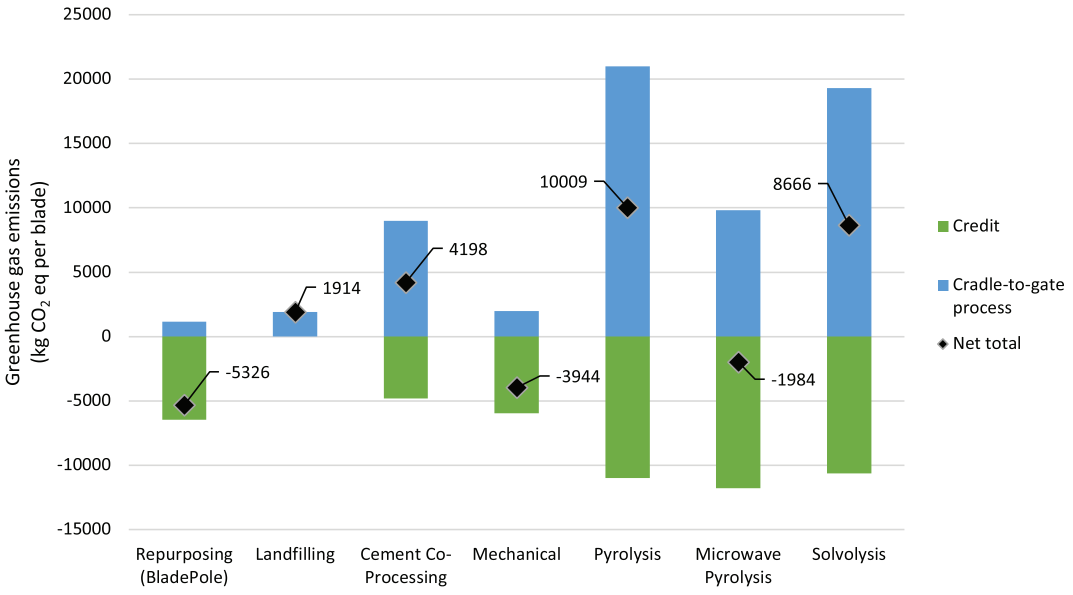


Fig. 5. (Color) Comparative LCA emission results between the BladePole and other wind blade end-of-life applications. (Adapted from Sproul et al. 2023.)

steel poles (6,469 kg CO_2eq, Table 5). The comparative LCA emission results can be found in Fig. 5 where repurposing has the lowest greenhouse gas emissions overall. A sensitivity analysis about these results is provided in the Supplemental Materials. A consequential LCA could determine if this substitution can induce a change in flows in steel material supply chain, but this is beyond the scope of this study.

LCA Sensitivity Analysis

Even though the results analyzed in our case study show the prevailing impact that transportation has on fossil fuel depletion and global warming potential, these results are based on transporting blades for 1,610 km (1,000 mi). Fig. 6 presents the results for analyzing each supply chain stage by their reference unit to determine the impact of transportation (per 100 mi) and installation (per crane hour) in the overall supply chain.

Per Fig. S9, transportation is no longer the most critical stage of the supply chain for fossil fuel depletion and global warming for distances under 100 mi. These results provide a first look at the impact per unit that crane usage has per hour in comparison with transportation. BladePole installation is a critical stage of the BladePole supply chain with high impact on acidification, fossil fuel depletion, global warming, and respiratory effects. Since transportation still poses a high impact on fossil fuel depletion and global warming impact categories for more than 100 mi, Table 6

	Initial Cost per blade	Remanufacture	Transportation (1000miles)	Foundation	Installation	Hardware	Repair and Maintenance	Deconstruction
■ Scenario 1	$0	$2,230	$42,197	$64,906	$75,544	$31,076	$6,000	$75,544
■ Scenario 2	-$5,000	$1,673	$35,008	$45,858	$43,420	$17,035	$4,500	$43,420
■ Scenario 3	-$10,000	$1,115	$27,818	$18,343	$19,592	$10,189	$3,000	$19,592

Fig. 6. (Color) LCC Results for Scenario 1, 2, and 3 for each of the BladePole supply chain stages.

