Active Control of Wind Turbine Blades to Increase Efficiency

Exploring the Ecological Effects of Wind Farm Development

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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 Current Wind Turbine Industry

Since the 1990’s the height of wind turbines has increased by 59%, and most are now reaching heights of 90 meters (EERE, 2021). For context, 90 meters is about the height of the Statue of Liberty. The taller wind turbines produce more energy than their smaller counterparts due to the fact that the swept area, or area that is traveled by the blades of the turbine, is directly proportional to the amount of power the turbine is able to produce (Sarkar & Behera, 2012).

There are many other interesting methods that have been tested to see if they increase the efficiency of wind turbines. One example is including tubercles on the trailing edge of the blade. Tubercles are ridges that are modelled after the ones found on the fins of humpback whales. There are multiple ways that they improve upon current turbine blade designs. They have the ability to reduce the turbine noise, increase power generation at low speeds and respond well to fast changes in wind speed (Hamilton, 2020). Additionally, the United States Department of Energy (US DOE) was looking into creating a tower that would house four separate rotors using extending arms (Paquette, YEAR). This would maximize the amount of power being produced by a singular tower.

Despite these numerous ideas, the leading method for increasing turbine power output is still to increase the length of the blade. A larger rotor diameter requires more support, so the diameter of the tower holding the turbine also has to increase. Transportation of large turbine components has been a consistent issue and a larger tower diameter adds to the problem (Allen, 2020). They won’t fit under bridges and breaking the tower component into smaller pieces introduces new problems. Increasing the number of components in the system introduces possible failure points and increases the likelihood for future maintenance. Due to this, there is still a large oppurtunity for alternative solutions to improve wind turbines and maximize their power output. The technical project seeks to create an innovative solution to this issue and explore how altering the shape of traditional turbine blades can increase the amount of power generated.

Improving Wind Power Generation with an Active Control System

The overarching goal of this project is to design a mechanism that actively changes the shape of a wind turbine blade to improve overall turbine efficiency under varying wind speeds. Current methods of raising turbine efficiency include pitch control, larger blades, and changing blade shape. The equation for turbine power generation is:

$$P = \frac{1}{2} C_p \rho V^3 A \tag{1}$$

where P is power, C_P is the coefficient of performance, ρ is the density of the air, V is the velocity of the wind, and A is the swept area of the blade (Sarkar & Behera, 2012). Only swept area and the coefficient of performance are modifiable, so any designs must involve improving these values. The trend has been to create larger and larger turbines, but as previously mentioned, this causes concerns with transportation, construction, and lifespan. A less common approach is to actively change the blade shape to improve C_P. This approach will be explored with this project.

More specifically, this project aims to increase the efficiency and reliability of the General Electric (GE) 2.75MW-120m turbine across wind speeds from 3 m/s to 20.5 m/s. As shown in Figure 1, these wind speeds represent the designed minimum and maximum operating wind speeds for the turbine, referred to as the cut-in and cut-out speeds (Bauer & Matysik, 2021). Outside these speeds the turbine stops spinning entirely.

