Thesis Prospectus

Wind Turbine Blades: Modifications to Reduce Aerodynamic Noise
(Technical Topic)

Evaluating the Social Factors that Impact the Implementation of Wind Turbines in the U.S.
(STS Research Topic)

An Undergraduate Thesis Prospectus

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Megan Anderson

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Technical Project Team Members:

Nathan Jacobson
Caleb Owen
Levi Otis
Justin Smith

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

Advisors

S. Travis Elliott, Department of Engineering and Society

Dr. Michael Momot, Department of Mechanical and Aerospace Engineering

Introduction

Since the environmental movement kicked off in the late 1960s, the public push for stricter legislation against pollution has driven the explosive growth of the renewable energy sector. More specifically, the development of technology has allowed the electricity sourced from wind energy to reach 7.3% of total domestic electricity generation, equivalent to 300 billion kilowatts-hours, in 2019 (Energy Information Administration [EIA], 2020). However, it is important to understand the sociotechnical factors that influence the development of wind energy to best outline and support its expansion.

The technical project aims to optimize the rotor blade design of a horizontal axis wind turbine to reduce noise generation. General stress and finite element analysis of the blade types will be performed before validation of the model blades through product testing in a wind tunnel. To determine the impact of the blade design on system characteristics, the team intends to measure sound production and power generation in conjunction with wind speed and compare these results to a standard wind turbine blade.

Furthermore, the STS research project aspires to analyze the societal factors that shape the development of wind energy in the United States. Using historical context to examine the evolution of wind turbine technology by ways of legislation and social change, this project intends to qualify the influence of these sociotechnical relationships on the growth of the wind energy sector.

Technical Project Topic: Examining the Effect of Blade Design on the Propagation of Wind Turbine Noise

The objective of the technical project is to develop a design that reduces noise generation from rotor rotation. For the fall semester, the team will focus on concept design to generate a scale prototype optimized using structural analysis techniques. This research will culminate in a technical report that summarizes the experimental results of product testing through quantitative measurements of power generation, efficiency, and sound production.

As the most rapidly growing sector of renewable energy, a common complaint about wind turbines from nearby residents stems from noise disturbance. A review conducted by an expert panel distinctly linked turbine noise to increased levels of annoyance with some evidence pointing towards a correlation between the noise and sleep disturbance (Council of Canadian Academies, 2015). Further studies indicate that residents are more irritated by wind turbine noise than transportation noise of the same magnitude (Pedersen & Perssen, 2004). This adverse social response to wind turbine expansion, especially in rural settings, proposes a barrier to further growth of the industry. Through this technical project, the team aims to investigate the fluid dynamics of popular turbine blade designs and their impact on noise generation.

Technical Background

The noise generated from turbines falls into two distinct categories based on source: mechanical and aerodynamic noise. Mechanical noise originates in the nacelle due to the various mechanical components including the gearbox, cooling fan, generator, and other subsidiary devices (Dai, Bergot, Liang, Xiang, & Huang, 2015). It has a tonal quality, meaning that the sound is characterized by a discrete range of frequencies that occur due to instabilities as air passes over discontinuities in the material like holes or slits (Dai et al., 2015). While this form of noise is considered harsh to the ear, it can be easily resolved through the proper insulation of the nacelle and the use of sound absorbent materials to increase vibration suppression (Deshmukh, Bhattacharya, Jain, & Paul, 2019).

Consequently, the goal of noise reduction primarily focuses on aerodynamic noise, the resultant disturbances due to the interaction between air flow and blade surface. This noise classification can be further divided into the subcategories of inflow turbulence, trailing edge, and tip noise. Turbulence inflow noise comes from the impact between the blade surface and the inflow. According to Curle's unsteady surface pressure theory, the atmospheric turbulence generates unsteady pressures on the rotor that develop into sound waves as they hit the blade (Buck, Oerlemans, & Palo, 2016). This sound source is responsible for the low frequency broadband noise and remains highly dependent on the atmospheric turbulence intensity and structure (Buck et al., 2016). Its dependence on variable atmospheric inflow conditions make it difficult to moderate the source of this noise. However, some modifications to the leading edge of the blade have shown promise in minimizing its effects. For example, troughs generate vortices that increase momentum exchange to stabilize the boundary layer of incoming airflows, reducing sound propagation (Deshmukh et al., 2019).

Trailing edge noise is considered a dominant component of total noise generation attributed to wind turbines. When the boundary layer interacts with the sharp trailing edge, the turbulent eddies that form produce the high pitch sound most commonly associated with the spinning blades (Deshmukh et al., 2019). Additionally, the trailing edge noise is most significant at higher velocities because the region of noise generation shifts towards the blade tip, where the air flow is the most turbulent (Deshmukh et al., 2019). Moreover, the proportionality relationship between sound scattering and eddy path indicates that noise generation is maximized when the flow follows a perpendicular path and drops off the trailing edge (Hall & Williams, 1970). Consequently, blade modifications that soften the trailing edge and reduce angle of the flow path have proven effective at mitigating this form of noise.

