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COMPARATIVE LIFECYCLE ANALYSIS BETWEEN WIND TURBINE BLADES REPURPOSED AS ENERGY TRANSMISSION POLES AND CONVENTIONAL STEEL POLES

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ABSTRACT

The wind industry is starting to have a rising blade waste problem that cannot be overlooked. Producing wind blade second life solutions is on the front end of our research. This study focuses on comparing the production and transportation of steel poles with transporting wind turbine blades repurposed as energy transmission poles (BladePoles). Our initial results of the comparative life cycle assessment show that using BladePoles in the energy transmission industry is environmentally viable. In the worst-case scenario, the primary energy demand and global warming potential of the BladePole is higher than the Steel pole after they have been transported 5,400 miles and 1100 miles respectively. Overall, BladePoles can be transported 550 additional miles than steel poles.

KEYWORDS

Life Cycle Assessment, Wind Turbine Blade, Energy Transmission Pole, Repurpose, Circular Economy

INTRODUCTION

Wind energy is considered a green renewable energy source that has an established circular supply chain that uses mostly recyclable materials, like concrete and steel, to produce its components for the tower and rotor. Unfortunately, the wind industry currently does not fully implement a circular economy where a 100% of the components are recirculated in the process. It has been a challenge to reintroduce wind turbine blades into this circular supply chain due to its composite nature: they are made of glass (or glass and carbon) fiber reinforced polymer (FRP), balsa wood, polyethylene, and copper wiring. Therefore, separating these materials after blades are decommissioned is a particularly high energy intensive and polluting process. Wind turbine blades follow a linear supply chain where raw materials are extracted for blade manufacturing, then blades are used and maintained for approximately 20-25 years until they are deemed for decommissioning or repowering (WindEurope, 2020). Thousands of wind turbine blades will be decommissioned per year in the United States (Bank et al., 2021). Current end-of-life options for blades are either becoming socially unacceptable, such as landfill and incineration (EPRI 2018), or are cost prohibitive, such as chemical or thermal recycling (EPRI 2020). Mechanical grinding of blades and processing in cement kilns is another possibility, but market establishment has been slow. Yet, none of these alternatives take advantage of the residual structural properties of the FRP blades that has been demonstrated to be significant.

Previous and current research has not only demonstrated the structural integrity of decommissioned wind turbine blades, but also its flexibility and durability (Alshannaq, 2021). Because of these attributes, repurposing of the blades into large civil infrastructure could improve resilience in infrastructure systems and contribute to a circular supply chain. This paper focuses on repurposing wind turbine blades as energy transmission poles as a higher value second life. Because of the increasing demand in the electricity grid and the structural resistance of wind turbine blades, repurposing blades as energy transmission poles is a viable solution structurally (Alshannaq, 2021). Further research is required to understand and quantify the environmental impact of this solution.

Previous research has studied the lifecycle assessment comparison between conventional energy transmission poles (Bolin & Smith, 2011; Lu & El Hanandeh, 2017). This paper goes beyond previous end-of-life and comparative LCAs and focuses on developing a comparative lifecycle assessment between energy transmission poles made of decommissioned wind turbine blades and conventional steel poles used in the energy transmission industry. Initial production of steel is the largest source of global emissions (Allwood et al., 2010). In 2019, iron and steel production emitted more than 40 million tons of carbon dioxide which in perspective is lower than 1990 emissions due to effective improvement in steel production and the increase in recycling steel scrap (EPA, 2022). On the other hand, steel demand in infrastructure accounts for more than 20% of the annual global steel demand (Cullen et al., 2012; Moynihan & Allwood, 2012), and therefore, replacing a percentage of steel poles with wind turbine blades can help reduce the impact of steel production while meeting transmission pole demand.

Our research aims to quantify the environmental impact through a comparative life cycle assessment of steel transmission poles and transmission poles made with discarded wind turbine blades. This paper focuses on understanding the limiting factors when deploying wind turbine blades as BladePoles compared to steel poles by performing a life cycle assessment at different stages.

