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Optimization of Wind Turbine Efficiency during Severe Weather

Nana Kofi Annor[1]
Michael Ramirez[2]
Cafer Kucukbasol[3]

Abstract

Due to the importance of energy in society as well as the negative environmental impact of many commonly used energy sources, namely fossil fuels, it is essential to develop and improve sources of renewable energy. Wind energy is a prominent, widely accessible, and environmentally friendly form of renewable energy created when wind turbines convert the kinetic energy of wind to electricity. Severe weather is one area of concern for wind turbines. This article primarily examines the effects of high wind speeds and lightning on wind turbines. To aid in improving and fostering renewable energy, this article aims to study the effects of lightning and high wind speeds on wind turbines, evaluate current solutions, and suggest improvements where possible. After examining several sources, the advantages and disadvantages of current methods were discussed along with proposed improvements. Due to the restrictions of our research being purely virtual, lacking resources, and time constraints, we are unable to conduct tests and physical research of wind turbines and these meteorological events for more thorough first-hand exploration. Following our research, the next step would be to utilize the evaluations and proposed improvements to current wind turbine designs and analyze the effects.

Keywords: severe weather conditions, wind turbines, optimization, high wind speeds, lightning

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[1] Rice University Internship, Houston, TX, USA, nanakofiannor1246@gmail.com
[2] Rice University Internship, Houston, TX, USA, mramirez.michael.mr@gmail.com
[3] Rice University Internship, Houston, TX, USA, caferkbasol82@gmail.com

Introduction

Energy is essential to a functioning society. Energy is used in multiple facets, from medicine, to transportation, to infrastructure, and more. Traditional sources of harvesting energy focus on nonrenewable energy, including coal, natural gas, and oil. Converting these fossil fuels to energy creates severe damage to the environment. Climate change can lead to more severe weather storms, sea level rise, and various types of pollution (*Fact Sheet | Climate, Environmental, and Health Impacts of Fossil Fuels (2021) | White Papers | EESI*, n.d.). In response to this, various forms of renewable energy sources have been developed, along with governmental programs promoting them. Wind, solar, and hydroelectricity are among a few prominent renewable energy sources. These sources provide alternative methods of collecting energy that are less damaging to the environment.

Wind is created by the sun. As the sun unevenly heats different areas of the Earth, air moves around to counter this imbalance, resulting in wind. Wind energy is very environmentally friendly, as hardly any emissions or pollutants are released in the conversion of wind to electricity (Hammond & Cooperman, 2022). Moreover, wind energy is more accessible compared to other energy sources. While different areas have different amounts of wind, wind can occur everywhere. Wind energy is a very prominent source of energy. In 2023, nearly 8% of the world's energy came from wind (*Global Wind Energy Share in Electricity Mix 2023*, n.d.). Wind is one of the largest sources of renewable energy in the US, accounting for approximately 10% of the US's energy in 2023 (*Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)*, n.d.).

A wind turbine converts the kinetic energy of wind into electrical energy through a generator. There are two major shapes for wind turbine blades: horizontal-axis blades and vertical-axis blades. Horizontal-axis wind turbines are shaped like a traditional propeller and typically have three blades. These turbines are usually upwind, so the turbine orients to face the wind. Vertical-axis wind turbines include a variety of shapes and are omnidirectional, meaning they do not need to be adjusted to varying wind directions and can operate in whichever direction the wind is blowing (*How Does a Wind Turbine Work?* n.d.). Multiple wind turbines form a wind farm or wind plant. These can be land-based or offshore. Land-based wind plants install turbines on land. Most wind farms are land-based, and this form of wind plant is less expensive than offshore wind turbines. Offshore wind turbines are constructed in the ocean, on a floating platform, or anchored to the ocean floor. Offshore wind farms offer the advantages of taller towers and larger blades (Hammond & Cooperman, 2022).