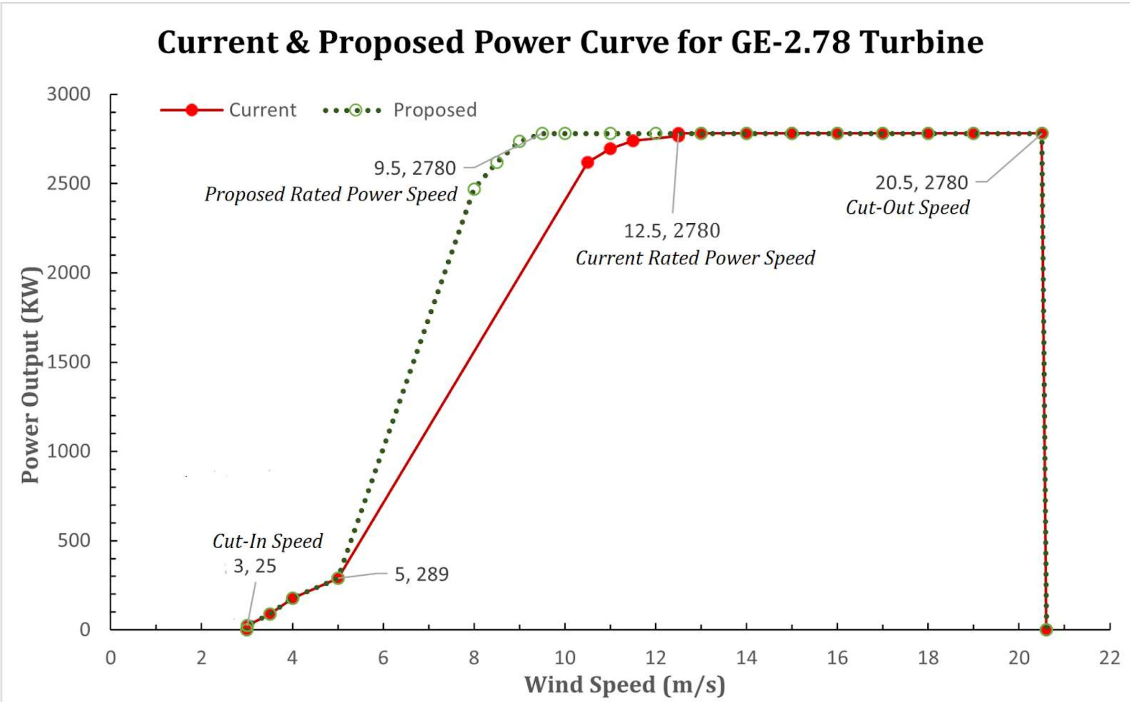

Figure 1. Current and Proposed Power Curve for GE-2.78 Turbine.

Cut-in speed is typically invariable; there must be a minimum energy present in the wind for a turbine to collect and transform into electricity, see Figure 1. However, the wind speed at which the turbine reaches its rated power can be reduced by improving the aerodynamic efficiency of the turbine. The team's goal—shown in Figure 1—is to decrease the rated power wind speed from 12.5 m/s to 9.5 m/s. Preliminary analysis of the graph shows that this would result in an annual 6% increase in electrical power generation.

For the last few decades, wind turbine manufacturers have used pitch control, changing the angle of attack (AoA) of turbine blades relative to the wind, to alter the aerodynamic coefficients of lift and drag. These variations in the AoA, lift, and drag coefficients determine the rated power wind speed and allow the turbines to spin at a constant rotational speed during its rated power phase (Muljadi & Butterfield, 1999). A constant rotational speed is paramount to maintaining a reliable connection with the national electrical grid, by harmonizing the frequency phase of the electricity the turbine generates and the phase of electricity needed for distribution. While pitch control systems are effective, they are complicated, with a typical system consisting of over 4,000 subcomponents and many sensitive electronic modules. According to a 2011 report, 23% of all wind turbine downtime was directly related to pitch control system failures. Additionally, the study found that pitch control systems marked the highest failure rate of any turbine component, at 21%. Remarkably, these systems only have a reliability of 5,700 hours, or a little over half a year, while a typical turbine lifetime is expected to be well over 20 years (Wilkinson et al., 2011).

Clearly, there is a demand for an alternative active control system that captures the aerodynamic efficiency improvements of pitch control that performs reliably over the course of the life of the turbine. During the screening and scoring process, the team considered manufacturing costs, system simplicity, performance improvements, and reliability and decided on an extendable and retractable flap system on the trailing edge of the turbine blades, analogous to flaps on the trailing edges of airplane wings.

3D CAD models of the proposed active control system will be created using SOLIDWORKS software and validated using Ansys Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) tools. Next, the team will 3D print and prototype the proposed mechanism into a scaled down turbine, which will be verified using wind tunnel testing. Finally, the team will complete a failure mode & effects analysis (FMEA) and levelized cost of energy (LCoE) analysis to evaluate the importance of the solution to the turbine manufacturing industry.

Responsible Innovation and the Wind Industry

Innovation within the wind industry promotes further development of wind farms. The remainder of this paper will focus on exploring the ecological implications of this development. To do this I will be approaching this topic using the framework of Responsible Innovation. More specifically I will be exploring the topic through the sustainability and humility lenses using papers written by Leidy Klotz (Klotz, 2018, pp. 225-233) and Sarah Hartley (Hartley, 2016, pp. 1-6). Responsible Innovation as a whole focuses on the importance of morality and accountability when it comes to the innovation and design process.

Within engineering there is an unspoken standard that must be upheld to maintain trust between society and innovators. This standard implies the need for sustainable practices. Klotz defines sustainable design practices as those without outcomes that "improve the well-being of current generations without compromising the well-being of future generations and the environments on which we all rely" (Klotz, 2018, p. 225). To assess how sustainability plays a role in innovation, the design process is broken down into general steps that include: identifying needs, defining a problem, creating concepts, selecting a concept, developing the details, and implementing and evaluating. Within each of these there are obstacles and opportunities to make environmentally conscious decisions. An example of this falls within the "Identifying Needs" step of the design process. This obstacle is possibility for there to be too much emotional empathy. Klotz highlights that too much emotional empathy can "mislead designers through user perspectives that discount the needs of future others" (Klotz, 2018, p. 226). There needs to be an evaluation of whether the issue at hand is more dire than a problem that it could cause later. This is important in the context of renewable energy sources. One of the main ecological concerns surrounding wind farms is the amount of bird and bat fatalities that their operation directly causes. Wind turbines have been estimated to kill over 140,00 birds every year in just the US (Hogan, 2020). While this is an unfortunate circumstance there are many other manmade objects that cause greater harm to the avian community. It comes down to whether the lives of future generations that will be directly affected by climate change outweigh the lives of the birds and bats that are being hurt now.

