Assessment of the Environmental Effects of Wind Turbines and BPA Emissions

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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THE WIND ENERGY SYSTEM

The technological system of combustible fuels and hydrocarbons in recent years has faced an increasing concern regarding their technologies and practices of sustainability. The foremost and most obvious concern regards the extractive nature of the combustible fuel system. Critics have directed attention to the apparent dwindling of the oil supply; BP in their 2019 Statistical Review of World Energy estimated a remaining world reserve of 1.73 trillion barrels of crude oil at the end of 2018 (BP, 2019). The conclusion for the combustible fuel system made was a 50-year limit if production were to remain at the 2018 average of 82-84 million barrels per day. This concern increased proportional to the continual increase in oil extraction, to the 2021 figure of 89.9 million barrels per day. Similar dismal criticisms have since been made regarding coal and natural gas, with the Energy Information Administration reporting a continual decrease in the United States' proven natural gas reserves – from 473.3 trillion cubic feet in 2020 from the estimated 495.4 trillion cubic feet the year prior – marking a 4% decrease (U.S. EIA, 2020). Excluding any unproven reserves of natural gas and applying the assumption of a constant consumption rate, the United States' proven natural gas reserve will last the nation a mere 12 years. The disappointing statistics have brought forth a societal frenzy attempting to decouple the energy industry from natural gas, coal, and combustible fuels.

The technological system of wind turbines has since been proposed as an alternative, renewable source of electricity generation. The mechanical concept is simple; strong air currents impart a force against the turbine blades. The movement of the blades imposes torque onto a mechanical shaft connected to an electromagnetic induction generator, resulting in electric current. As of the year 2021, there were 341,000 wind turbines in operation throughout the world, yielding a power generation of 1870.3 TWh of electricity; a 273 TWh increase from the year prior, and power capacity of 830 GW (IEA, 2022). Wind farms in the United States is considered the greatest source of renewable energy, contributing 27% of the total renewable energy generated in 2021. The average onshore wind turbine is designed with a capacity of 2.5-3 MW and 3.6 MW for offshore variants, designed to provide more than 6 million kWh a year. Recent developments of offshore wind turbines have introduced offshore wind turbines rated at 6 MW, namely the Haliade 150, with 2035 projections to attain power ratings of 17 MW, towering at 495 ft with a rotor diameter of 820 ft. If applied directly to the average household electricity consumption, a conventional onshore wind turbine could supply adequate electricity to 1500 European homes or 940 American households (U.S. Energy Information Administration, 2021).

The technology of the wind turbine as an alternate, secondary power generation source has been proven through onshore and offshore wind farms. A wind farm housing anywhere from a 10 to a few dozen can adequately supply energy to a small town without issue. However, this is a system that has been proposed to replace the hydrocarbon fuel energy system on the grounds of clean, renewable energy. This paper seeks to answer the question: how clean and renewable is energy sourced from wind turbines? Can engineers make a case for the wind turbine system without compromising any ethical boundaries?

Evaluating the Technological System of Wind Turbines

The growing scale of wind turbine rotor blades has resulted in the widespread implementation of fiber-reinforced composite materials. These are axial particulates embedded in a matrix material, resulting in a material with high specific strength and stiffness properties, ideal for slender load-bearing structures. Fiber-reinforced composites have exhibited great performance as primary materials of wind rotor blades, with longitudinal strength of carbon-reinforced fiber composites exceeding that of steel without the requirement of extensive machining processes. Most modern blade designs employ composites featuring a thermoset polymer matrix, such as epoxy or polyester reinforced by glass or carbon fibers. The applications of these composites are widely varied; from laminates of multiple and variably oriented, unidirectional plies at thin sectioned regions of the blade, to a laminate of biaxial or triaxial weave plies for maximizing macroscopic strength (Keegan, 2013). Larger blade designs can reduce blade weight by replacing the section core with a sandwich of materials including balsa wood and polymer foams as mitigative measures against buckling near the trailing edge and central spar (Buckney, 2012).

Wind turbines must operate in areas of frequent inclement weather; the volatile meteorological conditions cause the rotor blades to suffer impacts from raindrops, hailstones, and particulate matter at high speeds. This interaction with the environment removes material from the blades, reducing turbine efficiency and drastically increasing the fatigue rate of the wind turbine if maintenance is negligent; decreases in turbine performance due to leading edge erosion can manifest after only two years of operation, a mere tenth of the expected 20-year lifespan (Wood, 2011). Dry climates with less exposure to inclement weather exhibit similar negative conditions on turbine operations. Composite materials are especially vulnerable to these effects.