A wind turbine is composed of various parts that enable it to accomplish its function. Unique or innovative designs can incorporate altered or new components and systems, straying (partially) away from the traditional design. However, some of the main components of a wind turbine include the foundation, the tower, the nacelle, the generator, and the blades. The foundation is a massive structural concrete block at the base of the wind turbine that supports it and the forces acting on the turbine (*Wind Turbine: What It Is, Parts and Working | Enel Green Power*, n.d.). One of the largest components, the tower supports the nacelle, the rotor, the blades, and other components attached (*How Do Wind Turbines Survive Severe Weather and Storms?* n.d.). The tower enables the turbine to reach great heights, greatly increasing the amount of wind it can access. The nacelle contains most of the components needed for electricity generation, including the generator. Driven by a high-speed shaft, the generator produces electricity through copper windings being fed through a magnetic field. The turbine blades are used to capture wind. The typical wind turbine features 3 blades, each being over 170 feet, but this can vary with design (*How Do Wind Turbines Survive Severe Weather and Storms?* n.d.).

Due to the growing need for renewable energy sources and the prominence of wind as a form of renewable energy, it is essential to explore methods to improve wind turbines, create solutions to issues, and ensure their continued success. One area of concern for wind turbines includes the effects of severe weather. Extreme storms can produce high wind speeds and lightning strikes. High wind speeds and lightning can cause severe wind turbine damage. High wind speeds can break, bend, or destroy rotor blades, leading to structural failure and shutdowns (El-Henaoui, 2012). If not properly protected, the heat from lightning can cause varying degrees of damage to a wind turbine blade or create a fire (Yokoyama, 2011). Failure of a lightning protection system can also lead to electric current flowing to different parts of the turbine and potentially damage different components.

This article will aim to study the effects of severe weather on wind turbines and propose potential solutions to the problems wind turbines face during these events. By doing this, we aim to improve wind turbine operations, decrease downtime, and foster the incorporation of wind turbines.

Methodology

After initial research on wind energy and wind turbines, more specific research was conducted on the difficulties wind turbines face during severe weather. Following this, potential solutions were generated.

High Wind Speeds

Wind turbines start generating electricity after a certain wind speed has been achieved. Wind turbines operate within specific ranges, defined by cut-in speed, rated speed, and cut-out speed. Electricity generation increases as wind speed increases until rated speed has been reached (*How Do Wind Turbines Survive Severe Weather and Storms?* n.d.). As the wind speed increases from the cut-in speed and the rated speed (where the maximum output is reached) the power output will increase cubically along with the wind speed. This x^3 efficiency ratio makes wind speed a key factor for wind power (*Wind Power - Energy Education*, n.d.). Rated speed refers to the maximum amount of electricity the turbine can generate with the wind's speed. Once the rated speed is reached, power generated from the turbine remains constant until the wind becomes abundantly fast and dangerous for the turbine to generate (cut-out speed). The risks can cause life and property damage. Even though the turbine blades and rotors are designed to withstand high wind speeds, exceeding this threshold can stress the rotor blades and other components excessively. To determine the speed of the wind and prevent it from causing damage, every wind turbine has an anemometer (an instrument that measures the speed and pressure of the wind). In a scenario where the cut-out speed is met (the amount of wind speed depends on the turbine), the turbine shuts down to prevent unnecessary strain on the rotor (El-Henaoui, 2012).