Another important aspect of responsible innovation is humility. Sarah Hartley's paper, "Essential Features of Responsible Governance of Agricultural Biotechnology," dissects the ways that responsibility should be incorporated into the governance of biotechnology. While this paper is not focused on the same scientific topic, many of her points are applicable across a wide range of scientific fields of study. Governance of any scientific knowledge should be held to the same standards to maintain levels of trust between innovators, scientists, and stakeholders. Hartley breaks down this responsibility into five essential features:

1. commitment to candor
2. recognition of underlying values and assumptions
3. involvement of a broad range of knowledges and actors
4. consideration of a range of alternatives
5. preparedness to respond.

She highlights the need for candor and humility within science and engineering and that "candidly recognizing and truthfully representing scientific uncertainties and the full range of concerns at stake does not reflect a lack of competence" (Hartley, 2016, p. 3). Knowing the limits to a design does not make it less innovative or ingenious.

Within the wind industry there is the notion that bigger is better. Larger rotors produce more energy but there are factors that limit the size that rotors can reach. As stated earlier there is a lack of viable transportation for the blades and tower components to the build sites (Allen, 2020). Larger blades also reach great speeds at the tips and have a greater swept area increasing the likelihood an animal will be hit when flying through wind farms (EERE, 2021). The increased speed also puts greater stress which could lead to more breakages and a greater need for maintenance.

Due to the fact that wind technology is consistently improving, wind turbines are being outfitted with new blades at half of their expected operating lifespan of 25 years (Martin, 2020). The blades that are being replaced end up in landfills as there are very few programs in place to recycle them. The wind industry continually changing the blade design has improved the power output of turbines but has also caused a waste of blades. Assessing the positive and negative benefits to constant improvement of turbine design could shed light on why so many blades meet this fate.

Researching and Evaluating the Ecological Impacts of Wind Farms

This thesis will explore ways that wind turbines impact their surrounding environments and attempt to answer the question: What are the ecological implications of further windfarm development? There are many ways in which wind farm development can affect and alter the surrounding environment and its inhabitants. Both the positive and negative implications of the continued installation and operation of wind farms will be explored.

The research will focus on finding studies with cases where a change in the environment post-installation was observed. This will include a study done at an onshore wind facility in North China observing environmental factors before and after construction of the farm (Luo, 2021) and a review summarizing studies of observed effects of offshore wind farms (Farr, 2021)

Another source that will be assessed are statistics and studies regarding bird and bat deaths caused by wind farms and other manmade structures for comparison. Specifically this will include a study conducted by Western Ecosystems Technology that compares the number of bird fatalities caused by anthropogenic factors (Erickson, 2003). Other sources that will be examined include literature on the effects of offshore wind turbines on the aquatic community, plans for future wind farms, and documents detailing how development sites are chosen. The Responsible Innovation STS framework will be used to evaluate the findings from the research. Specifically, I will be looking at the sustainability of the wind farm development process and how the benefits of switching to wind energy weigh against the environmental effects that were previously discussed. The role of humility within the wind industry will also be examined, focusing on the limitations associated with the expansion of wind power.

Conclusion

Renewable power sources are at the forefront of alleviating the impending effects of global warming and climate change. Wind energy is going to continue to grow as an industry and power source. New ideas for improvement will be needed to support this growth. The research conducted for this paper accompanied by the Responsible Innovation analysis will most likely yield results in favor of the wind industry. While there are unfortunate consequences to building new wind farms, ultimately the expansion of wind energy and other renewable power is a necessity.

References

Allen, G. (2020, May 25). The logistical challenges of wind turbine transport in the US. Retrieved November 01, 2021, from https://www.nsenergybusiness.com/features/wind-turbine-transport-us/

American Wind and Wildlife Institute, *Wind Turbine Interactions with Wildlife and their Habitats* [PDF]. (2014, January). American Wind and Wildlife Institute. Retrieved November 01, 2021, from https://awwi.org/resources/summary-of-wind-power-interactions-with-wildlife/

Arnett, E. B., & Johnson, G. D. (2013, March). *A Synthesis of Operational Mitigation Studies to Reduce Bat Fatalities at Wind Energy Facilities in North America* [PDF]. Golden, CO: The National Renewable Energy Laboratory.