Table 6. Blade transportation cutoff point in km (miles) per hour of crane operation during installation of BladePole for environmental impacts of fossil fuel depletion and global warming potential

Installation (crane hour)	1	2	3	4	5	6	7	8	9	10
Fossil fuel depletion										
Transportation cutoff point (km)	116	232	348	464	580	696	812	928	1,044	1,160
Transportation cutoff point (miles)	98	196	294	392	490	588	686	784	882	980
Global warming										
Transportation cutoff point (km)	187	373	560	747	933	1,120	1,307	1,493	1,680	1,867
Transportation cutoff point (miles)	158	315	473	631	789	946	1,104	1,262	1,419	1,577

presents the cutoff point after which transportation becomes a critical supply chain stage per installation crane hour. In our initial assumption of 5 h of installation time required, installation is the critical stage in fossil fuel depletion as long as the blade is transported for up to 580 km (490 mi) before transportation becomes the critical stage.

Compared to the rest of the processes, the use of a circular saw in the remanufacturing stage has a higher environmental impact per hour on impact categories like eutrophication and respiratory effects. The blade cutting process has similar environmental impacts as concrete cutting which include air pollution, water pollution, and noise pollution. Additional steps can be taken to mitigate the impact by applying dust control measures like water misting and vacuum systems. These processes will involve additional environmental and cost analysis and are outside the scope of this study.

Any additional crane work hour can increase global warming by a factor of 98 per mile of heavy-duty transportation. Therefore, even though transporting blades for 1,000 miles has a higher global warming impact than using a crane to install a BladePole for 5 h, the impact of additional hours of work has a clear drastic effect on the overall global warming potential. Nonroad equipment for installation has higher respiratory effects than transportation. Nonroad equipment like cranes tend to be less restricted and therefore have a higher environmental impact than on-road equipment like heavy duty trucks that are more strictly regulated.

Life Cycle Cost Results

LCC of BladePole at Each Supply Chain Stage

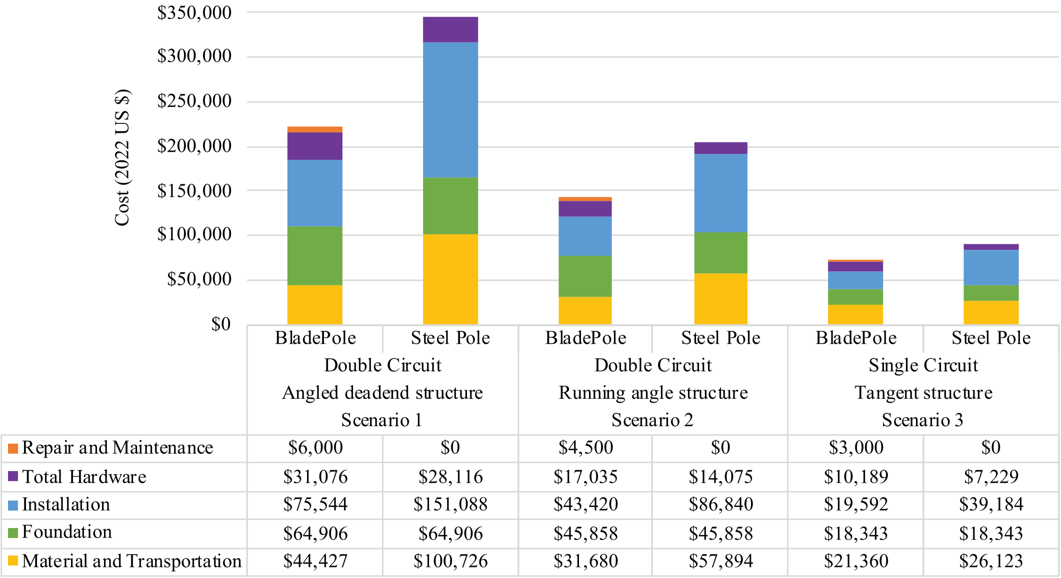
Fig. 6 presents the cost analysis results for the three scenarios and for each supply chain stage presented in Table 2. Negative values represent revenue and positive values represent costs. The range of total life cycle costs is [USD 90,000; USD 180,000; USD 290,000] for Scenarios 1, 2, and 3, respectively. From Fig. 6, the top two cost critical stages are the foundation and installation/deconstruction stages. The foundation design and construction are predetermined for each type of transmission pole and any changes to its parameters go beyond this study.