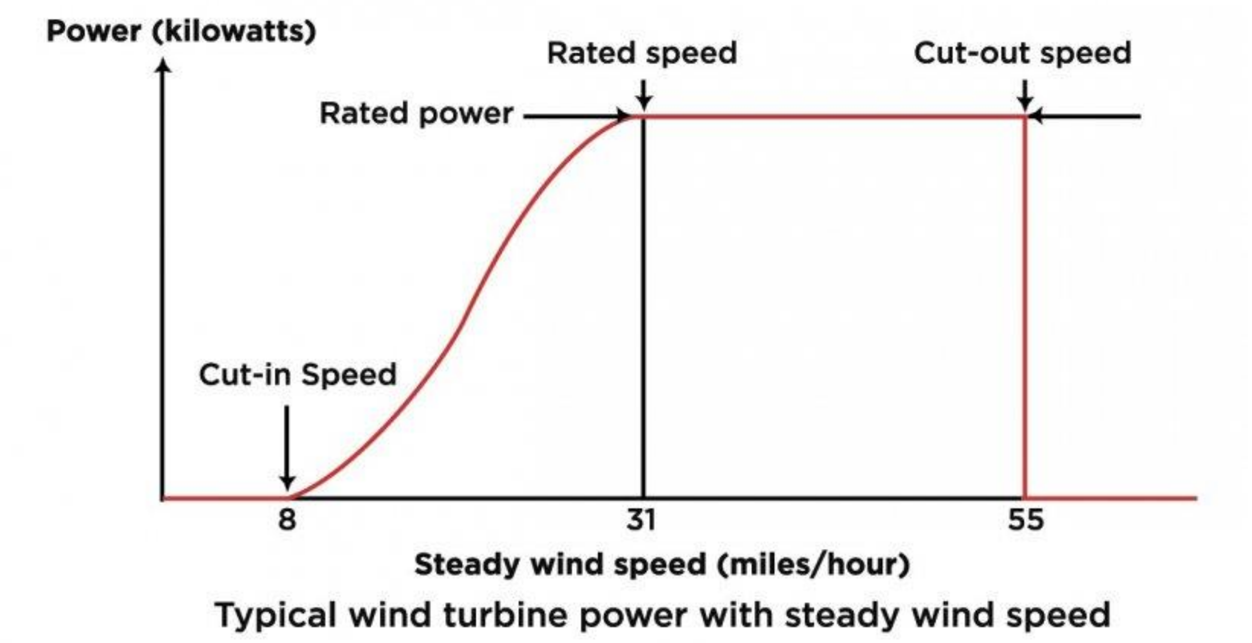

Figure Credit: Sarah Harman (ENERGY.GOV) (*How Do Wind Turbines Survive Severe Weather and Storms?* n.d.)

The high wind speeds can cause immense damage to the blades, rotors, and turbine gears. One example of these high wind speeds is hurricanes. Powerful meteorological events, hurricanes utilize heat from tropical waters as fuel (*Global Wind Energy Share in Electricity Mix 2023*, n.d.). These natural events happen over the ocean. They often begin as tropical waves. However, as they move around, the warm ocean air rises into the storm, causing a low-pressure area and allowing air to rush in. As the air rises it meets with a cooling temperature resulting in clouds and thunderstorms." Thunderstorm clouds begin to rotate around an area of low atmospheric pressure called a tropical depression" (US Department of Commerce, n.d.). If the wind speed in the storm reaches 74 miles per hour (119 kilometers (about 73.94 mi) per hour) the storm is classified as a "Hurricane". This event is important for offshore wind turbine plants because the best spots to maximize wind energy generation are remote areas and tropical wind makes offshore plantations of wind turbines tempting. However, as said before wind speed is a key factor, and hurricanes put offshore wind turbines at elevated risk. For example, a study underscored that almost half of wind turbines in hurricane-prone areas could be destroyed over 20 years if certain measures are not enacted to prevent possible damage.

A study that was conducted in 2018 “Hurricane risk assessment of offshore wind turbines” presented quantifying the risk of failure of OWTs (Offshore Wind Turbines) to hurricane resulted wind and waves via Adapting and developing a well-established risk assessment framework used in earthquake engineering <Hurricane risk assessment of offshore wind turbines>. The research highlights the vulnerability of offshore wind turbines, primarily because of the extreme wind speed caused by storms and hurricanes surrounding wind turbines. Empirical models have been developed to evaluate the damage caused by various hurricane categories. For instance, one of the probability analyses that was conducted due to the lack of data during the research process showed that 46% of turbine towers could experience significant problems in a Category 3 hurricane. In a Category 3 hurricane, the winds’ speeds can reach between 111mph (178.637 kilometers (about 111 mi) per hour) and 130mph (209.215 kilometers (about 130 mi) per hour). Underscoring the need to improve design components to withstand high wind speeds and emphasizing the need to incorporate "robustness" checks similar to those used in the oil and gas industries. The framework presented aims to improve the design by allowing it to withstand greater amounts of wind speeds and wave forces than the International Electrotechnical Commission (IEC) standards allowed in hurricane-prone areas (*Wind Energy | IEC*, n.d.). Aiming to reduce the extensive losses due to hurricanes and ensure the safety of the wind turbines in prone areas. Collecting data from the specific place where the wind turbine is planned to be planted can be a crucial part of determining the vulnerabilities that area can have. Another suggestion is to implement backup power systems to ensure the continuity of the position of the wind turbine in case of grid failure. When the grid fails to determine its surroundings the wind turbine can be weak against and unprepared for the winds’ route resulting in extensive damage. The system that is suggested aims to prevent the possibility of damage caused by grid failure and protect against the prevailing winds. The study talks about an internal detection system for the stressed parts of the turbine after extreme weather while monitoring in real-time, detecting potential damages and preventing further hazardous conditions with immediate reaction. Overall, improving the offshore wind turbine plantations in prone areas.