The major disadvantages of fiber-reinforced composites are their poor performance with respect to transverse shear stresses and high sensitivity to environmental factors. Exposure to ultraviolet light has been shown to decrease the ultimate strength, tensile modulus, and failure strain of polyester resin composites by 30%, 18%, and 15% respectively (Shokrieh and Bayat, 2007). Glass fiber reinforced polyester composites, under same conditions, experienced a 20% decrease in the shear modulus. Carbon reinforced epoxy composites, under UV exposure, experienced a reduction of matrix-dominated properties; namely, a 29% reduction in transverse tensile strength (Kumar, et al., 2002). While composite fibers do not typically bear transverse loads, the reduction in material properties have significant impacts on the overall lifespan of the rotor blade. Rotor blades experiencing leading edge erosion subsequently exhibit a decrease in available protective surface coating, exposing the composite substrate to water, hail, humidity, and saline effects. Of typical composite matrix materials used in wind rotor blades, epoxy resins exhibit good resistance to water degradation, whereas polyester and vinylester do not. A thin polyester laminate, after a year of water immersion, retained only 65% of its interlaminar shear strength, and 90% of epoxy laminates (Gurit, 2013). Experiments conducted by the University of Strathclyde indicated for turbine blades constructed with an uncoated epoxy matrix, rainfall conditions of 50 mm per month resulted in a corresponding 0.037% mass loss, and for rainfall conditions of 500 mm per month, mass loss could be expected to reach 0.199%, with an expected 40% increase of mass loss for salinity conditions (Pugh and Stack, 2021). Turbine blades classified in the 2-3 MW range with an uncoated epoxy matrix were then expected to shed an approximate 3.7-5.97 kg of pure BPA annually in mild to moderate rainfall, low particulate (sand, hail) and low salinity conditions due to erosion factors.

The direct consequences of microplastics are severe, especially concerning composites with an epoxy-resin matrix. Epoxy, in contrast to polyester, contains a Bisphenol A (BPA) composition content of 33-35%. BPA can be found in a myriad of products polycarbonate plastics and resins, covering a diverse span of industries and applications; BPA particulates can transfer from their container resins to food and water in the case of physical wear, thermal shock, rises in temperature, microwave exposure, or through chemical reactions via contact with acidic or alkaline substances. Deposition of BPA-containing products and particulates into rivers and marine bodies of water are significant sources of aquatic environment pollution. BPA concentrations is significantly noticeable in wastewater treatment plants of high plastic waste generation; analysis of wastewater sludge indicates a significantly greater composition of BPA than wastewater (Meesters, and Shroder, 2002).

BPA is biodegradable by composition and can be degraded by aerobic bacteria, posing an environmental half-life of 4.5-4.7 days. This process, however, slows down significantly in oxygen-depleted conditions, decomposition rates in anaerobic sediments can extend upwards to several weeks (Voordeckers, et al., 2002). BPA that becomes partitioned in water evaporates slowly due to its moderately high solubility (120 mg/l) and low partitioning coefficient with respect to octane and water (Borrirukwisitsak, et al., 2012). In environments of soil with high water content, BPA can become trapped for significantly longer than its biodegradable half-life. BPA has been indicated to adversely affect plant growth and aquatic ecosystems through diffusion of BPA particulates in the soil, water, and air; moderate to high BPA concentrations suppressed root growth of plants (Li, et al., 2018), and has significant correlations with adverse neural development of aquatic animals (Franzellitti, et al., 2019).

In conjunction to environmental detriments, the health risks of BPA exposure are diverse and severe. Strong correlations have been shown of BPA exposure and chronic kidney disease (Gonzalez-Parra, et al., 2013). BPA disrupts the production and management of endocrine, leading to disruption of thyroid function (Moriyama, et al., 2002). Studies have been conducted that indicate moderate to strong correlations of chronic BPA exposure and genetic diseases, albuminuria and cardiovascular disease, reduction in sperm and ovary quality (Yang, et al., 2016), and behavioral and cognitive impairments in children (Rodriguez-Carrillo, et al., 2019). Studies using animal models have displayed BPA interference with germ cell nest disintegration (Zhou, et al., 2015). BPA has been indicated to function as an obesogen. This is due to the activation of certain nuclear transcription factors such as peroxisome proliferator-activated receptor (PPAR) alpha, delta, gamma, and some steroid hormone receptors that regulate the proliferation of adipocytes; these receptors influence lipid metabolism, of which the abnormal interaction and activation with BPA has contributed significantly to weight gain (Andujar, et al., 2019).