LCC Comparison between BladePole and Steel Pole

The life cycle cost comparison of the BladePole and a conventional steel pole is presented in Fig. 7. When using a BladePole instead of a steel pole, there is a cost reduction of 36%, 28%, and 9% for Scenarios 1, 2, and 3 respectively. Installation costs are the largest single contributors to total LCC. Additionally, pole material and transportation are the third critical supply chain stage for BladePole after installation and foundation. Additional information can be found in the Supplemental Materials.

LCC Sensitivity Analysis

For the sensitivity analysis we study the effect that the pole transmission voltage and installation costs have on the cost results.

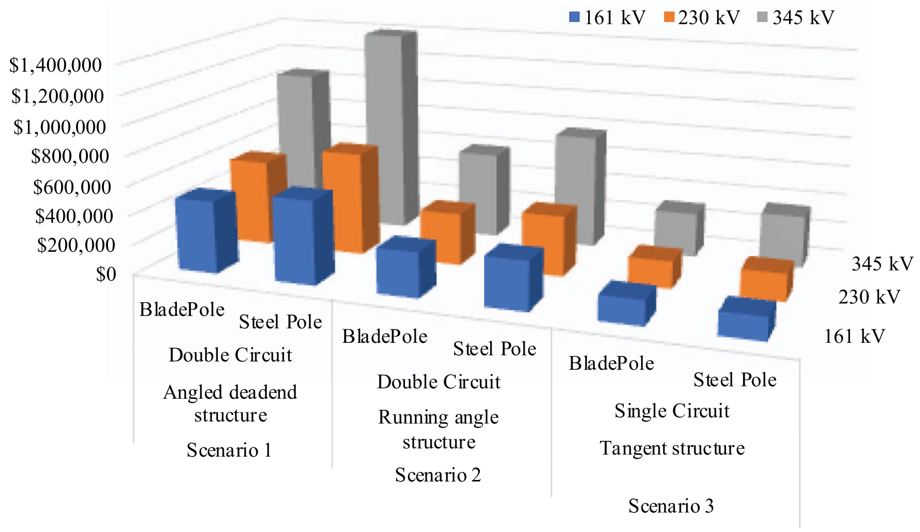


	BladePole	Steel Pole	BladePole	Steel Pole	BladePole	Steel Pole
	Double Circuit Angled deadend structure Scenario 1		Double Circuit Running angle structure Scenario 2		Single Circuit Tangent structure Scenario 3	
🟧 Repair and Maintenance	$6,000	$0	$4,500	$0	$3,000	$0
🟪 Total Hardware	$31,076	$28,116	$17,035	$14,075	$10,189	$7,229
🟦 Installation	$75,544	$151,088	$43,420	$86,840	$19,592	$39,184
🟩 Foundation	$64,906	$64,906	$45,858	$45,858	$18,343	$18,343
🟨 Material and Transportation	$44,427	$100,726	$31,680	$57,894	$21,360	$26,123

Fig. 7. (Color) LCC comparison between a BladePole and a conventional steel pole (230 kV voltage class).

Table 7. BladePole and Steel Pole LCC comparison for different transmission voltages for the three case scenarios

		Scenario 1		Scenario 2		Scenario 3	
		Angled deadend structure		Running angle structure		Tangent structure	
		Double circuit		Double circuit		Single circuit	
Transmission voltage	Pole height (m)	BladePole	Steel pole	BladePole	Steel Pole	BladePole	Steel pole
161 kV	30	USD 187,608	USD 277,910	USD 121,856	USD 163,849	USD 63,663	USD 73,562
230 kV	30	USD 221,953	USD 344,836	USD 142,493	USD 204,667	USD 72,484	USD 90,879
345 kV	45	USD 390,996	USD 681,892	USD 234,908	USD 385,653	USD 112,549	USD 170,506



	Scenario 1		Scenario 2		Scenario 3	
	Angled deadend structure		Running angle structure		Tangent structure	
	Double Circuit		Double Circuit		Single Circuit	
	BladePole	Steel Pole	BladePole	Steel Pole	BladePole	Steel Pole
■ 161 kV	$488,950	$564,154	$301,376	$326,489	$164,005	$150,840
■ 230 kV	$581,590	$700,310	$352,183	$406,896	$182,357	$183,007
■ 345 kV	$1,062,320	$1,398,111	$589,777	$769,429	$299,745	$350,742

Fig. 8. (Color) Total costs for a BladePole and conventional steel pole for Scenarios 1, 2, and 3.