MATERIALS AND METHODS

Life Cycle Assessment Model

Scope Definition

The comparative life cycle assessment focuses on energy transmission poles and the different materials used in their production. Conventionally, there are concrete, steel, wood, and composite poles in production. The focus of this paper is to identify wind turbine blades that are coming out of service and refurbish them as transmission poles to compare their environmental impact against conventional steel transmission poles. General Electric GE37 blades are selected since they are a common type of blade currently being decommissioned. A 230 kV energy transmission pole is set as the comparison pole specification because its specified height is similar to the length of the decommissioned wind turbine GE37 (37 m). This study aims to understand and quantify the environmental impacts of BladePoles compared to conventional steel poles with the same specifications.

Functional Unit

For this analysis, a 100 ft long utility pole for power transmission was selected as the functional unit because it is the common length for 230 kV energy transmission poles with a 60-year life span (Bolin & Smith, 2011).

System Boundary

The boundary conditions follow a cradle-to-site life cycle assessment from the Institution of Structural Engineers (Gibbons and Orr 2020). Using the code ISO 21931 LCA on infrastructure projects (A0-D granularity) (ISO 2006), each phase is presented with its inputs and outputs and the associated emissions in Figure 1.

The boundary of this initial study is cradle-to-site, therefore the initial stages of producing (A1-A3) and transporting (A4) are included. The construction and installation process stage (A5) is assumed to be the same for both types of poles per the construction steps presented in Al-Haddad et al. (2022). Future research will expand this study to all life cycle stages (cradle to grave approach) including maintenance, repair, and end-of-life. Further, future work will also include a sensitivity analysis study of the results.

Energy and Environmental Impact Assessment

This study focuses on quantifying the primary energy demand (PED) and environmental impacts of the initial stages of an installed steel pole and a BladePole. The environmental impact potentials considered in this study include global warming potential (GWP) in kg CO_2 eq, freshwater eutrophication potential (EP) in kg P eq, terrestrial acidification potential (AP) in kg SO_2 eq, human/ecosystem damage ozone formation (HDOF/EDOF) in kg NO_x eq, and particulate matter formation (PM) in kg $PM_{2.5}$eq.