Onshore wind turbines are similar to offshore wind turbines both harness their energy from the wind, yet they have distinctive differences. Offshore wind turbines usually generate higher amounts of energy when compared to onshore wind turbines. Offshore wind turbines can also be built at a larger scale due to the free space of the ocean, allowing for maximum energy generation. Because of their size and the frequency of wind in the ocean offshore wind turbines can generate the same amount of energy as onshore wind turbines with fewer wind turbines.

Even though offshore wind turbines are more efficient at generating energy, this efficiency comes with a price. In this case, the expense of installing one of the offshore wind turbines is more expensive due to its more complex systems: foundation, size, grid connection, etc. compared to onshore wind turbines which are easy to build and transport (MITAGS). Both turbine styles have their own specific maintenance requirements. Offshore wind turbines are designed to withstand the impact of seawater, corrosion, and harsh weather conditions yet maintenance is still required which can be detected by real-time detection systems and needs specially trained crews and ships for the longevity of the turbines (MITAGS). Onshore wind turbines, however, are on land and ease transportation, making them easier for access maintenance.

A recent study (*Onshore vs. Offshore Wind Onshore vs. Offshore Wind | MITAGS*, 2024) gives an overview of onshore wind turbines and offshore wind turbines by their distinctive characteristics, advantages, and challenges. One of the challenges faced is environmental damage. Wind turbines are meant to be environmentally friendly therefore talking about environmental damage can be shocking. Onshore wind turbines usually have a small amount of carbon footprint during operation, however, manufacturing and installing processes can contribute to greenhouse gas emissions. These turbines can change local ecosystems risking hitting flying animals on the path where the onshore turbines are located. The blades of turbines spin at high speeds that can generate loud noises, these noises can disturb surrounding citizens who live near the turbines. Offshore wind turbines are located over the seas and oceans which makes them isolated from most of the surface world but there is a whole different world under the sea. Like onshore wind turbines, offshore wind turbines also create noise pollution, and this noise pollution can disturb marine life and force them to leave their homes. These causes need careful consideration of the designs and monitoring to improve current designs. With these in mind, the overall environmental damage caused by the onshore wind turbines is significantly lower when compared to the low-cost energy sources (fossil fuels), and with a few improvements over the current designs, the damages are caused by the onshore wind turbines.

In the study, we are presented with data about onshore wind turbines and offshore wind turbines underscoring their differences (the expenses, environmental impacts, efficiencies, etc.) and the importance of life-cycle impact assessments (LCA) for the wind turbines. An important part of the article is about life-cycle impact assessment (LCA) this model is used to evaluate the environmental impacts of renewable energy sources throughout their lifecycle, in the article chosen renewable energy source is wind turbines. This system allows stakeholders to have a better grasp of how the energy source is performing, giving precise pieces of information. The method has 4 key phases at first the goals and the reasons for the (LCA) are defined. The second phase is when the data are collected for energy and environmental input and outputs making a comprehensive library of data (14). The third phase is the analyzing part where the data is gathered and checked for significant impacts on the environment. Lastly, with all the data gathered considered the results are compared to the goals, and determined how can it be improved and solutions to give equivalent results to wanted goals.