Cost Comparison with Different Transmission Pole Voltages

The total life cycle cost comparison between a BladePole and steel pole of voltages 161 kV, 230 kV, and 345 kV is presented in Table 7 and Fig. 8. The BladePole total cost is consistently lower than the steel pole for the three different transmission voltages selected and the three case scenarios presented in this paper.

Cost Comparison for Variable BladePole Life Span

Because of limited data on the life span of BladePoles, our base assumption is that they last the same as conventional poles. To evaluate the impact of this assumption, we perform a sensitivity analysis where BladePole's life span is 2/3 of steel poles. Fig. S12 of Supplemental Materials summarizes the total costs for different voltage classes for BladePole and steel pole. For Scenario 3, the BladePole breaks even with the steel pole for a voltage class of 230 kV and the cost of the BladePole is higher than the steel pole for a voltage class of 161 kV. In all other scenarios, the BladePole overall cost comes lower than a steel pole.

Conclusions

Our study examines environmental and financial implications for implementing an innovative application for management of construction demolition waste, through the repurposing of wind turbine blades as transmission poles. This work complements prior research that focus primarily on estimating mass flows at blade end-of-life for recycling solutions, which typically involve the size reduction and separation of the composite material fiber and matrix fractions. This case study addresses a lack of examples in the literature where large structural elements from buildings and civil infrastructure are repurposed in new infrastructure rather than recycled. This work aims to highlight that component reuse in construction is sufficiently promising to motivate stakeholders to implement structural reuse as part of circularity in construction materials, leading to reduced waste, while reducing emissions and cost. The goal is to focus attention on the potential for this new form of circularity, where high quality materials and structures can be reused in construction, as an alternative to conventional materials that are difficult to recycle or reuse.

Our contribution to the literature includes industry-grounded examples of environmental and financial impacts across the life cycle of this construction demolition waste repurposing application. Using discarded wind turbine blades as a case study, this paper focuses on using environmental and economic calculations to inform decision makers when implementing materials in construction that otherwise would have been discarded. With our results, construction project managers can focus on reducing time, cost, and emissions associated to critical stages, especially in nonconventional projects. In our initial results we found that transportation (1,000 mi assumed) played a key role in the environmental emissions of a BladePole, but according to our sensitivity analysis, installation dominates when each activity is evaluated on a per unit basis. Therefore, we conclude that:

- Minimizing transportation distance is key to minimize emissions.
- The use of cranes has the highest sensitivity for environmental impacts.
- The installation stage has the highest cost in the scenarios presented in this study.

Additionally, we calculate that overall BladePoles will be cheaper than steel poles. From our case study cost results (Fig. 7) we found that installation and foundation have the highest cost in the supply chain stages with total transportation coming in third place. Therefore, we present evidence that transportation should not be the main barrier for repurposing wind turbine blades. These results inform end-of-life decision making of WTB by providing a positive outlook to repurposing whole blades and focusing on the reduction of nonroad equipment (cranes) use with a faster installation process of high-voltage transmission poles. We found that this reduction in runtime equipment reduce both environmental and financial impacts. Assuming that a decommissioned wind turbine blade can successfully function for the 60-year life span of a transmission pole is a limitation of this study that will need to be further studied. Finally, we present the importance of quantifying material decommissioning not just by weight, but also by type, location, quantity, and time of decommissioning.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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Supplemental Materials

Figs. S1–S12 and Tables S1–S15 are available online in the ASCE Library (www.ascelibrary.org).

References

AISC. 2022. “Environmental product declarations | American Institute of Steel Construction.” Accessed June 23, 2023. https://www.aisc.org/why-steel/resources/leed-v4/#112583.

Albers, H., S. Greiner, H. Seifert, and U. Kuehne. 2009. “Recycling of wind turbine rotor blades. Fact or fiction? Recycling von Rotorblaettern aus Windenergieanlagen. Fakt oder Fiktion? DEWI-Magazin.” Accessed June 15, 2023. https://www.osti.gov/etdeweb/biblio/21214142.

Al-Haddad, T., A. Alshannaq, L. Bank, M. Bermek, T. R. Gentry, Y. Henao, S. Li, A. Poff, J. Respert, and C. Woodham. 2022. “Strategies for redesigning high performance FRP wind blades as future electrical infrastructure.” Accessed April 3, 2023. https://www.re-wind.info/conference-papers/2023/1/20/al-haddad-et-al-2022-strategies-for-redesigning-high-performance-frp-wind-blades-as-future-electrical-infrastructure.