Evaluating the Environmental Case for Wind Turbines

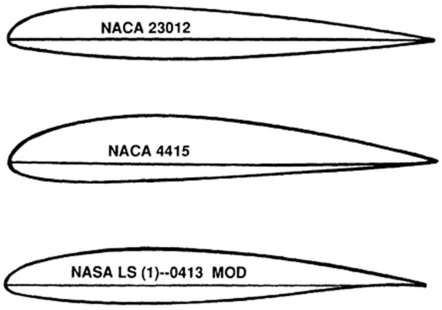

Figure 1. Common, early Wind Turbine airfoils (National Research Council, 1991)

The maximum BPA concentration of drinking water is defined at 1.5 mg/L by the United States Environmental Protection Agency. The WHO's definition for the advised maximum BPA concentration as 0.1 micrograms per liter (World Health Organization, 2019). A simple conversion of scale would yield the relation of 1 gram of BPA as sufficient for polluting 10 million liters of water. Wind turbines formed of epoxy composites expect a BPA weight factor of roughly 13-15% of the rotor blade; for wind turbines that utilize Bisphenol A diglycidlyl ether (abbreviated as BADGE or DGEBA) as the primary liquid resin infusion, the pure BPA content amounts to roughly 2 wt% (United States Library of Medicine). This residual BPA is not trapped within the reinforced epoxy matrix, and as such can directly precipitate out of the structure through temperature and chemical interactions. The approximate BPA content dedicated to the leading edge is dependent on the airfoil geometry. For early horizontal axis wind turbine designs, the leading edge can be approximated to

5-7% of the total epoxy required, as characterized by the figure on the right. From this approximation, a 3.5 MW wind turbine has a potential pure BPA content of 1.56 kilograms to 2.52 kilograms embedded along the leading edge of each 12-ton blade. A wind turbine of such power rating and blade sizing, equipped with 3 blades, the leaching of pure BPA particulates alone would then possess a theoretical maximum polluting potential of 46.8 to 75.6 million liters of water according to the WHO's standards, or 1,040-1,680 liters by the limit established by the Environmental Protection Agency. This figure is only bound to increase once erosion effects are considered; if the Strathclyde study is taken at face value, a single turbine blade operating in worst-case environmental scenarios could contribute to an additional 0.57 to 3.58 kilograms of epoxy particulates dispersed into the surrounding environment per month.

The evaluation of conventional wind turbines in academia with regards to LEE is framed under the concept of annual energy produced, or AEP, instead of monthly mass loss rates. The concept of AEP can be sourced from the derivation of the Betz limit, as treating the rotor hub as an actuator-disk model allows for an approximation of the power available to a wind turbine such that $Power = \frac{1}{2} A\rho c_f v_{wind}^3$ (Ahammed, 2021). This approximation has been further refined through the introduction of computational fluid dynamics simulations, of which the specific chord lengths, chamber, and curves of the airfoil can be modeled for a more accurate calculation of the power output. Analysis of wind turbines and their operations can give insight to their long-term performance in a designated environment, and overall, their profitability in the face of detrimental phenomena such as LEE. In the case of LEE, academia has brought forth several estimates for reductions and losses in AEP – of up to 7% loss in AEP for a 5 MW Turbine (Schramm, et al., 2017), with an estimated range of 3-5% of AEP loss for light erosion and up to 25% for severe erosion (Sareen, et al., 2012) for turbine blades with protective tape coatings. Conventional, lifespan estimations of LEE define AEP losses of more than 5% (U.S. Department of Energy, 2017) and potentially up to 7% (Chamberlain, 2017).

Correlating AEP losses to monthly mass erosion rates is beyond the scope of this paper as the principal methods of such involve highly intensive computational fluid dynamics models, stress and fatigue analyses involving rain and hail impact simulations. Even the assumption via the power equation proves difficult as the reduction of wind velocity corresponding to AEP losses must be known for any estimates on the reduction of mass along the leading edge to be derived. Visual observations can however provide a preliminary estimates on the mass losses of LEE for conventional wind turbines, as depicted in Appendix A.

