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Evaluation of Existing Materials Used in Wind Turbine Blade Construction: Assessing their Structural Characteristics, Sustainability and Performance

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Abstract: The study investigated the existing materials used in wind turbine blade construction: assessing their structural characteristics, sustainability and performance. The study employed Finite Element Analysis (FEA) to assess various materials' performance, considering factors such as deformation, stress, and safety. Materials examined include Aluminum 2024-T4, Carbon Fiber-Reinforced Polymer (CRFP), Glass Fiber-Reinforced Polymer (GRFP), Bamboo, Aramid Fiber, Pine, and Glulam. The analysis covered a range of angular velocities to simulate real-world conditions. Results indicated that material choice significantly impacts blade performance. The study acknowledges limitations such as simplified environmental conditions, limited consideration of moisture effects, and the absence of fatigue and thermal studies. Recommendations include future research in Computational Fluid Dynamics (CFD) analysis, geographical-specific designs, and advanced materials research. Finally, this work underscores the importance of sustainable material choices in wind turbine blade design. The findings offer valuable insights for engineers, researchers, and policymakers seeking to advance wind energy technology with environmental responsibility at its core. In conclusion Wind energy is a pivotal player in the global transition towards sustainable power generation. Wind turbines, specifically their blades, constitute the driving force behind this transformation. The selection of materials for these blades is a crucial endeavor, entailing a delicate balance between sustainability, performance, and cost-effectiveness. In this pursuit, sustainability is a lodestar guiding the way. One of the recommendations made was that tailoring material choices to specific wind energy projects is essential.

Keywords: Existing Materials, Wind Turbine Blade Construction, Structural Characteristics, Sustainability and Performance.

Introduction

The study of wind turbines and the aerodynamics governing their operation forms the bedrock of our pursuit for sustainable and efficient energy production. The promise of wind energy, with its potential to significantly offset our reliance on fossil fuels, makes the exploration of this domain a subject of critical interest. Among the various components of wind turbines, the design, structure, and material of the blades significantly influence the overall efficiency and energy output of the turbines. As such, this literature review will delve into the critical aspects of wind turbine blades to establish a well-rounded understanding of this crucial domain.

Materials utilized in wind turbine blade design have evolved over time, from traditional materials like wood and steel to advanced composite materials. This evolution reflects a continued effort to improve the strength-to-weight ratio of the blades, optimize their aerodynamics, and enhance their resistance to environmental factors (Sutherland et al., 2013). Therefore, understanding the characteristics of these materials, their pros and cons, and their impact on the blade performance under different environmental conditions will be a significant aspect of this literature review.

These composite materials, particularly carbon fiber and fiberglass, offer advantages like high strength-to-weight ratios, improved fatigue resistance, and adaptability to different designs and sizes. Furthermore, the material choice for these blades significantly influences their resilience and efficiency in energy conversion (Veers et al., 2004). Hence, a careful analysis and selection of blade material can greatly enhance the turbine's performance and longevity, contributing to the broader goal of sustainable energy production.

However, the decision to select an ideal material for turbine blades is complex and multifaceted. Multiple factors such as weight, strength, durability, cost, and environmental impact need to be weighed (Paquette et al., 2007). This material complexity of wind turbine blades necessitates advanced modeling techniques capable of accurately predicting their behavior under varying loading conditions. Finite Element Analysis (FEA) has emerged as a crucial tool in this respect. FEA is a numerical method that enables the analysis of complex structures under different loading conditions by breaking them down into smaller, simpler elements. This method allows for accurate predictions of stress distribution, deformation, and potential failure modes, thereby facilitating the design and material optimization of wind turbine blades (Mishnaevsky et al., 2017). FEA enables engineers to model the structural response of wind turbine blades to the multitude of forces they are subjected to, identifying potential weak points and enabling proactive, predictive maintenance (Masters et al., 2015).By applying FEA, engineers can simulate the behavior of different materials under expected load conditions, leading to an optimized choice for enhanced performance and durability. However, despite its significant potential, the application of FEA in wind turbine blade analysis and design is still under-explored. While some studies have used FEA to analyze specific aspects of wind turbine blade design, other various studies have focused on individual aspects such as load analysis, fatigue life, or material selection, a holistic, Finite Element Analysis (FEA)-based study that integrates all these aspects is notably lacking (Song et al., 2022; Chen et al., 2019). This study, therefore, seeks to address this gap in the literature by conducting a comprehensive FEA-based structural analysis of wind turbine blades to identify an optimal material that maximizes performance, durability, and efficiency.