Alshannaq, A. A., L. C. Bank, D. W. Scott, and T. R. Gentry. 2021. “Structural analysis of a wind turbine blade repurposed as an electrical transmission pole.” *J. Compos. Constr.* 25 (4): 04021023. https://doi.org/10.1061/(ASCE)CC.1943-5614.0001136.

Anuar Sharuddin, S. D., F. Abnisa, W. M. A. Wan Daud, and M. K. Aroua. 2016. “A review on pyrolysis of plastic wastes.” *Energy Convers. Manage.* 115 (Feb): 308–326. https://doi.org/10.1016/j.enconman.2016.02.037.

AquAeTer, Inc. 2013. “Environmental life cycle assessment of chromated copper arsenate-treated utility poles with comparisons to concrete, galvanized steel, and fiberreinforced composite utility poles.” Report prepared for Arch Wood Protection. Accessed June 22, 2023. https://woodpoles.org/Resources/Technical-Library#enviro.

Bank, L. C., E. L. Delaney, J. McKinley, R. Gentry, and P. G. Leahy. 2021. “Defining the landscape for wind blades at the end of service life.” Accessed August 20, 2022. https://www.compositesworld.com/articles/defining-the-landscape-for-wind-blades-at-the-end-of-service-life.

BCSE (Business Council for Sustainable Energy). 2021. “2021 sustainable energy in America Factbook.” Accessed August 20, 2022. https://bcse.org/factbook/.

Bennet, L. 2021. “Sustainable decommissioning: Wind turbine blade recycling.” Accessed June 14, 2023. https://ore.catapult.org.uk/?orecatapultreports=energy-transition-alliance-blade-recycling-report-aefull-version.

Bolin, C. A., and S. T. Smith. 2011. “Life cycle assessment of pentachlorophenol-treated wooden utility poles with comparisons to steel and concrete utility poles.” *Renewable Sustainable Energy Rev.* 15 (5): 2475–2486. https://doi.org/10.1016/j.rser.2011.01.019.

Brown, P. R., and A. Botterud. 2021. “The value of inter-regional coordination and transmission in decarbonizing the US electricity system.” *Joule* 5 (1): 115–134. https://doi.org/10.1016/j.joule.2020.11.013.

Caltagirone, P. E., et al. 2021. “Substitution of virgin carbon fiber with low-cost recycled fiber in automotive grade injection molding polyamide 66 for equivalent composite mechanical performance with improved sustainability.” *Composites, Part B* 221 (Apr): 109007. https://doi.org/10.1016/j.compositesb.2021.109007.

Chen, C.-C., L. Dai, L. Ma, and R.-T. Guo. 2020. “Enzymatic degradation of plant biomass and synthetic polymers.” *Nat. Rev. Chem.* 4 (3): 114–126. https://doi.org/10.1038/s41570-020-0163-6.

Coates, G. W., and Y. D. Y. L. Getzler. 2020. “Chemical recycling to monomer for an ideal, circular polymer economy.” *Nat. Rev. Mater.* 5 (7): 501–516. https://doi.org/10.1038/s41578-020-0190-4.

Cole, W. J., D. Greer, P. Denholm, A. W. Frazier, S. Machen, T. Mai, N. Vincent, and S. F. Baldwin. 2021. “Quantifying the challenge of reaching a 100% renewable energy power system for the United States.” *Joule* 5 (7): 1732–1748. https://doi.org/10.1016/j.joule.2021.05.011.

Conte, N. 2022. “Mapped: US wind electricity generation by state. Visual capitalist.” Accessed June 16, 2023. https://www.visualcapitalist.com/mapped-u-s-wind-electricity-generation-by-state/.

Cooperman, A., A. Eberle, and E. Lantz. 2021. “Wind turbine blade material in the United States: Quantities, costs, and end-of-life options.” *Resour. Conserv. Recycl.* 168 (Apr): 105439. https://doi.org/10.1016/j.resconrec.2021.105439.

Coughlin, D., C. Ludwig, S. Ozcan, D. Hartman, and R. Ginder. 2021. *Controlled pyrolysis: A robust scalable composite recycling technology.* IACMI/R001-2021/6.4. Knoxville, TN: Institute for Advanced Composite Manufacturing Innovation.