Tip noise is generated by a mechanism similar to trailing edge noise, where a vortex formed from the pressure differential cross-flow interacts with the sharp tip edge and produces noise (Deshmukh et al., 2019). The broadband sound covers a wide spectrum of high frequencies fluctuating randomly, making it more perceptible and irritating to human ears. Consequently, the mitigation of tip noise has become a primary focus for turbine experts. Moreover, computational models indicate that the delay of vortex separation acts as the best mechanism for tip noise reduction (Deshmukh et al., 2019).

Technical Project Outline

Based on this research, the team has devised blade modifications that address each of the noise sources, such as nodes along the leading edge, trailing edge serrations, and winglets. The design specifications are subsequently enumerated in order to evaluate the success of the prototype following product testing. Using SolidWorks, the various rotor designs are developed alongside the standard horizontal wind turbine blade to serve as a control. These models will be run through finite element analysis software to examine the fluid flow over the blade and address any structural flaws before construction. More specifically, we will use the software to determine the necessary mesh fill for our 3D-printed blades to achieve the best balance between cost and structural integrity. The final steps before blade fabrication include dimensioning and tolerancing each of the designs to produce a scale model of a wind turbine.

The model turbine consists of a generator mounted atop a stand, where a 3D-printed hub assembly allows us to easily swap out each set of turbine blades. The generator will measure the power output of each of the turbine models as it responds to the laminar air flow sourced from the wind tunnel. Using a diaphragm to transform the vibrations into an electrical signal for measurement, we will record this data and compare it to that of the control blade taking into account the ambient sound. The difference in sound propagation across blade configurations will be verified by ear as well. Furthermore, we plan to minimize the noise interference from the wind tunnel by placing the turbine behind the apparatus, relying on the laminar exhaust air.

STS Research Topic: Evaluating the Social Factors that Affect the Implementation of Wind Turbines in the U.S.

Although the rise of wind energy has shocked the industry with a forecasted 17% growth in 2020, the contribution of this sustainable energy continues to represent a small minority of the energy generation in the U.S. (EIA, 2020). As the impact of past and current pollution continues to contribute to climate change, it's imperative to devise strategies that reduce the carbon footprint without sacrificing quality of life. The public acknowledges the importance of this issue with an overwhelming majority of 77% of those surveyed favoring the development of renewable energy sources (Funk, 2019). However, the general support of the public alone cannot alter the infrastructure of the energy sector nor erase the societal links to fossil fuels. The purpose of this STS research is to better understand these social influences and their impact on American wind energy. improving the ability of the public and policymakers to implement these systems successfully.

Definition of STS Framework

Using the Social Construction of Technology (SCOT) framework, the circumstances surrounding the development of wind energy can be analyzed through the lens of the stakeholders. Based on the concept that human actions and biases influence the success or application of a technology, this framework offers a unique perspective that enables a more complete evaluation of important social factors. Since the energy sector sits at the core of American industry and daily life, the sociotechnical analysis of these deep-rooted, social interactions is necessary to fully understand and subsequently improve wind energy implementation. Furthermore, the SCOT framework will help unravel the complexity of the issue through inspection of the historical context, the environmental reputation of wind energy, and the consequential policy and infrastructure of the electricity grid.

The key facets of this framework aside from relevant social groups are the concepts of interpretative flexibility and stabilization. Interpretative flexibility expresses that a technology can represent varying ideals across social groups, where biases influence the overall positive, negative, or neutral perception of a device. Through the analysis of the different reactions by specific subsets of a community, the gradual approval of wind turbines can be more thoroughly understood. As the relevant social groups coalesce around a single design, this point represents the stabilization of the technology and its role in society. The point of stabilization illustrates the fundamental function of the technology and the principal characteristics that render it acceptable by the public. Both of these concepts are necessary to paint a clear picture of wind turbines and the various influences that contribute to its capacity for acceptance.

Impact of Coal-Fired Industrialization on Public Perception

Widespread utilization of wind energy in America dates back to the mid-1800s, where traditional windmills were established to grind grain and pump water on farms as settlers migrated west (O'Connor & Cleveland, 2014). However, the simultaneous discovery of anthracite coal and its revitalization of iron manufacturing led to further technological developments that boosted industrialization along the eastern seaboard. With this cheap, abundant fuel, the development of machinery grew to promote the expansion of transportation through the steam engine and domination of railroads (Chandler, 1972). While coal had cemented itself as the backbone of American industry, the invention of electricity and the first coal-fired, centralized power plant in 1882 ensured its authority over the early factory economy.

Furthermore, the development of AC power stations combined with the extensive transportation networks eventually eliminated the necessity of windmills through rural electrification programs in the 1930's (Tuttle et al., 2016).

This historical context of energy in the early industrialization of the United States offers insight into the firm hold that fossil fuels have on American society. The technological advancements offered by industrialization promoted the rise of the middle class, offering them luxuries from ornate furniture to childhood education (Corbett, 2014). According to interpretative flexibility, the positive impacts that the exploitation of coal had on the overall quality of life distorted public reception to favor it. It fueled the economy, driving the advertisement of consumer products to exploit the burgeoning capacity of electricity. The association of coal with wealth and opportunity alongside materialism drove the technology forward while wind turbines remained on the sideline. It was unable to satisfy the needs of a rapidly growing country. Moreover, American industrialization propelled the nation to become an international superpower, fueling a predisposition passed down through generations to support fossil fuels and consequently neglect wind power.