The implementation of FEA allows for a detailed examination of the behavior of materials under different load conditions, providing valuable insights into the mechanical properties and performance of the materials used for turbine blades (MishnaevskyJr et al., 2007). By considering multiple performance parameters and environmental factors, this study strives to generate data-driven insights that may enhance the efficiency of wind turbines, advancing the global sustainability agenda.

Moreover, this research's relevance extends beyond technological and economic factors. As the world strives for a sustainable future, the environmental footprint of materials used in energy infrastructure becomes significant. The choice of materials for wind turbine blades can impact the overall lifecycle environmental impact of wind turbines, and therefore, contributes to the broader picture of environmental sustainability (Martinez-Luengo et al., 2016). By incorporating this dimension, the research presented here aligns itself with a holistic understanding of sustainability.

As our world continues to grapple with the impacts of climate change and energy scarcity, the importance of optimizing wind energy production has never been more pressing. Consequently, the body of research dedicated to FEA-based analysis of wind turbine blades and their potential contributions to sustainable energy production must be thoroughly understood and critically evaluated. It is this compelling demand that undergirds the need for the present literature review and the subsequent study.

Statement of problem

Wind turbine blades, crucial for efficient energy production, are exposed to various structural loads and environmental conditions. This exposure can lead to fatigue damage, influencing the performance and lifespan of these blades. The choice of blade material plays a pivotal role in managing these challenges. However, despite significant research in this area, a comprehensive FEA-based study integrating load analysis, fatigue life, and material selection is noticeably absent.

Research Objective

To achieve this aim, the study will pursue the following objectives:

1. **Structural Load Assessment**: Analyze the different types of structural loads (gravitational, aerodynamic, operating) that wind turbine blades encounter under various operational and environmental conditions.

Research Question

1. The research question guiding this study is: "What is the ideal material for wind turbine blades that optimizes performance, durability, and efficiency under various structural loads and environmental conditions, while adhering to the BS EN 61400 UK standard?"

CONCEPTUAL REVIEW

Concept of Wind Turbine

The utilization of wind as an energy resource can be traced back thousands of years, reflecting humanity's historical relationship with this naturally occurring power source. Ancient civilizations, including the Persians in the 7th century AD, employed simple windmills for tasks such as grain grinding and water pumping (Ahmed, 2010). Windmills in medieval Europe, with designs adapted to the local conditions and needs, further highlight the adaptability and utility of wind energy (Langdon, 2004).

Figure 1: Modern Wind Turbine Source: https://www.audubon.org/magazine/spring-2022/off-east-coast-massive-network-wind-turbines.

The transition from traditional windmills to modern wind turbines occurred in the late 19th to early 20th century. Pioneers like Poul la Cour in Denmark transformed windmills to generate electricity, setting a foundation for modern wind turbine design (Petersen et al., 2012). As the 20th century progressed, the need for alternative energy sources, coupled with advancements in aerodynamic theories and computational tools, catalyzed rapid innovations in wind turbine designs.

The science of aerodynamics is fundamental to the efficacy of wind turbines. Simply put, aerodynamics deals with the motion of air and how it interacts with solid bodies – in this case, turbine blades (Batchelor, 1967). As wind flows over the blades, the aerodynamic forces of lift, responsible for turning the blades, and drag, which opposes this motion, are generated. Understanding and optimizing these forces is vital to maximizing the efficiency of wind turbines. The lift-to-drag ratio, for instance, is an important parameter that defines the effectiveness of blade design in capturing wind energy (Anderson, 2010).

Over the decades, wind turbine designs have undergone significant refinements, driven by advancements in aerodynamics and materials science. Today's turbines are highly efficient machines, benefiting from decades of research and aerodynamic optimization. However, there remains an ever-present need to push the boundaries of design and materials, to meet the growing energy demands sustainably.

Types of Wind Turbine Blades

The design of wind turbine blades is crucial, determining efficiency, power generation, and turbine lifespan. Broadly, turbine blades can be categorized based on their material composition, structural design, and aerodynamic profiles.

Material-Based Classification:

I. **Composite Blades**: These are the most common type used in modern turbines, often made from a combination of fiberglass and reinforced polymers. They offer a superior strength-to-weight ratio and durability (Sutherland et al., 2013).