The article argues for updating the current methods of capturing data and improving them for more accurate planning in future applications. It also suggests more sophisticated techniques for life-cycle impact assessment (LCA) capturing better data on resource use and emission related to onshore and offshore wind turbines. Utilizing this system with the Internet of Things (IoT) and digital twin technologies can help to find limitations caused by traditional data-gathering methods.

Lightning

Annually, in the US, lightning strikes create more than $100 million in damages to wind plant operators, along with being responsible for 60% of blade losses and causing approximately 80% of downtime (Yokoyama, 2011). Wind turbine size has been continuously increasing. This increased height along with the addition of more conductive material, such as copper fiber, makes wind turbines more vulnerable to lightning strikes. Furthermore, difficulties replicating the exact effects of lightning in a lab setting during testing increase the risk of wind turbines being vulnerable to lightning (Yokoyama, 2011).

The traditional method of protecting wind turbines from lightning is a lightning protection system (LPS). Provided by the International Electrotechnical Commission, the IEC 61400-24 provides standards for the construction of wind turbine lightning protection systems (MDPI). An LPS is meant to direct the electric current from lightning to the ground. For a wind turbine, a lightning receptor is constructed into the tip of the blade with a cable connected to it. The current follows through the cable to the ground or into the ocean for offshore turbines. However, wind turbine LPSs are not foolproof, as indicated by the previously mentioned data on lightning damage.

There are three major components of a wind turbine LPS: an external component, an internal component, and an Earthing System (Modular Lightning). An article by MDPI regarding wind turbine LPS lays out three major aspects a lightning system should possess: operate safely with a wind turbine, have efficient cost, and meet site-specific conditions (MDPI). Utilizing this as a template, our evaluation of a traditional wind turbine lightning protection system will have three criteria: effectiveness, protection (of wind turbines, property, and living beings), and cost.

As established, the primary goal of an LPS (lightning protection system) is to prevent wind turbines from facing damage due to lightning. The first criteria evaluate the effectiveness of traditional LPS in accomplishing this goal. The IEC 61400-24 standards dictate wind turbines should protect against 98% of lightning strikes. However, due to the increasing and persistent threat of lightning, it’s clear wind turbines must require better inspection to ensure they meet this standard or for the standard to be altered. While not completely effective, wind turbine LPSs still offer protection from lightning, and are better than the alternative: no protection. Moreover, installation of an LPS adds to the cost of wind turbines, and failure to properly protect turbines from lightning strikes leads to significantly monetarily losses, compiling financial damage to owners.

Proposed Solution

Due to this, we created a theoretical solution to protect wind turbines from lightning. We suggest producing a layer of negatively charged particles on the surface of a wind turbine as a method of lightning protection. The reason for this proposed solution lies in the formation of lightning and attempts to solve the problem at its source. As ice crystals in clouds rub against each other, positively and negatively charged ice crystals are formed due to friction charging (UCAR). The positively charged ice particles rise to the top of the clouds as the negatively charged particles fall to the bottom (UCAR). As the negative charges build up at the bottom of the clouds, they repel the negative charges at the bottom, making the ground positively charged (UCAR). Once the buildup of charges at the base of the cloud is great enough to overcome the insulation of air, lightning is formed as the negatively charged particles at the bottom of the clouds rush towards the positively charged particles on the ground (UCAR). Tall objects are often struck due to their proximity to lightning: it is easier for lightning to move toward them (UCAR). Due to the nature of like-charged particles repelling each other, we hypothesize that an object significantly encased in negatively charged particles would repel a lightning strike to an alternative source. However, this approach still requires significantly more support.

Discussion

The increasing use of wind energy as a power source makes the study of high-efficiency and strong resistant turbines a popular subject, especially under harsh weather conditions. Very recently, an H-Type Darrieus Vertical Axis Wind Turbine subjected to high winds was modeled by CFD, and many insights obtained could serve most efficiently towards optimization of turbine performances in such environments.