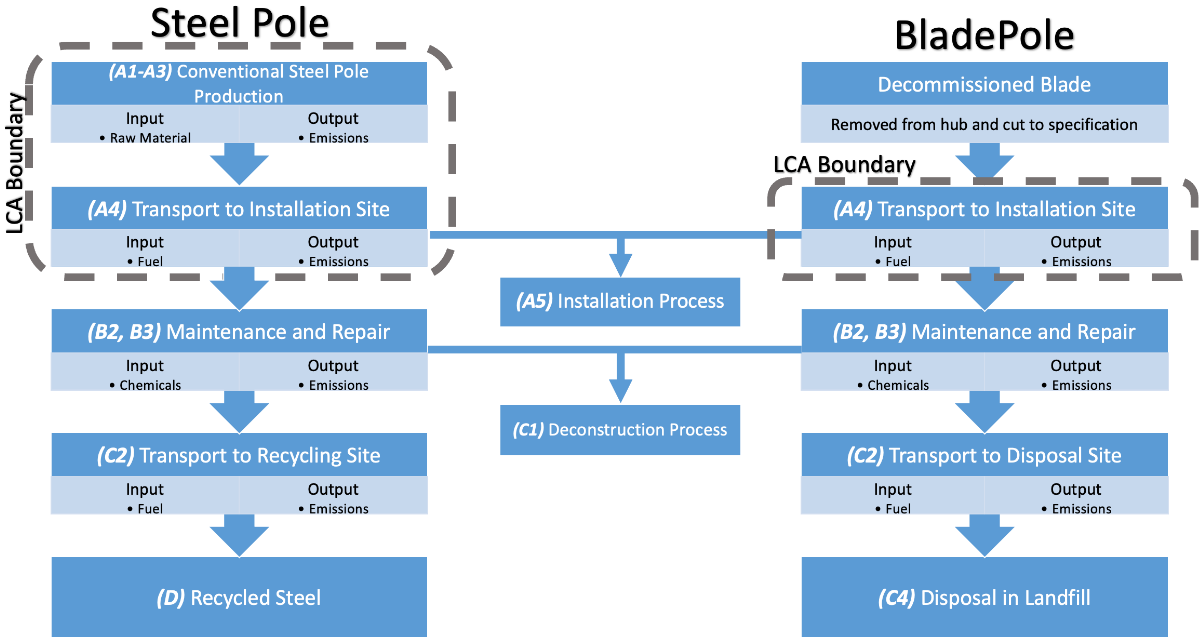


Figure 1 Boundary conditions for Steel Pole on the left and BladePole on the right. This study includes life cycle stages A1-A4 for the steel pole and stage A4 for the BladePole.

Life Cycle Inventory Data

All data was collected from 2019 databases since it was the latest and most complete data across sources. The emissions and energy consumption of the production of steel components was obtained from the American Galvanizer Association environmental product declaration of hot-dip galvanized steel after fabrication (AGA EPD 2022). The transportation emissions and energy consumption of a combination truck were obtained from the U.S. Environmental Protection Agency (U.S. Bureau of Transportation Statistics, 2019, 2021b, 2021a).

RESULTS

For the product and construction stage of the process per Figure 1, the data collected is presented and analysed to recognize its significance in the LCA process:

Product Stage

Module A1-A3 Raw material supply, transportation, and manufacturing

Conventional Steel Pole:

Only higher-grade applications of steel, like rolled sheet, are made from virgin materials (Allwood 2014); therefore, steel poles are typically made of recycled steel. Furthermore, hot dip galvanizing after steel fabrication is used to reduce steel corrosion for applications subjected to harsh environments, just like it is the case of energy transmission poles. Energy and emissions data was collected from the AGA EPD in their cradle-to-gate study (Modules A1-A3) of hot-dip galvanized steel after fabrication of hollow structural sections (2022). The EPD results are provided per metric ton, and therefore, an average pole weight of 2.952 tons is used to calculate the energy and environmental emissions for one steel pole (see Table 1). The primary energy demand consists of the sum of the renewable and non-renewable primary resources used as energy carrier presented in the AGA EPD (2022).

Table 1. Resource Use and Environmental Impact: Production of one Hot-Dip Galvanized Steel Pole

Resource Use	**Unit**	**Total**
Primary energy demand	PED (MJ)	102,611
Environmental Impact	**Unit**	**Total**
Global Warming Potential	GWP (kg CO_2 eq)	7,321
Acidification Potential	AP (kg SO_2 eq)	17.9
Eutrophication Potential	EP (kg N eq)	1.1

Repurposed Composite Pole:
Decommissioning: this stage is not included in the analysis because this study considers the blade on the ground at the wind farm as raw material, as the removal of the blade from the hub is a process that would have happened regardless of repurposing, recycling, or disposing of the blades.

Re-Manufacturing: In this stage of the process, manufacturing of the pole is not considered in this study because the composite blade was initially designed and accounted for as a wind turbine; only the re-manufacturing of this object into a pole is considered. The remanufacturing stage consists of either using a blade with a similar pole length (GE37) or cutting the blade to the required length (100 ft). For a GE37 wind blade (125 ft long approx.) to be converted into a 100 ft pole, a specialized diamond blade circular saw is used to cut the tip of the blade at the 100 ft mark. This process lasts less than an hour and it is considered to have a minimal effect on the overall results. Therefore, the remanufacturing process is considered neglectable.

Construction Process Stage
Module A4 Transportation
Transportation energy demand and environmental emissions can be found in Table 2. Because the distance between pick up point and drop off destination varies, the values in Table 2 are provided per mile to account for the variability in distances.