Cousins, D. S., Y. Suzuki, R. E. Murray, J. R. Samaniuk, and A. P. Stebner. 2019. “Recycling glass fiber thermoplastic composites from wind turbine blades.” *J. Cleaner Prod.* 209 (Sep): 1252–1263. https://doi.org/10.1016/j.jclepro.2018.10.286.

Cruz Sanchez, F. A., H. Boudaoud, M. Camargo, and J. M. Pearce. 2020. “Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy.” *J. Cleaner Prod.* 264 (Apr): 121602. https://doi.org/10.1016/j.jclepro.2020.121602.

del Río, P., A. Calvo Silvosa, and G. Iglesias Gómez. 2011. “Policies and design elements for the repowering of wind farms: A qualitative analysis of different options.” *Energy Policy* 39 (4): 1897–1908. https://doi.org/10.1016/j.enpol.2010.12.035.

de Simone Souza, H. H., Â. M. F. Lima, K. O. Esquerre, and A. Kiperstok. 2017. “Life cycle assessment of the environmental influence of wooden and concrete utility poles based on service lifetime.” *Int. J. Life Cycle Assess.* 22 (12): 2030–2041. https://doi.org/10.1007/s11367-017-1293-z.

Enevoldsen, P., and G. Xydis. 2019. “Examining the trends of 35 years growth of key wind turbine components.” *Energy Sustainable Dev.* 50 (Jun): 18–26. https://doi.org/10.1016/j.esd.2019.02.003.

EPRI (Electric Power Research Institute). 2020. “Wind turbine blade recycling: Preliminary assessment (3002017711).” Accessed February 1, 2023. https://www.epri.com/research/products/000000003002017711.

Gentry, T. R., T. Al-Haddad, L. C. Bank, F. R. Arias, A. Nagle, and P. Leahy. 2020. “Structural analysis of a roof extracted from a wind turbine blade.” *J. Archit. Eng.* 26 (4): 04020040. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000440.

Ghosh, T., R. Hanes, A. Key, J. Walzberg, and A. Eberle. 2022. “The circular economy life cycle assessment and visualization framework: A multistate case study of wind blade circularity in United States.” *Resour. Conserv. Recycl.* 185 (Jan): 106531. https://doi.org/10.1016/j.resconrec.2022.106531.

Gibbons, O. P., and J. J. Orr. 2022. *How to calculate embodied carbon*. London: Institution of Structural Engineers.

Grubert, E., and J. Krieger. 2020. “Integrated decision support tool (iDST) life cycle costing module for distributed stormwater control measures (SCMs).” Accessed December 21, 2022. https://smartech.gatech.edu/handle/1853/62873.

Hanes, R., T. Ghosh, A. Key, and A. Eberle. 2021. “The circular economy lifecycle assessment and visualization framework: A case study of wind blade circularity in Texas.” *Front. Sustainability* 2 (Jun): 671979. https://doi.org/10.3389/frsus.2021.671979.

Henao, Y., R. Gentry, T. Al-Haddad, L. C. Bank, and J. E. Taylor. 2022. “Construction assessment framework of electrical transmission structures from decommissioned wind turbine blades.” In *Proc., Construction Research Congress 2022*, 588–598. Reston, VA: ASCE. https://doi.org/10.1061/9780784483954.061.

Hoen, B. D., J. T. Diffendorfer, L. A. Kramer, C. P. Garrity, and H. E. Hunt. 2023. *United States wind turbine database (v6.0) [dataset]*. Washington, DC: USGS. https://doi.org/10.5066/F7TX3DN0.

Holger, D., and G. Petroni. 2022. “Cement makers burn turbine blades as wind power faces recycling headache.” Accessed June 12, 2023. https://www.wsj.com/articles/cement-makers-burn-turbine-blades-as-wind-power-faces-recycling-headache-11650967200.

ISO. 2019. *Sustainability in buildings and civil engineering works*. ISO 21931-2:2019. Geneva: ASTM.

Kaushal, J., M. Khatri, and S. K. Arya. 2021. “Recent insight into enzymatic degradation of plastics prevalent in the environment: A mini—Review.” *Cleaner Eng. Technol.* 2 (Aug): 100083. https://doi.org/10.1016/j.clet.2021.100083.

Kim, A., P. R. Cunningham, K. Kamau-Devers, and S. A. Miller. 2022. “OpenConcrete: A tool for estimating the environmental impacts from concrete production.” *Environ. Res.: Infrastruct. Sustainability* 2 (4): 041001. https://doi.org/10.1088/2634-4505/ac8a6d.