It has been found from the CFD study that due to the change in wind speed, variable amounts of aerodynamic forces act on the wind turbines and critically identifies vorticity and the amount of aerodynamic stress that turbines experience during higher gusts. These empirical data provide solid grounds for understanding the dynamic action of the turbines in extreme weather conditions, which is a vital input to the development of their increased resistance.

For instance, the estimation of VI and IVSC through CFD modeling depicts quantitative measures that can assist in the assessment of structural integrity and operational efficiency in turbines under stress. These metrics should be integrated into the design process, where this would help in tailoring turbine components to better resist high wind speeds and turbulent conditions, hence reducing the incidence of mechanical failures while increasing overall energy output.

Additionally, the simulation data from the CFD study can be used to validate and further enhance the theoretical models. Such integration also lends empirical weight to theoretical proposals and ensures that suggested improvements such as improved blade geometry or more resistant structural materials are based on proven analytical methodologies.

Second, the methods that are to be used in carrying out the CFD analysis, particularly those techniques that will be used in analyzing the wind/turbine structure interactions, can also be applied to the study of the effectiveness of lightning protection systems. Utilizing simulations of electrical discharges interacting with turbine structures in much the same way that wind interactions are modeled, researchers can test and refine the effectiveness of lightning protection strategies. This would help in limiting one of the major reasons for turbine downtime and damage, improving the reliability and safety of the wind energy systems during adverse weather conditions.

This, in turn, would give a more comprehensive and realistic insight into CFD modeling of VAWTs operating at high winds, which is beneficial in optimizing wind turbine design and operation. This will not only enhance the propositions being developed for improving turbine resilience to severe weather, but such innovations will be feasible and effective in a practical sense. The data-driven approach to design and evaluation can enable the wind energy sector to substantially enhance its state of the art in efficiently harnessing wind power, even under extreme environmental conditions.

The consolidated discussion uses technical findings from the CFD study to support and further develop the strategies that could be utilized for improving turbine efficiency in extreme weather. The consolidated discussion, therefore, gives a well-rounded empirically supported framework for future research and development into wind turbine technology.

In terms of the effects of severe conditions on wind turbines, this academic article aims to find ways to optimize energy efficiency in these conditions. Wind speeds are essential parts of wind turbines, yet wind turbines have limits and increased amounts of wind speed create more torque than the turbines can handle and damage the turbines' blades. The damaged blades decrease the efficiency of energy being produced and need to be replaced. Depending on the size of the turbine the blades can cost more. Another condition that causes problems for wind turbines is lightning damage. Intra-cloud lightning occurs when lightning is produced between opposite charges inside the same thunderstorm cloud. On the contrary, cloud-to-ground lightning transpires when lightning forms between the opposing charges of the cloud and the ground. Furthermore," If a lightning flash is going to strike the ground, a channel develops downward toward the surface" (NSSL) and tall objects like trees, electrical posts, tall buildings, and most importantly in this article: wind turbines (NOAA Weather Partners, 2020). Due to their height turbines have a high chance of getting struck by lightning which like high-speed winds can harm the blades and can damage them. These lightning strikes cause $100 million in damage to U.S. wind plant operators.

Limitations

While researching the effects of severe weather on wind turbines, we faced several constraints. Our research was purely virtual, and thus, we were unable to physically explore or study the operations of wind turbines after encounters with high wind speeds or lightning strikes. This also means we did not have access to advanced laboratories for analysis of wind turbine components or meteorological events. However, we explored numerous sources to aid in providing quality and accurate information. Moreover, our research was limited to the time frame of approximately 3 months. As a result, the time we had to conduct said research was restricted. Additionally, the authors of this article do not possess advanced degrees in engineering or related fields. Due to this, despite the immense effort put into providing proper research and analysis, detailed information and analysis may not match those of an engineering student.

Conclusion

This research investigates the problems wind turbines face during extreme weather conditions from the perspective of blade integrity and vulnerability regarding lightning strikes. The expected outcome of this research is the next step in the technological development of turbines that can resist environmental stressors such as high winds and lightning.