II. **Wood and Wood Laminates**: Historically, many blades were crafted from wood due to its abundance and flexibility. Today, some designs use laminated wood for its sustainability and cost-effectiveness (Breton & Moe, 2009).

III. **Fiberglass Blades:** These are the most common type of blades used in modern wind turbines. Fiberglass offers an excellent balance between weight and strength, allowing for efficient energy capture (Sutherland et al., 2013).

IV. **Carbon-Fiber Blades:** Lighter and stronger than fiberglass, carbon-fiber blades enable the construction of longer blades that can capture more wind energy (Griffith &Ashwill, 2011).

Structural Design:

I. **Solid Blades:** These are non-hollow and are typically used in smaller turbines.

II. **Shell Blades:** Made from two shell parts glued together, these hollow blades are lighter and are used in larger turbines (Burton et al., 2011).

Aerodynamic Profiles:

I. **Straight Blade**: Found mostly in VAWTs, they run straight along their length.

II. **Tapered and Twisted Blade**: These blades, common in HAWTs, are aerodynamically optimized to extract more energy from wind, considering the change in wind speed along the blade length (Schubel&Crossley, 2012).

Continuous research in blade design aims to maximize efficiency, reduce noise, and enhance durability, making it a critical area in wind energy technology.

Materials Used in Blade Design

Wind turbine blades are paramount components, directly influencing the efficiency and longevity of the turbine. The choice of material for these blades is a critical decision, influenced by various factors such as longevity, cost, durability, efficiency, and more. This literature review delves into various materials that have been employed in blade design, their attributes, and potential gaps in existing knowledge.

Glass Fibre Reinforced Polymer (GFRP) in Wind Turbine Blades

Glass Fibre Reinforced Polymer (GFRP), often referred to simply as fiberglass, has become a predominant choice for wind turbine blade fabrication. Its ubiquity in the industry can be attributed to several intrinsic properties.

GFRP is a composite material made by embedding glass fibres in a polymer matrix. This integration offers an impressive strength-to-weight ratio, a property vital for the dynamic loading conditions faced by wind turbines (Liu et al., 2012). One of the hallmark features of GFRP is its remarkable fatigue resistance, making it apt for long-term exposure to repetitive wind loads. Moreover, it possesses good durability against environmental factors, ensuring reduced maintenance needs for blades in diverse climatic zones (MishnaevskyJr et al., 2017).

Cost-effectiveness is another compelling argument for GFRP's popularity. While providing good mechanical strength, GFRP remains less expensive than materials like Carbon Fibre Reinforced Polymer (CFRP), making it a suitable choice for a wide spectrum of turbine sizes (Zhou et al., 2016).

However, as with every material, GFRP isn't without its limitations. The weight can become a constraining factor when designing larger blades, prompting manufacturers to seek hybrid solutions or alternative materials.

Carbon Fibre Reinforced Polymer (CFRP) in Wind Turbine Blades

Carbon Fibre Reinforced Polymer (CFRP) represents the next frontier in wind turbine blade materials. Boasting a strength-to-weight ratio superior to that of GFRP, CFRP is increasingly utilized, especially in large-scale turbine blades where material weight becomes critically influential The carbon fibres confer incredible tensile strength, enabling the design of longer blades with improved aerodynamic efficiency. Furthermore, the material's enhanced stiffness helps in reducing blade deflections, thus minimizing tower strikes in high wind conditions (Petersen et al., 2015). However, these benefits come at a price; CFRP is significantly costlier than GFRP. Its application is typically justified only where the performance gains outweigh the increased material costs. While promising, widespread adoption of CFRP demands cost-effective manufacturing techniques and lifecycle considerations (Schubel&Crossley, 2012).

Metals and Alloys (Steel and Aluminium) in Wind Turbine Blades

Steel and aluminium are metals that have been historically essential in wind energy technology. Steel, with its excellent strength and fatigue properties, has been extensively used in the wind turbine towers and foundations (Tavner, 2012). However, its application in the blades is less common, mainly because of its weight. The significant mass of steel is a critical drawback in blade design as it increases the load on the turbine structure and reduces the overall efficiency (MishnaevskyJr et al., 2017).

Aluminium, on the other hand, has a better strength-to-weight ratio than steel, making it more favourable for certain components of the blade, such as the spar cap or the internal structure (Manwell et al., 2010). Yet, its application is still limited due to its relatively high cost and susceptibility to fatigue, a significant concern for wind turbine blades constantly under cyclic loads.