Korey, M., E. Sproul, M. L. Rencheck, and B. L. Ennis. 2023. “Development of wind turbine blade recycling baselines in the United States.” *IOP Conf. Ser.: Mater. Sci. Eng.* 1293 (1): 012018. https://doi.org/10.1088/1757-899X/1293/1/012018.

Lee, J., and F. Zhao. 2022. “Global wind report 2022.” Accessed June 14, 2023. https://gwec.net/global-wind-report-2022/.

Li, X., R. Bai, and J. McKechnie. 2016. “Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes.” *J. Cleaner Prod.* 127 (Feb): 451–460. https://doi.org/10.1016/j.jclepro.2016.03.139.

Liu, P., and C. Y. Barlow. 2016. “The environmental impact of wind turbine blades.” *IOP Conf. Ser.: Mater. Sci. Eng.* 139 (1): 012032. https://doi.org/10.1088/1757-899X/139/1/012032.

Liu, P., F. Meng, and C. Y. Barlow. 2022. “Wind turbine blade end-of-life options: An economic comparison.” *Resour. Conserv. Recycl.* 180 (Aug): 106202. https://doi.org/10.1016/j.resconrec.2022.106202.

Lu, H. R., and A. El Hanandeh. 2017. “Environmental and economic assessment of utility poles using life cycle approach.” *Clean Technol. Environ. Policy* 19 (4): 1047–1066. https://doi.org/10.1007/s10098-016-1299-4.

Meyer. 2020. “Meyer light duty and distribution class steel poles.” Accessed June 24, 2023. https://meyerutilitystructures.com›wp-content›uploads›2021›05›Meyer_LD_Catalog_2020.pdf.

Mishnaevsky, L., and K. Thomsen. 2020. “Costs of repair of wind turbine blades: Influence of technology aspects.” *Wind Energy* 23 (12): 2247–2255. https://doi.org/10.1002/we.2552.

MISO (Midcontinent Independent System Operator). 2022a. “2022 MISO transmission expansion plan.” Accessed June 19, 2023. https://www.misoenergy.org/planning/transmission-planning/mtep/mtep22-report/.

MISO (Midcontinent Independent System Operator). 2022b. “Transmission cost estimation guide for MTEP22.” Accessed August 20, 2022. https://cdn.misoenergy.org/Transmission%20Cost%20Estimation%20Guide%20for%20MTEP22337433.

Mohanan, N., Z. Montazer, P. K. Sharma, and D. B. Levin. 2020. “Microbial and enzymatic degradation of synthetic plastics.” *Front. Microbiol.* 11 (Apr): 580709. https://doi.org/10.3389/fmicb.2020.580709.

Moreno, E., F. R. Beltrán, M. P. Arrieta, G. Gaspar, L. M. Muneta, R. Carrasco-Gallego, S. Yáñez, D. Hidalgo-Carvajal, M. U. de la Orden, and J. M. Urreaga. 2020. “Technical evaluation of mechanical recycling of PLA 3D printing wastes.” *Proceedings* 69 (1): 19. https://doi.org/10.3390/CGPM2020-07187.

Nagle, A. J., G. Mullally, P. G. Leahy, and N. P. Dunphy. 2022. “Life cycle assessment of the use of decommissioned wind blades in second life applications.” *J. Environ. Manage.* 302 (Sep): 113994. https://doi.org/10.1016/j.jenvman.2021.113994.

OpenLCA. 2022. “OpenLCA.org ∣ openLCA is a free, professional life cycle assessment (LCA) and footprint software with a broad range of features and many available databases, created by GreenDelta since 2006.” Accessed February 5, 2023. https://www.openlca.org/.

Pronk, S. 2022. “Repurposing wind turbine blades as a construction material.” Master, Dept. of Civil Engineering, Delft Univ. of Technology.

Rahimi, A., and J. M. García. 2017. “Chemical recycling of waste plastics for new materials production.” *Nat. Rev. Chem.* 1 (6): 0046. https://doi.org/10.1038/s41570-017-0046.

Rathore, N., and N. L. Panwar. 2022. “Environmental impact and waste recycling technologies for modern wind turbines: An overview.” *Waste Manage. Res.* 41 (4): 744–759. https://doi.org/10.1177/0734242X221135527.