Blade Improvement: The research featured herein stipulates that blades need to be designed more robustly to deal with extreme weather impacts. Next-generation composites of high tensile strength and flexibility are proposed in this regard. Material systems in this study were characterized by their ability to absorb and dissipate energy with a negligible risk of failure when exposed to extreme wind conditions. Among the other subjects to be discussed in the study are new adaptive blade technologies such as variable pitch mechanisms and shape morphing mechanisms, capable of changing the profiles of the blades based on current data of wind flow. These technologies reduce structural stress and further improve aerodynamic efficiency for enhanced energy capture in fluctuating weather conditions.

Lightning Protection Strategy: Some inadequacies in traditional lightning protection systems are noted, and two further directions of approach are put forward. Firstly, charge transfer systems serve to remove electrical charge accumulation on and around the turbine structure, preventing the formation of local zones of high charge that could attract a lightning discharge. Secondly, conductive coatings with integrated conductive materials, such as copper nanoparticles, allow the surface distribution of electrical charge and reduce peak charge accumulation, hence reducing the likelihood of a lightning strike.

Integration and field validation represent an advance in the study of the design and operation of wind turbines through blade improvements and innovations in lightning protection. Field trials and pilot projects will be required to validate the performance of these advanced materials and designs in realistic operating conditions and to further improve these technologies based on empirical data and operational feedback.

While the response places a very strong emphasis on the technological advancement and innate resilience of wind turbines in their modern design, one should consider just how nuanced that argument was such technologies remain at the mercy of reality. Whereas the original discussion acknowledged such advancements, it brought attention to just how great the leap is from a controlled environment to the real world, where extreme conditions such as hurricanes pose serious risks. Theoretical proposals on the use of negatively charged particles for lightning protection have, of course, a very significant role in expanding the envelope of what is currently feasible and show ways in which new solutions might be found and developed into useful technologies.

Even more, a focus on narrower technological improvements is complemented appropriately with broader systemic solutions: improvements in turbine blade material and structural design provide resiliency for the whole system, when adaptive operational protocols among other systemic approaches prove more effective. Case studies and industry standards showing improved resiliency actually highlight the importance of continuous research and adaptation, which are the themes central to the original paper (Katsanos et al., 2016).

In this respect, the continuous research and focusing of the main emphasis on practical implementation reflected in the original article corresponded to a general academic and industrial consensus: although several steps forward had been made, significant challenges were still present. For example, the extensive review presented in "An Evaluation of Sustainable Power System Resilience in the Face of Severe Weather Conditions and Climate Changes" depicted that various weather conditions do continue to stretch the operational limits of power systems, including wind turbines. This ascertains the gravity of the need for such research and proposals, just like those presented in the original article, if they fill the current gaps and also help in burgeoning more robust and efficient turbine technologies. The perspective of the original article thus is not only valid but also highly essential for furtherance of the evolution and enhancement of wind energy systems.

Future Research Directions: As the dependence on wind energy increases, research into refining turbine technologies will be of the essence to elicit improved performance and durability. Longitudinal studies to track performance in enhanced turbines in extreme weather-prone regions are necessary. As such, material scientists, meteorologists, and renewable energy engineers will have to continue their innovation and adaptation of turbine technologies as climate patterns shift and new environmental information becomes available.

The present research stands as a beacon for the wind energy industry in its quest to harness wind power to its fullest, making turbines increasingly efficient and strong in the face of climatic adversities, thereby helping the sustainable development of renewable resources across the world.

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Contributions

All authors conceived this review, conducted the literature searches, oversaw the accuracy of systematic literature review processes, acquired, analyzed, and interpreted incoming data, wrote versions of the manuscript, participated in research conferences, and came to a consensus on the publication of the final research paper.

Supplemental Information

All authors presented at the 13th London International Conference, LIC. It was during this conference that we were able to share our research ideas, abstracts, methods, and objectives with other scholars and professors. The settings at the conference had no bearing on the publication of this paper, nor did any person from those conferences or associated professors have anything to do with providing feedback or any assistance.

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