Bio-based Materials (Flax and Jute) in Wind Turbine Blades

Bio-based materials like flax and jute represent a recent, eco-friendly innovation in wind turbine blade design. Flax and jute fibres are increasingly being considered as alternatives to glass and carbon fibres due to their comparable mechanical properties, lower density, and lower environmental impact (Shah, 2013). For instance, flax fibres exhibit a tensile strength close to that of glass fibres, and yet, they are 30% lighter (Le Duigou et al., 2014).

Another key advantage of flax and jute fibres is their positive environmental profile. They are biodegradable, renewable, and require less energy to produce compared to glass and carbon fibres (Charlet et al., 2017). However, their hydrophilic nature presents challenges, like moisture absorption, that can lead to a decrease in mechanical properties over time. Additionally, the lower stiffness compared to carbon fibres limits their application in larger blades. Thus, while promising, flax and jute fibres are currently more suitable for small to medium-sized blades.

Hybrid Combination of Glass and Carbon Fibre in Wind Turbine Blades

The hybrid combination of glass and carbon fibres offers a compelling solution for wind turbine blade design. Glass fibres provide cost-effectiveness and resistance to corrosion, while carbon fibres contribute to higher strength, stiffness, and fatigue resistance (Koutroulis et al., 2019). This combination, therefore, presents an ideal compromise between cost, weight, and mechanical performance, key factors in blade design (Hayman et al., 2018).

Pros of using a hybrid combination include its higher fatigue resistance compared to using glass fibres alone, thereby increasing blade longevity (Zhang et al., 2017). It also allows for a reduction in blade weight compared to using entirely glass fibres, thereby increasing the efficiency of energy conversion. Cons, however, include higher costs compared to using glass fibres alone due to the inclusion of carbon fibres. Additionally, the combination of two different materials may lead to challenges in recycling (Molent et al., 2020).

The extensive literature review reveals a consistent trend towards adopting hybrid materials in recent blade designs, underlining the advantages of combining the properties of glass and carbon fibres to meet the demanding requirements of modern wind turbines.

Wood Epoxy and Bamboo in Wind Turbine Blades

Wood epoxy and bamboo are emerging as innovative materials for wind turbine blade design. These bio-based materials are drawing attention due to their renewability, low cost, and relatively low environmental impact (Khan &Savi, 2020). Wood epoxy composites, composed of wood fibres embedded in an epoxy matrix, are not only renewable but exhibit good mechanical properties, including high strength and stiffness, which are crucial for wind turbine blade performance (Li et al., 2019; John &Anandjiwala, 2008). Similarly, bamboo, a natural composite with a high strength-to-weight ratio, offers good structural properties and resistance to fatigue loads (Lopez et al., 2017).

The use of wood epoxy and bamboo presents several advantages. They are low cost and have a lower environmental impact compared to conventional materials like glass and carbon fibres (Breton & Moe, 2009). Furthermore, they are readily available and can be sourced sustainably. However, there are also limitations. These materials have a higher density compared to conventional composites, which could lead to heavier blades. Additionally, the variability in natural materials may lead to inconsistencies in material properties (Kusiak&Zastrozny, 2019; John &Anandjiwala, 2008).

Despite these limitations, the extensive literature review and in-depth understanding of the current state of research suggest that wood epoxy and bamboo could offer a viable and sustainable alternative for wind turbine blade design, warranting further investigation in this dissertation work.

Methodology

The research approach adopted for this study is a combination of a comprehensive literature review and a rigorous computational analysis using Finite Element Analysis (FEA).Finite Element Analysis (FEA) is a computer-aided engineering (CAE) tool employed to simulate the physical behavior of structures and materials.This tool allows for detailed analysis under a multitude of conditions, including various types of loading and environmental stresses.The first step in the FEA-based structural analysis is to develop a model of the wind turbine blade.Structural loads on wind turbine blades primarily consist of gravitational, aerodynamic, and centrifugal forces.Environmental conditions play a pivotal role in the performance and durability of wind turbine blades.The analysis procedure will be an iterative process that employs Finite Element Analysis (FEA) methods for structural evaluation.The chosen approach, involving Finite Element Analysis (FEA), is justified due to its proven effectiveness in predicting the structural response of complex structures such as wind turbine blades under varying loading conditionsWhile the Finite Element Analysis (FEA) approach is a powerful tool for modeling and analyzing the structural behavior of wind turbine blades, it comes with some limitations.To minimize these limitation, the model will be validated against experimental data, and a sensitivity analysis will be performed to assess the impact of the different parameters on the results.