Table 2. Resource Use and Environmental Impacts: Transportation

Resource use	**Unit**	**Total**
Primary Energy Demand	MJ/mile	20.98
Environmental Impacts	**Unit**	**Total**
Global Warming Potential	kg CO_2 eq/ mile	7.34
Acidification Potential	kg SO_2 eq/mile	1.65E-03
Human Damage Ozone Formation	kg NO_x eq/mile	4.61E-03
Ecosystem Damage Ozone Formation	kg NO_x eq/mile	4.63E-03
Particulate Matter Formation	kg $PM_{2.5}$ eq/mile	1.39E-04

Conventional Steel Pole:
To calculate transportation energy and emissions, this study calculates transportation from the manufacturing facility to the installation site. Also, emissions are considered for the return of the empty truck to the manufacturing facility at an 80% capacity. Steel poles are transported in sections and assembled on site. Typically, steel poles have a base diameter of 30 in for a 100 ft long pole. In this study, we perform a sensitivity analysis that calculates for best case, base case, and worst-case scenario as one, one and a half, and two steel poles are fitted per truck, respectively. The best-case scenario is considered when one steel pole is transported per truck since it gives BladePoles a one-on-one transportation comparison and an advantage for the resources used and greenhouse gas emissions from the production of steel poles.

Repurposed Composite Pole:
For BladePoles, this study calculates energy and emissions due to transportation from the decommissioned wind farm location to the installation site. Also, emissions are considered for the return of the empty truck to the wind farm at an 80% capacity. Because BladePoles are light weight and high in volume, typically only one blade can be transported per truck. The calculations and results in Table 2 are applied to the BladePole transportation calculations.

Comparison between BladePole and Steel Pole
Equation 1 presents the methodology for calculating the total primary energy demand and environmental impacts of producing and transporting a steel pole and transporting a BladePole. The results can be found in Table 3.

$$Total_{ij} = Production_{ij} + \mathrm{c} \cdot \left(\frac{Transportation_i}{n_j} \cdot Miles\right) \qquad \text{Eq. 1}$$

Where,

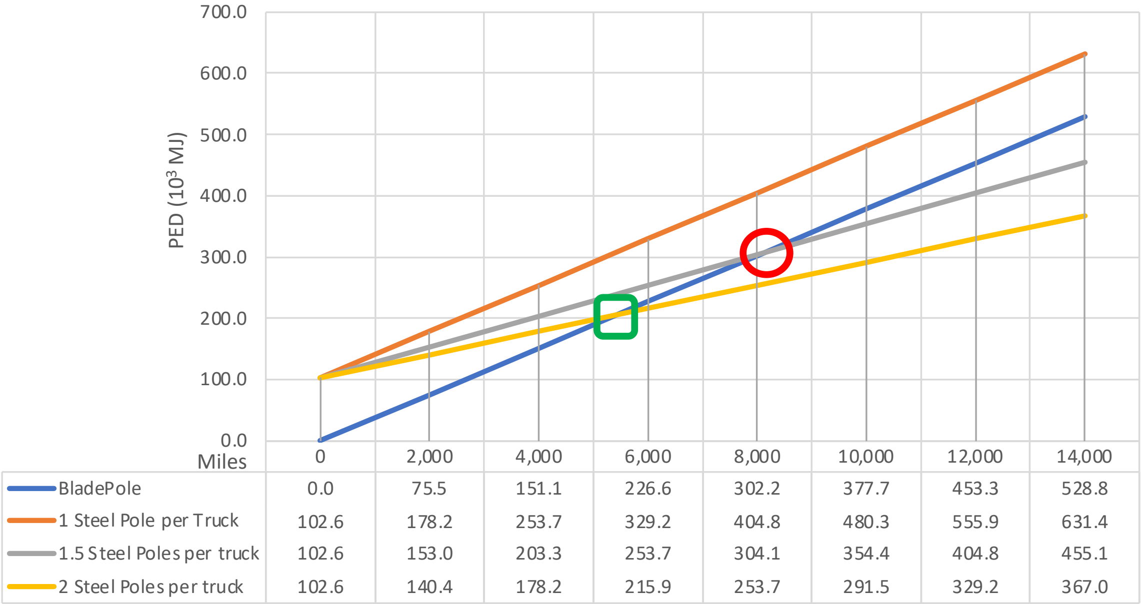
i=1, Primary Energy Demand; i=2, Global Warming Potential
j=1, BladePole; j=2, steel pole
Production: refer to Table 1 for steel pole, BladePole $\text{Production}_{11}=\text{Production}_{21}=0$
c=1.8, accounts for transportation from pick up to drop off location and 80% return (refer to Module A4 Transportation)
n=number of poles transported per truck
Transportation: refer to Table 2
Miles: distance from pick up to drop off (refer to Module A4 transportation)