Impact of Political Ideology on Public Perception

The transition from coal to oil occurred post-World War II during the automotive boom with major companies like Ford using the assembly line to cut costs (O'Connor & Cleveland, 2014). Newly attainable prices drove the automobile to become a stamp of the upper middle class. Consequently, the suburban infrastructure evolved to rely heavily on cars and unfettered access to plentiful, cheap oil. Shortly thereafter, the 1973 OPEC oil crisis pushed the country to reconsider its dependence on fossil fuels, forcing the public and government alike to focus on the diminishing supply of domestic reserves (Resilience, 2019). This international event coincided with the environmental movement that expanded throughout the 1970s, pushing legislation that would establish protections against pollution. Amidst this political turmoil, the wind turbine was revived with an alternate meaning: the solution to fossil fuel dependency and pollution.

With government policies and programs like Project Independence, the U.S. government poured money into renewable energy research and development with advancements in wind turbine technology led by NASA (Resilience, 2019). The circumstances of the time combined with the outpour of funds served to rebrand wind energy as a means of economic security for corporate entities that benefited from the boom of electricity. Additionally, the threat of foreign power associated wind turbines with the proud ideals of nationalism and independence in the eyes of the general public. Fundamental to the individualism deep-rooted in American identity, the resurgence of these principles in connection to wind energy redirected the spotlight back onto wind power.

Moreover, the acclaimed professor Bill Heronemus established the fundamentals of modern wind turbines and its importance to the environmental movement in the early 1970s (Stoddard, 2002). His congressional debate on energy policy centered the environmentalism movement around renewable technologies, while his research and design of the Wind Furnace at the University of Massachusetts-Amherst demonstrated a solution (Stoddard, 2002). As a tangible instrument of power generation, the environmental movement latched onto wind turbines as a remedy to the environmental damage caused by American industry. Given that a majority acknowledge the necessity of alternate energy resources, the environmentally friendly reputation of the technology established by the environmentalism campaign continues to influence its development today.

Impact of Infrastructure on Corporate Perception

The perception of wind energy is not only shaped by the political ideology of environmentalism, but also policy and industry infrastructure itself. Limited by the Power plant and Industrial Fuel Use Act of 1978, the utility sector instituted ambitious plans for large-scale nuclear and coal-fired power plants to substantiate demand due to their inability to access cheaper natural gas (Tuttle et al., 2016). However, the high expense of these build-outs opened the market to small-scale, independent renewable power plants selling their electricity to utilities. The government subsequently passed the Public Utility Regulatory Policies Act of 1978 to support these plants and ensure output purchase by utilities at favorable terms (Gipe, 1991). A decade later, the FERC restructured the utility sector further to promote wholesale competition via the 1992 Energy Policy Act; a fifteen percent tax credit enabled non-utility generation facilities to sell their power at market prices (Tuttle et al., 2016).

The political reconstruction of this industry with the aim to revive its domestic energy markets has marked wind energy with conflicting connotations. Tax credit and government subsidies signify minimal cost, linking wind energy with the positive ideas of prosperity and opportunity. As a result of the utility sector infrastructure, the independent nature of wind power firms further associate an entrepreneurial spirit with the technology. However, the political pressure to achieve reduced carbon emissions can cast wind power technology as a necessary yet futile endeavor in comparison to more marketable resources like natural gas. Since the utility industry structure as a wholesale market requires a reliable source of energy, the intermittent nature of wind power generation discolors it as burdensome to corporations. The unpredictability and ineffective forecasting techniques further support these interpretations since the utility systems are responsible for the subsequent reconfiguration of the power dispatch to meet grid requirements (Tuttle et al., 2016).

Temporary Stabilization of Wind Turbines in American Society

Since its widespread implementation in the early 21st century, the energy industry has changed little despite the introduction of wind turbines. For example, wind power technology has adapted to accommodate the traditional utility structure, developing as large scale wind farms remote from the load (Tuttle et al., 2016). Regardless, the public opinion corroborates a positive shift in reputation, where 85% of those surveyed in 2016 were in support of wind power expansion (Funk, 2019). This general satisfaction with the technology combined with technical and infrastructure limitations demonstrate a temporary stabilization of wind turbines as a worthwhile, secondary yet growing energy source. Moreover, the government's initial investment spurred the development of wind turbines, policy driving the technology to evolve and assert its position in the utility sector.

Conclusion

Given the global mission to rectify climate change, energy sources that are sustainable and carbon neutral are paramount to the preservation of the modern American lifestyle. By examining the historical context and policy that shapes American energy industry through the lens of SCOT, the mechanisms that promote and limit the development of wind energy can be identified and subsequently applied to nourish growth of the sector in the United States. This greater understanding will direct research to optimize wind turbine design and implementation, taking into account the social impacts of the technology and the barriers that challenge its acceptance by both industry and the public.

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