The Ethical Case of Wind Turbines

Professional engineers are expected to adhere to and are judged by codes of conduct and guiding protocols respective of their professional field, each referencing in some part the code of ethics defined by the Society of Professional Engineers (NSPE) Code of Ethics. Many ethical codes center around the core tenets of honesty, impartiality, fairness, equity, and dedication to the protection of public health, safety, and welfare. Engineers must "not only perform under a standard of professional behavior that requires adherence to the highest principles of ethical conduct" (National Society of Professional Engineers, 2019), but also make known to their employers or clients of any deceptive elements or practices made known to their notice. Many ethical codes of specialized professions make certain of the rules of conduct expected from every member of their society, not excluding the precautions against scientific misconduct, conflicts of interests and abuses of power, standards of publications, and measures of maintaining accountability. These codes of ethics establish the boundary of engineering responsibility as within the specialized field determined by the association; the American Society of Mechanical Engineers, for example, restricts the role of engineers from providing services beyond their professional competence, albeit as a means of preventing unfair competition (American Society of Mechanical Engineers, 2023) with regards to opportunity and merit.

The figures in Appendix A indicate a significant possibility for the core epoxy matrix to be exposed after a year of operation for onshore turbines, and significant delamination after 5-10 years. While it is unlikely for the upper bounds established by the Strathclyde study to be observed in practical operations, exposing the epoxy matrix along just a third of the leading edge can potentially result in kilograms of epoxy-resin particulate laden with BPA to be released monthly – more when considering the precipitation of pure BPA particulates from changing temperature, humidity, and salinity conditions. Replacing carbon emissions with BPA emissions – can the case truly be made in good moral and ethical considerations when the adverse effects of BPA on humans and wildlife are known? Concerns regarding the health effects of BPA have been made known since the early 2000s, with 50 μg of BPA per kilogram of body mass per day was set as the tolerable daily intake by the European Food Safety Authority (ESFA, 2007) and the United States Environmental Protection Agency (EPA, 2009) from ingestion, inhalation, and precipitation of BPA. This concern can only exacerbate as the number of wind turbines increases.

The societal demand from wind turbines is continual electricity generation of sufficient scale for industry, transportation, and residential needs. As wind turbine blades create turbulence in the surrounding land area, the requisite space required for wind turbine operation can range from 150 meters from any nearby obstruction to 7 rotor diameter lengths for maximum efficiency (Meyers, 2011). A 2 MW onshore wind turbine with an 80-meter rotor diameter would require a minimum of 560 meters of spacing from any obstruction for maximum efficiency, or half a square kilometer. If the assumptions of maximum capacity factor of 45% for modern wind turbines is applied

(Burton, et al., 2021) and ideal operating conditions are applied, to match the annual power generation of a 500 MW coal-fired plant operating at 33% efficiency for coal-fired power plants (United States Department of Energy, 2023) requires 450 2 MW wind turbines and 225 square kilometers of land. This configuration would then correspond with a collective maximum potential pure BPA content of 2835 kilograms along the leading edge of the wind turbines disregarding LEE erosion rates. For offshore wind turbines, with greater power ratings and subsequent blade lengths and mass, would require far greater spacing to maintain efficiency, and generate far more BPA emissions over a greater region.

In no case can an ethical or good-faith argument be made in favor of replacing carbon emissions with BPA emissions as a proposal to replace hydrocarbon fuels with wind energy. This is even more true when considering that the energy yield of wind turbines is far inadequate to justify a major energy transition; the energy consumption of the United States in 2021 amounted to 98 quadrillion Btu or 28.7 quadrillion watt-hours, 12% of such figure sourced from renewable sources and 27% of such renewable sources dedicated to wind energy (United States Energy Information Administration, 2021), or 3.2% of the total energy consumed. If socio-political resolutions such as the Green New Deal are to be considered that intend to “meet 100 percent of the power demand in the United States through clean, renewable, and zero-emission energy sources” (H.R. 109, 2019), and the proportion of wind energy to other renewable sources is maintained, just the potential precipitation of pure BPA particulate along the leading edge of such wind turbines can exceed 22.9 million kilograms, disregarding all other forms of particulate emission, required land or marine territory.