Table 3 LCA Results, per one 100 ft long energy transmission pole

			Miles							
Options	Impact	Units	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000
BladePole	PED	10^3 MJ	-	37.8	75.5	113.3	151.1	188.9	226.6	264.4
(One per truck)	GWP	ton CO_2 eq	-	13.2	26.4	39.7	52.9	66.1	79.3	92.5
	AP	kg SO_2 eq	-	2.97	5.94	8.90	11.87	14.84	17.81	20.77
	HDOF	kg NO_x eq	-	8.30	16.59	24.89	33.19	41.49	49.78	58.08
	EDOF	kg NO_x eq	-	8.33	16.66	24.99	33.32	41.65	49.98	58.30
	PM	kg PM2.5e	-	0.25	0.50	0.75	1.00	1.25	1.50	1.75
Steel Pole	PED	10^3 MJ	102.6	140.4	178.2	215.9	253.7	291.5	329.2	367.0
(One per truck)	GWP	ton CO_2 eq	7.3	20.5	33.8	47.0	60.2	73.4	86.6	99.9
Best case	AP	kg SO_2 eq	17.9	20.8	23.8	26.8	29.7	32.7	35.7	38.6
	EP	kg N eq	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	HDOF	kg NO_x eq	-	8.3	16.6	24.9	33.2	41.5	49.8	58.1
	EDOF	kg NO_x eq	-	8.3	16.7	25.0	33.3	41.6	50.0	58.3
	PM	kg PM2.5e	-	0.3	0.5	0.8	1.0	1.3	1.5	1.8
Steel Pole	PED	10^3 MJ	102.6	127.8	153.0	178.2	203.3	228.5	253.7	278.9
(1 ½ per truck)	GWP	ton CO_2 eq	7.3	16.1	24.9	33.8	42.6	51.4	60.2	69.0
Base case	AP	kg SO_2 eq	17.9	19.8	21.8	23.8	25.8	27.8	29.7	31.7
	EP	kg N eq	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	HDOF	kg NO_x eq	-	5.5	11.1	16.6	22.1	27.7	33.2	38.7
	EDOF	kg NO_x eq	-	5.6	11.1	16.7	22.2	27.8	33.3	38.9
	PM	kg PM2.5e	-	0.2	0.3	0.5	0.7	0.8	1.0	1.2
Steel Pole	PED	10^3 MJ	102.6	121.5	140.4	159.3	178.2	197.0	215.9	234.8
(Two per truck)	GWP	ton CO_2 eq	7.3	13.9	20.5	27.1	33.8	40.4	47.0	53.6
Worst case	AP	kg SO_2 eq	17.9	19.3	20.8	22.3	23.8	25.3	26.8	28.2
	EP	kg N eq	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	HDOF	kg NO_x eq	-	4.1	8.3	12.4	16.6	20.7	24.9	29.0
	EDOF	kg NO_x eq	-	4.2	8.3	12.5	16.7	20.8	25.0	29.2
	PM	kg PM2.5e	-	0.1	0.3	0.4	0.5	0.6	0.8	0.9