Analysis and Data

Turbine Blade Design Parameters

Blade Length

One common approach to determine the blade length is to use the power formula for wind turbines, which relates the power output (P) to the wind speed (V), the density of air (ρ), and the swept area (A) of the rotor. The formula is as follows:

$P = 0.5 \times \rho \times A \times V^3 \times C_p$ **eqn (27)**

Where:

- ✓ P is the power output of the wind turbine.
- ✓ ρ is the air density.
- ✓ A is the swept area of the rotor.
- ✓ V is the wind speed.

The swept area (*A*) is determined by the rotor diameter (*D*), which is twice the radius of the rotor (*R*):

$A = \pi \times R^2$ **eqn (28)**

Or

$A = \frac{\pi \times D^2}{4}$ **eqn (29)**

$D = 2R$ **eqn (30)**

To find the blade length (*L*), you can use the following formula:

$L = \frac{D}{2} = \frac{2R}{2} = R$ **eqn (31)**

Therefore, incorporating eqn (28) into eqn (27)

$P = 0.5 \times \rho \times \pi \times R^2 \times V^3 \times C_p$ **eqn (32)**

Making R subject of formula from eqn (32)

$R = L = \sqrt{\frac{P}{0.5 \times \rho \times \pi \times V^3 \times C_p}}$ **eqn (33)**

So, by specifying the desired power output of 4MW, the average wind speed 11.5m/s which was adopted from BSI (2019), and the air density 1.225kg/m3, the required blade length was calculated using eqn (33) above.

Angle of Attack

$\alpha = 9.5°$ **eqn (35)**

The angle of attack for eqn (35) was adopted from the airfoil data base for the NREL airfoil that was chosen for this project work.

The formula for calculating the lift (L) and drag (D) forces on a wind turbine blade, which are dependent on the angle of attack, can be expressed as follows:

$L = 0.5 \times \rho \times A \times C_l \times V^2$ **eqn (36)**

$D = 0.5 \times \rho \times A \times C_d \times V^2$ **eqn (37)**

Where:

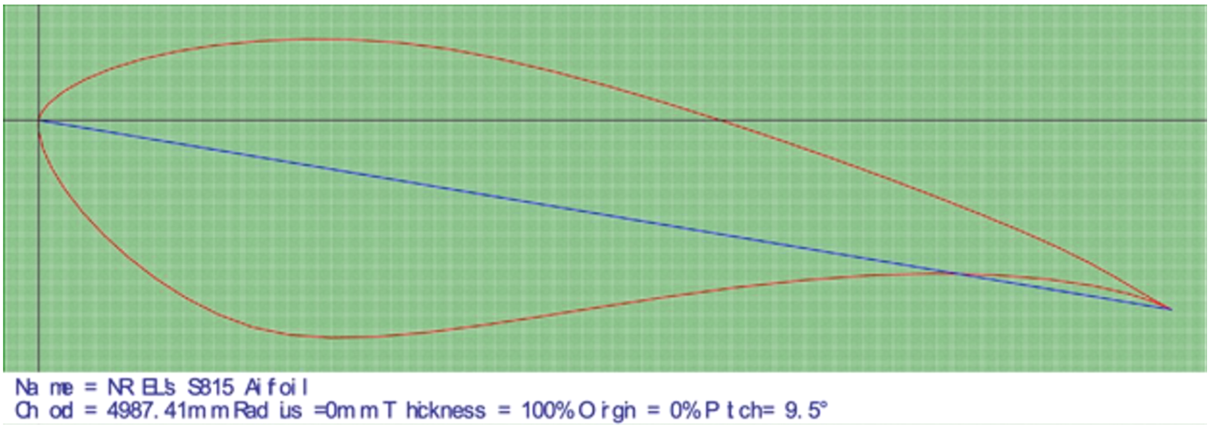
- ✓ C_l is the coefficient of lift.
- ✓ C_d is the coefficient of drag.
- ✓ ρ is the air density.
- ✓ A is the reference area (typically the blade's cross-sectional area).
- ✓ V is the wind speed.