This figure becomes grossly accentuated when considered alongside oncoming socio-technological trends. Recent years have observed an increased number of social, economic, and political institutions advocating for the use of electrified or hybridized methods of transportation on grounds of economic and environmental benefits. These advocates in the United States are supported by federal tax credit, state and utility incentives that attempt to offset some of the initial costs required in the implementation of electric vehicles. Namely, the Qualified Plug-In Electric-Drive Motor Vehicle Tax Credit provides individual customers with a $2,500-$7,500 tax credit for electric vehicle purchases from manufacturers not yet eligible for certain vehicle sales thresholds until the year of 2022 (Internal Revenue Service, 2023), with “clean vehicle credits” available for purchases made in 2023 and beyond, upwards of $4,000 for used vehicles and $7,500 for new electric vehicle purchases (Internal Revenue Service, 2023). Rebates can additionally be found per state policies, and several have passed laws that ban the sale of new gas-powered vehicles by 2035 as part of their zero-emission vehicle programs (California Air Resources Board, 2022). These factors, originating from social, political, or economic sources, converge into 10.6 million global electric vehicle sales for 2022 and a projected 14 million for 2023, a 35% increase (International Energy Agency, 2023). The powerplants of these vehicles would be decoupled from conventional sources of gasoline and diesel, and instead directly from electrical grids – grids that wind energy must account for should there be widespread implementation.

A standard electric vehicle can have a horsepower rating of 50 to 1000 hp, corresponding to 37 kWh-745 kWh. The most fuel-efficient category of commercial aviation, the turboprop, employs multiple engines rated at 2 MW each, a figure that increases dramatically when comparing against turbofan and turbojet aircraft utilized in domestic and international travel; the Boeing 737-800, the most popular commercial aircraft in the United States, wields an approximate 67840 hp of shaft power and burns a maximum of 62,913 kg of aviation fuel with a specific energy density of 11,944

Wh/kg (Boeing, 2013). If the engines on such an aircraft were to be converted to electric motors, the electricity required for a single 737-800 would be 751.43 MWh, the equivalent of 834.92 onshore 2 MW wind turbines operating in constant, ideal conditions. The United States alone has 841 of such Boeing 737-800s in their commercial aviation fleet during 2020 (AeroWeb, 2023) and hundreds of similarly rated, high-power aircraft. It additionally observes a national ownership of 278.06 million registered personal and commercial vehicles (United States Federal Highway Administration, 2023). The ongoing social demand is for the electrification of these vehicles and aircraft, even if by a minor fraction – electrification that wind energy must account for should it attempt to replace hydrocarbon fuels by any means. It rapidly becomes self-evident that the application of wind energy in its current state of technological development becomes unreasonable. The BPA emissions associated with such an endeavor would be too astronomical such that without major technological breakthroughs, completing the tradeoff of carbon emissions into BPA emissions in the wind turbine technology's current state would be completely unethical.

Conclusion and Future Work

The above sections have highlighted the mechanical, environmental, and health limitations of the wind turbine as an energy generation system. The scope of this paper cannot cover all limitations or characteristics of the wind turbine and its components, nor can it cover all of the potential consequences of utilizing epoxy-based materials in the construction of wind turbine blades. It is similarly impossible for this paper to proclaim a quantitative and definitive conclusion whether the health impacts incurred by the use of epoxy compounds in wind turbines are more severe than those caused by the burning of hydrocarbon fuels. There are, however, some clear cases of unethical behavior that this paper has not been able to cover; namely, the disposal methods for wind turbine blades and residual chemicals are highly not to environmental standards. The turbine blades cannot be recycled with normal measures and require extensive, highly cost-ineffective methods that have a severely negative environmental impact. As such, the industry delivers them to companies such as the Global Fiberglass Solutions; GFS, in this regard, has on multiple occasions in Iowa failed to adhere to deadlines in recycling the more than 1300 turbine blades in their disposal or burying them in certified landfills – an issue covered by multiple media outlets and unions in 2021 including Bloomberg, Union of Concerned Scientists, and Scientific American. Responses from the public indicating observations of discarded turbine blades at general landfills or alongside state or national highways, albeit not conclusive hard evidence, are indicative of unethical practices employed by the industry and their proponents. These concerns must be elevated when proposed implementations regarding wind turbines intend for this technology to be the primary source of energy generation for large-scale electricity consumers and developing technologies – electric cars, aircraft propulsion, and increasingly intensive AI applications with even higher calculation requirements – all of which are accompanied by the demand for a massive, uninterrupted electricity consumption. The hydrocarbon energy system is by all means flawed with regards to its sustainability and environmental impacts. However, to replace such a system with the wind turbine system in its current state of technological development and materials, would be to replace such a flawed system with one that is even worse.

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Appendix A. Leading Edge Erosion on Wind Turbines, Figures

Figure 2. Leading Edge Erosion. Sourced from: Rempel L 2012 Rotor blade leading edge erosion—real life experiences Wind Systems Magazine

Figure 3.Leading Edge Erosion, Onshore Wind Turbines, Years in Service. Sourced from: Powell S 2011 3M wind blade protection coating W4600 Industrial Marketing Presentation