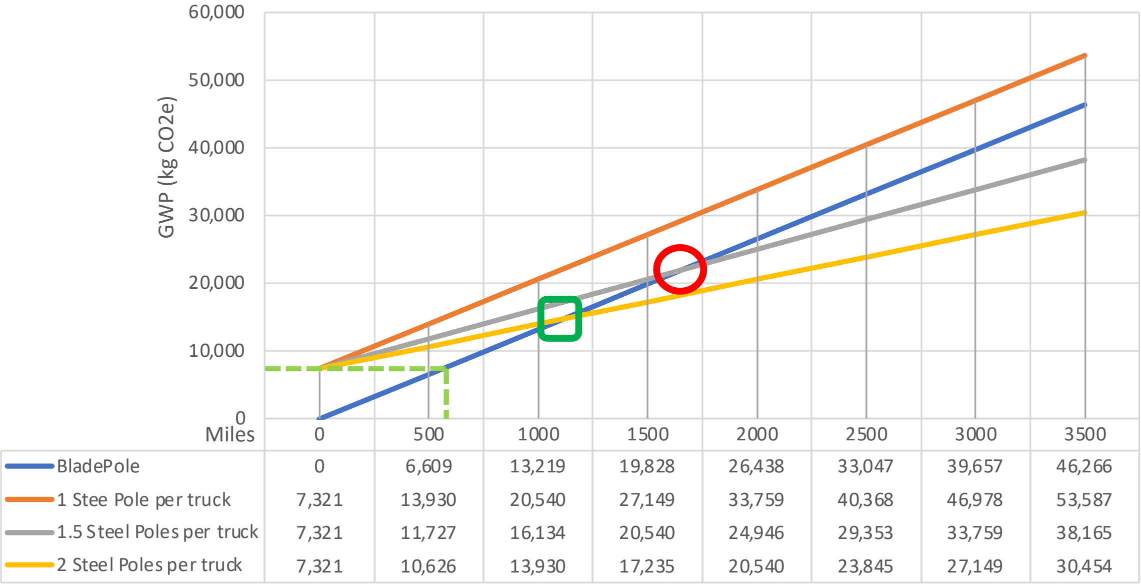
Primary Energy Demand

Table 1 and 2 primary energy demand values are considered to calculate the total energy demand for the production and transportation of a steel pole or BladePole per mile using equation 1. The results show that the production of a steel pole provides an initial advantage to the implementation of the BladePole. However, transportation plays a key role since BladePole energy demand increases at a higher pace than the steel pole for two or the three scenarios (worst and base case). In Figure 2, we find in the worst-case scenario that after two steel poles per truck and one BladePole per truck are transported for 5,400 miles (refer to green square in Figure 2), the primary energy demand of transporting a BladePole surpasses the production and transportation of a steel pole. In the base case where one and a half steel poles are transported per truck, the intersection point occurs at the 8,150 miles mark (refer to red circle in Figure 2). From this point on, the energy demand of BladePoles is higher than the steel poles, expect in the one-to-one best-case scenario.



Miles	0	2,000	4,000	6,000	8,000	10,000	12,000	14,000
BladePole	0.0	75.5	151.1	226.6	302.2	377.7	453.3	528.8
1 Steel Pole per Truck	102.6	178.2	253.7	329.2	404.8	480.3	555.9	631.4
1.5 Steel Poles per truck	102.6	153.0	203.3	253.7	304.1	354.4	404.8	455.1
2 Steel Poles per truck	102.6	140.4	178.2	215.9	253.7	291.5	329.2	367.0

Figure 2. Primary Energy Demand Comparison between BladePole and Steel Pole



Miles	0	500	1000	1500	2000	2500	3000	3500
BladePole	0	6,609	13,219	19,828	26,438	33,047	39,657	46,266
1 Stee Pole per truck	7,321	13,930	20,540	27,149	33,759	40,368	46,978	53,587
1.5 Steel Poles per truck	7,321	11,727	16,134	20,540	24,946	29,353	33,759	38,165
2 Steel Poles per truck	7,321	10,626	13,930	17,235	20,540	23,845	27,149	30,454

Figure 3. Global Warming Potential Comparison between (1) BladePole and (2) Steel Poles transported

Global Warming Potential

Like primary energy demand, global warming potential is calculated using equation 1. The results show that the production of a steel pole provides an initial advantage to the implementation of the BladePole. However, transportation plays a key role since BladePole greenhouse gas emissions increases at a higher pace than the steel pole for two or the three scenarios (worst and base case). In the worst-case scenario, the intersection occurs much earlier than in the primary energy demand at about 1100 miles (refer to green square in Figure 3). In the base case, the intersection point occurs at the 1,660 miles mark (refer to red circle in Figure 3). From this point on, the greenhouse gas emissions for BladePoles are higher than for steel poles, expect in the one-to-one best-case scenario. In this scenario, steel poles and BladePoles are transported one per truck, in which case the production of steel pole greenhouse gas emissions accounts for 550 miles of transportation (refer to dotted green lines in Figure 3). Therefore, BladePoles can be transported 550 additional miles than steel poles.