Bauer, L., & Matysik, S. (2021). Compare Power Curves of Wind Turbines. Retrieved October 31, 2021, from https://en.wind-turbine-models.com/powercurves

EERE (2021). Wind turbines: The bigger, the better. (2021, August 30). Retrieved November 01, 2021, from https://www.energy.gov/eere/articles/wind-turbines-bigger-better

Erickson, W. P., Johnson, G. D., & Young Jr., D. P. (2003). A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions. Retrieved November 15, 2021, from https://www.fs.fed.us/psw/publications/documents/psw_gtr191/psw_gtr191_1029-1042_erickson.pdf

Farr, H., Ruttenburg, B., Walter, R. K., Wang, Y., & White, C. (2021, June 15). Potential environmental effects of deepwater floating offshore wind energy facilities. Retrieved November 15, 2021, from https://www.sciencedirect.com/science/article/pii/S096456912100096X

Fattal, T. N. (2018, August). *Increasing Wind Turbine Efficiency* [PDF]. Gaziantep, Turkey: Department of Aircraft and Aerospace Engineering, University of Gaziantep.

Gheorghiu, I. (2020, December 09). GE announces first US wind turbine blade recycling program with Veolia. Retrieved October 18, 2021, from https://www.utilitydive.com/news/ge-announces-first-us-wind-turbine-blade-recycling-program-with-veolia/591869/

Hartley, S., Gillund, F., Van Hove, L., & Wickson, F. (2016). Essential features of responsible governance of Agricultural Biotechnology. *PLOS Biology, 14*(5). doi:10.1371/journal.pbio.1002453

Hamilton, T. (2020, April 02). Whale-inspired wind turbines. Retrieved November 01, 2021, from https://www.technologyreview.com/2008/03/06/221447/whale-inspired-wind-turbines/

Hogan, B. (2020, March 2). *Is it possible to build wildlife-friendly windfarms?* BBC Future. Retrieved September 27, 2021, from https://www.bbc.com/future/article/20200302-how-do-wind-farms-affect-bats-birds-and-other-wildlife.

Horwath, S. (2021, August). *Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations* [PDF]. Fairfax, VA: ICF Incorporated, L.L.C.

Kerrigan, S. (2018, March 28). The scientific reason why wind turbines have 3 blades. Retrieved November 01, 2021, from https://interestingengineering.com/the-scientific-reason-why-wind-turbines-have-3-blades

Klotz, L., Weber, E., Johnson, E., Shealy, T., Hernandez, M., & Gordon, B. (2018). Beyond rationality in engineering design for sustainability. *Nature Sustainability, 1*.

Luo, L. (2021, May 11). *Local climatic and environmental effects of an onshore wind farm in North China* [PDF]. Lanzhou, China: Northwest Institute of Eco-Environment and Resources.

Martin, C. (2020, February 6). *Wind turbine blades can't be recycled, so they're piling up in landfills*. Los Angeles Times. Retrieved September 27, 2021, from https://www.latimes.com/business/story/2020-02-06/wind-turbine-blades.

Martino, J. (2021, August 31). Advancements in wind turbine technology: Improving efficiency and reducing cost. Retrieved October 18, 2021, from https://www.power-eng.com/renewables/wind/advancements-in-wind-turbine-technology-improving-efficiency-and-reducing-cost/#gref

Muljadi, E. & Butterfield, C.P. (1999). *Pitch-Controlled Variable-Speed Wind Turbine Generation* [Presentation]. IEEE Industry Applications Society Annual Meeting, Phoenix, Arizona, US. https://www.nrel.gov/docs/fy00osti/27143.pdf

Paquette, J. (n.d.). Big Adaptive Rotor Project ID #T17 - Energy. Retrieved November 1, 2021, from https://www.energy.gov/sites/prod/files/2019/05/f62/SNL-T17-%20Paquette.pdf

Sarkar, A., & Behera, D. K. (2012). Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy. *International Journal of Scientific and Research Publications, 2*(2), 1-5. Retrieved October 31, 2021, from http://www.ijsrp.org/research_paper_feb2012/ijsrp-feb-2012-06.pdf

Wilkinson, M., Harman, K., Hendriks, B., Spinato, F., van Delft, T., Garrad, G. L., & Thomas, U. K. (2011, March). Measuring wind turbine reliability-results of the Reliawind project. In *EWEA Conference* (pp. 1-8).