Reed, L., L. Abrahams, A. Cohen, J. Majkut, A. Place, B. Phillips, and J. Prochnik. 2021. “How are we going to build all that clean energy infrastructure? Considering private enterprise, public initiative, and hybrid approaches to the challenge of electricity transmission.” *Electr. J.* 34 (10): 107049. https://doi.org/10.1016/j.tej.2021.107049.

RS Poles. 2022. “Assembly and installation guide of high performance composite utility poles.” Accessed January 24, 2023. https://www.rspoles.com/sites/default/files/2021-12/RS-PowerON-Pole-Assembly-and-Installation-Guide.pdf.

Ruane, K., et al. 2022. “Material and structural characterization of a wind turbine blade for use as a bridge girder.” *Transp. Res. Rec.* 2676 (8): 354–362. https://doi.org/10.1177/03611981221083619.

SPP (Southwest Power Pool). 2023. “2023 SPP transmission expansion plan report.” Accessed June 20, 2023. https://spp.org/documents/56611/2023%20spp%20transmission%20expansion%20plan%20report.pdf.

Sproul, E., M. Williams, M. L. Rencheck, M. Korey, and B. L. Ennis. 2023. “Life cycle assessment of wind turbine blade recycling approaches in the United States.” *IOP Conf. Ser.: Mater. Sci. Eng.* 1293 (1): 012027. https://doi.org/10.1088/1757-899X/1293/1/012027.

Stelzer, P. S., U. Cakmak, L. Eisner, L. K. Doppelbauer, I. Kállai, G. Schweizer, H. K. Prammer, and Z. Major. 2022. “Experimental feasibility and environmental impacts of compression molded discontinuous carbon fiber composites with opportunities for circular economy." *Composites, Part B* 234 (Aug): 109638. https://doi.org/10.1016/j.compositesb.2022.109638.

USEIA (US Energy Information Administration). 2023. "Electric power monthly, Table 1.14.B [Preliminary data]." Accessed January 23, 2024. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_1_14_b.

USEPA. 2020. *Exhaust emission rates for heavy-duty onroad vehicles in MOVES3*. Technical Rep. No. EPA-420-R-20-018. Washington, DC: USEPA.

USEPA. 2021. "Exhaust and crankcase emission factors for nonroad compression-ignition engines in MOVES3.0.2 [technical report]." Accessed February 5, 2023. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1013KWQ.pdf.

Walzberg, J., A. Cooperman, L. Watts, A. Eberle, A. Carpenter, and G. Heath. 2022. "Regional representation of wind stakeholders' end-of-life behaviors and their impact on wind blade circularity." *IScience* 25 (8): 104734. https://doi.org/10.1016/j.isci.2022.104734.

Webster, M. D., et al. 2020. "Achieving net zero embodied carbon in structural materials by 2050." In *Proc., SEI Sustainability Committee; Carbon Working Group*. Reston, VA: ASCE.

Williams, J. H., R. A. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, and M. S. Torn. 2021. "Carbon-neutral pathways for the United States." *AGU Adv.* 2 (1): e2020AV000284. https://doi.org/10.1029/2020AV000284.

Xu, M., H. Ji, Y. Wu, J. Di, X. Meng, H. Jiang, and Q. Lu. 2023. "The pyrolysis of end-of-life wind turbine blades under different atmospheres and their effects on the recovered glass fibers." *Composites, Part B* 251 (Sep): 110493. https://doi.org/10.1016/j.compositesb.2022.110493.

Yazdanbakhsh, A., L. Bank, and Y. Tian. 2018. "Mechanical processing of GFRP waste into large-sized pieces for use in concrete." *Recycling* 3 (1): 8. https://doi.org/10.3390/recycling3010008.

Zhang, Y., Y. Pontikes, L. Lessard, and A. Willem van Vuure. 2021. "Recycling and valorization of glass fibre thermoset composite waste by cold incorporation into a sustainable inorganic polymer matrix." *Composites, Part B* 223 (May): 109120. https://doi.org/10.1016/j.compositesb.2021.109120.

Zhao, J., P. Liu, J. Yue, H. Huan, G. Bi, and L. Zhang. 2023. "Recycling glass fibers from thermoset epoxy composites by in situ oxonium-type polyionic liquid formation and naphthalene-containing superplasticizer synthesis with the degradation solution of the epoxy resin." *Composites, Part B* 254 (Sep): 110435. https://doi.org/10.1016/j.compositesb.2022.110435.