In Figure 4, we can see a simplified scope of transporting BladePoles by truck in the United States. On the left side of Figure 4, we can see the best-case scenario with the 550 additional miles that a BladePole can be transported before a steel pole is even transported. The right side of Figure 4 presents the worst-case scenario and shows the extent to which both a steel pole and a BladePole can be transported per truck before BladePoles' GHG emissions surpass those of producing and transporting a steel pole. Further detailed research is required to account for miles on road and to further expand to other modes of transportation like rail roads.

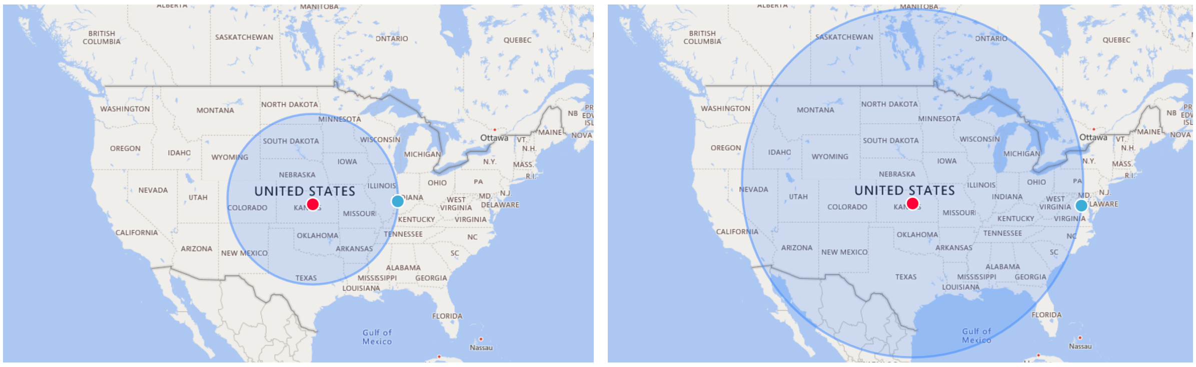


Figure 4 United States of America map radius of 550 miles (left) and 1100 miles (right) (Map Radius Calculator, 2015)

CONCLUSION

This study introduces the initial life cycle assessment of repurposing wind turbine blades into energy transmission poles. This structure, called the BladePole, fulfils the same functional requirements as traditional steel poles. Therefore, this research focuses on the comparative lifecycle assessment of the BladePole to conventional steel poles production and transportation. Based on the results of this preliminary study, we are looking to assess the environmental impacts of the decisions we make regarding transportation. Our results show that the environmental impact of wind turbine blades compared to conventional steel poles are dependent on the distance that the material would need to travel, and the total weight of the hot dip galvanized steel used for a steel pole. This research is looking to gage the sensitivity of transporting steel poles and BladePoles.

Our initial results of the comparative life cycle assessment show that using BladePoles in the energy transmission industry is environmentally viable. In the worst-case scenario, the primary energy demand and global warming potential of the BladePole is higher than the Steel pole after they have been transported 5,400 miles and 1100 miles respectively. In the best-case scenario, BladePoles can be transported 550 additional miles than steel poles.

We aim to expand our research to include all the lifecycle stages and include a sensitivity analysis for remanufactured blades, steel pole weight, and end-of-life decisions. Our research will also expand to an LCA/LCC analysis with cost and environmental data. Future research should also focus on concrete, wood, and composite poles. Understanding the environmental impact of a new material introduced in the energy transmission industry can motivate interested parties into including this material in new energy transmission projects, help increase the robustness of the energy grid, and reduce the current and projected blade waste that is estimated to escalate rapidly.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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