The angle of attack (α) directly influences the coefficients of lift and drag (C_l and C_d). To optimize the blade's aerodynamic efficiency, engineers adjust the pitch angle to control the angle of attack under varying wind conditions (Manwell et al., 2009).

Airfoil Shape

The selection of the airfoil shape for wind turbine blades stands as a pivotal design decision with far-reaching implications for aerodynamic performance and overall operational efficiency of the turbine. Within the context of this study, the meticulous process of airfoil selection unfolded, as thoroughly expounded upon in Chapter 2. The selection methodology encompassed a comprehensive appraisal of multiple airfoil candidates, underpinned by an exhaustive analysis of key parameters encompassing lift-to-drag ratios, structural integrity, manufacturability, and noise characteristics.

Among the diverse array of airfoils scrutinized, the NREL airfoil emerged as the preeminent choice, fortified by several compelling rationales. Foremost, it exhibited a highly favorable lift-to-drag ratio, emblematic of its prowess in harnessing wind energy with optimal efficiency. Moreover, its structural robustness conferred the requisite fortitude to withstand the formidable mechanical stresses and dynamic loads encountered during operational service. Additionally, its inherent manufacturability translated into practicality and feasibility in terms of mass production.



Name = NREL's S815 Airfoil
Chord = 4987.41mm Radius =0mm Thickness = 100% Origin = 0% Pitch= 9.5°

Figure 2: The NREL's S815 Airfoil.

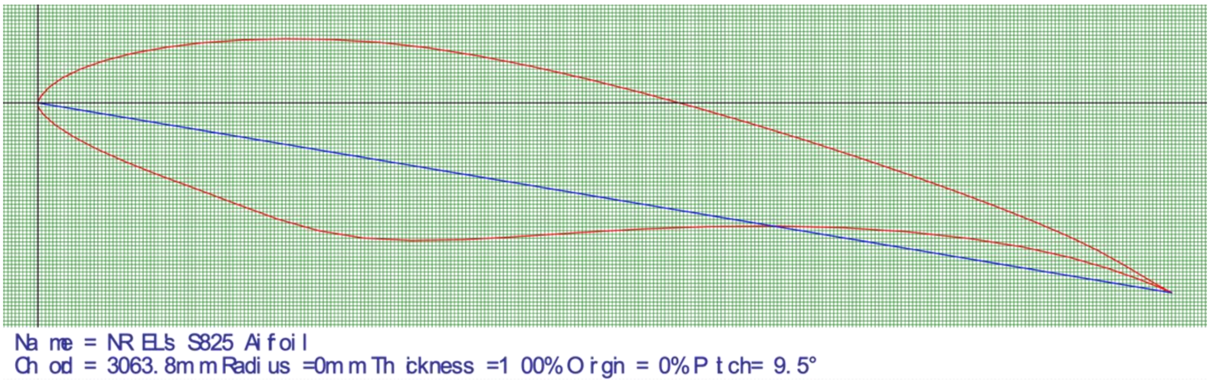


Figure 3: The NREL's S825 Airfoil.

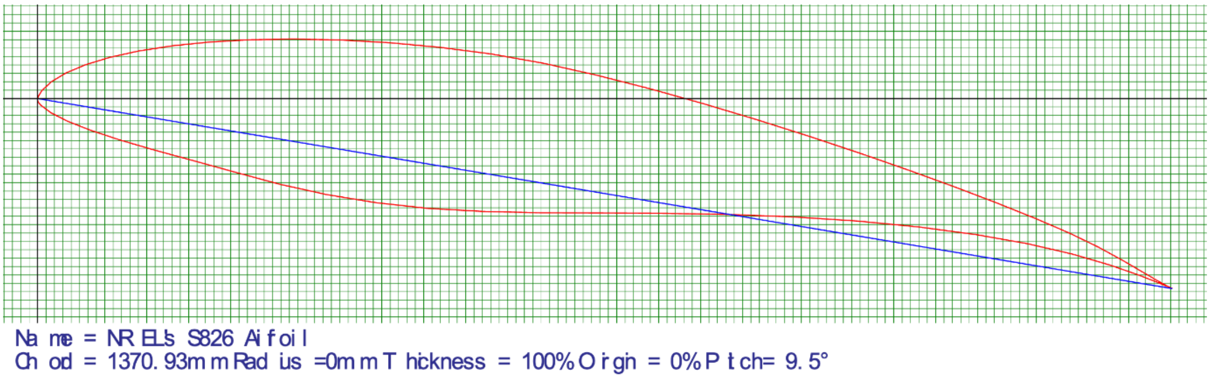


Figure 4: The NREL's S826 Airfoil.

Significantly, the selection of the NREL airfoil also took into judicious consideration noise characteristics. Recognizing the potential concern of wind turbine noise, particularly in the context of wind farm installations, the NREL airfoil's design exhibited characteristics conducive to mitigating noise generation.

It is imperative to underscore that the meticulous selection process extended beyond the airfoil choice alone. Parameters integral to the overall blade design, including blade length, chord length, twist angle, and thickness distribution, were meticulously scrutinized. These parameters were meticulously tailored to strike an equilibrium between aerodynamic efficiency and structural resilience. Moreover, the design protocol adhered rigorously to the stringent guidelines stipulated in the BS EN 61400 UK standard (BSI, 2011), ensuring the blade's conformance with essential safety, reliability, and performance standards.

This all-encompassing approach to airfoil selection and concurrent design parameters assumes paramount significance in the development of a wind turbine blade that attains peak efficiency in the conversion of wind energy into electrical power. This design, exemplified by the National Renewable Energy Laboratory (NREL) 4MW blade, has been meticulously conceived as a reference point for offshore system development, particularly in regions of the United Kingdom, including Scotland.

It is vital to delineate that while the NREL 4MW blade serves as a foundational reference, the geometric definition of the blade is primarily tailored to facilitate basic aerodynamic analysis. It does not encapsulate the level of detail requisite for the construction of a comprehensive three-dimensional real-world model. For the purposes of this analysis, one of the three blades constituting a Horizontal Axis Wind Turbine (HAWT) was modeled in solid geometry. The structural attributes of the blade are provided, albeit in the absence of complete composite or material layup specifics. Furthermore, the design incorporates a more intricate geometric definition, amenable to the generation of high-fidelity surface geometries.

Table 1: Properties of each Airfoil Cross-section along the Blade Length (50m).

Blade Span (m)	Airfoil	TE Type	Chord Length (m)	Pitch (degree)	Angle of Attack (degree)	Flow Angle (degree)
0	Round	Round	2.8	0	0	0
8	Round	Round	2.4	0	0	0
12.5	NREL S815	Flat	5.074	1.1	9.5	10.6
13	NREL S815	Flat	5.074	1.1	9.5	10.6
21.5	NREL S825	Flat	3.068	3	9.5	12.5
32	NREL S825	Flat	2.061	1.05	9.5	8.45
39	NREL S825	Flat	1.691	-2.54	9.5	6.96
48	NREL S826	Flat	1.374	-3.83	9.5	5.67
48.5	NREL S826	Shaped	1.319	-4.06	9.5	5.44
50	NREL S826	Shaped	0.29925	-4.06	9.5	5.44

The salient properties of each airfoil cross-section defining the NREL 4MW blade are meticulously cataloged in Table 1, encompassing details essential for establishing a foundational aerodynamic profile. This comprehensive data encompasses airfoil types, twist angles, and pitch axis locations, collectively contributing to the blade's aerodynamic performance characterization.

Conclusion

In conclusion Wind energy is a pivotal player in the global transition towards sustainable power generation. Wind turbines, specifically their blades, constitute the driving force behind this transformation. The selection of materials for these blades is a crucial endeavor, entailing a delicate balance between sustainability, performance, and cost-effectiveness. In this pursuit, sustainability is a lodestar guiding the way. It encompasses a multifaceted approach aimed at minimizing the environmental footprint while optimizing resource use. The ultimate goal is to create wind turbine blades that are not just effective energy harvesters but also eco-friendly, responsible, and economically viable.

Recommendations

1. Material Tailoring: Tailoring material choices to specific wind energy projects is essential. For large-scale, offshore installations, Carbon Fiber Reinforced Polymer (CFRP) remains a robust choice, emphasizing performance and longevity. Conversely, for small onshore turbines in regions with cost and sustainability as primary concerns, Pine and Bamboo exhibit substantial promise.Lifecycle Sustainability: Adopt a holistic approach to sustainability, encompassing material selection, production, usage, recycling, and disposal. Embrace recycling, repurposing, and eco-friendly disposal practices to minimize waste and environmental impact.

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