Optimization of Wind Turbine Power Generation Using Carbon Fiber Single Blade

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***Abstract*—The proposed research examines the effectiveness of a single-blade carbon-fiber wind turbine. A finite element analysis (FEA) is performed to evaluate the enhanced stiffness and vibration characteristics of the orthotropic carbon fiber. Moreover, the airflow patterns around the turbine blade at various angles of attack are also explored through comprehensive computational fluid dynamics (CFD) simulations. Although there are advantages, such as reduced weight, the carbon fiber single blade still faces challenges related to practical performance, manufacturing development, environmental impacts, and cost-effectiveness.**

***Index Terms*— carbon fiber single blade, computational fluid dynamics (CFD), fiberglass composite, finite element analysis (FEA), power generation, wind turbine.**

I. INTRODUCTION

Given the escalating energy demand, coupled with intensifying environmental concerns and the dwindling access to traditional energy sources, the advancement of renewable energy technologies has become an imperative global priority. Within the spectrum of renewable energy options, wind energy has emerged as one of the most sophisticated and promising avenues for power generation [1]. It has also been increasingly recognized for its potential to contribute meaningfully to a sustainable energy landscape.

Conventional wind turbines, characterized by their standard three-blade design, have long been used to capture and convert wind kinetic energy into electrical power efficiently. However, this traditional turbine framework faces several significant obstacles. This includes challenges associated with 1) the manufacturing process, 2) logistical issues during transportation, 3) complexities related to installation, and 4) ongoing maintenance requirements. These challenges can substantially hinder the widespread adoption of wind energy technologies, particularly in 1) certain geographical areas, or 2) under specific environmental conditions [1].

In response to these limitations, researchers and engineers have undertaken extensive investigations to develop innovative wind turbine designs that could enhance performance and broaden applicability. A novel approach that has garnered considerable attention is the single-blade wind turbine, which distinguishes itself from the conventional three-blade model. Single-blade turbines offer a range of compelling advantages. This includes: 1) a simplified manufacturing processes that reduce production costs, 2) a lighter overall weight that eases transportation and installation, 3) reduced maintenance demands due to fewer moving parts, and 4) the potential for improved aerodynamic performance, leading to greater energy efficiency [2].

The research project, entitled "Power Production from Renewable Sources Using a Carbon Fiber Single Blade Wind Turbine," focuses on exploring the synergistic potential of combining the inherent benefits of single-blade turbine technology with advanced carbon fiber materials. Known for its exceptional strength-to-weight ratio, carbon fiber is an optimal choice for fabricating wind turbine blades. It further enables lighter and stronger structures that can withstand harsh environmental conditions while maximizing energy output. This innovative combination of cutting-edge turbine design and advanced materials science has the potential to revolutionize the wind energy sector and significantly contributes to a more sustainable, environmentally friendly energy future.

The following are the research objectives of the proposed work:

- To simulate a wind turbine generator design blade using carbon fiber as the blade material.
- To compare the carbon fiber single-blade wind turbine's environmental footprint to that of traditional three-blade wind turbines in a thorough life cycle assessment (LCA) of its ecological effect.
- To undertake a cost-benefit analysis of the carbon fiber single-blade wind turbine, including aspects such as original investment, operational costs, maintenance expenditures, and possible income generation from energy sales

II. CARBON FIBER WIND TURBINE TECHNOLOGY

A significant advancement in renewable energy is the introduction of carbon fiber wind turbine technology, which provides an effective approach to enhance the performance, durability, and sustainability of wind turbine systems [4]. By leveraging the outstanding mechanical properties of carbon fiber composites, wind turbine blades can be designed to address major challenges associated with traditional turbine designs.

The remarkable strength-to-weight ratio of carbon fiber enables the creation of turbine blades that are both lightweight and strong. This attribute is particularly beneficial for reducing blade weight, which in turn boosts overall turbine efficiency and decreases mechanical stress on various components [1]. Furthermore, the reduced weight contributes to cost savings by lowering transportation and installation costs.

Moreover, the impressive fatigue resistance and corrosion resistance properties of carbon fiber enhance the longevity of wind turbine blades. This results in reduced downtime and decreased maintenance, which increases availability and boosts energy output [5]. By prolonging the service life of wind turbines and consequently increasing their economic viability, carbon fiber blades' improved durability may be essential.

A multitude of research studies has focused on the application of carbon fiber in conventional three-blade wind turbine models, showing benefits like enhanced energy capture and reduced blade deflections [6]. Nevertheless, the utilization of carbon fiber technology in single-blade wind turbines presents an entirely new area for exploration and advancement. As illustrated in **Fig. 1**, due to their simpler designs, single-blade wind turbines could leverage the advantages of carbon fiber to address challenges related to structural integrity and dynamic performance.

It is important to keep in mind that although carbon fiber wind turbine technology offers numerous benefits, it also presents challenges. The initial widespread adoption encounters financial hurdles due to the high costs associated with carbon fiber materials and manufacturing processes [7]. Additionally, ensuring reliable production methods and quality assurance is essential to avoid defects and ensure safe operation.

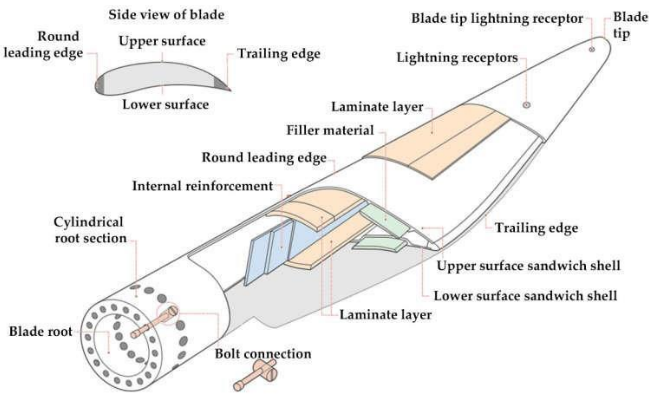

Figure 1. Typical carbon-fiber blade [3].

III. FEA AND CFD ANALYSIS AND RESULTS

To enhance the stiffness, shape, and angle of attack of a carbon fiber wind turbine blade for specific wind loads and velocities at a site, this project used CFD and FEA modeling. The modal frequencies and structural stability of the blades are evaluated using FEA. The CFD analysis focuses on investigating aerodynamic performance, including 1) lift, 2) drag, and 3) pressure distributions.

A. FEA Analysis

Table I below compares carbon fiber and fiberglass composites based on material properties and FEA results. Carbon fiber, with aligned continuous fibers and epoxy resin, shows orthotropic behavior and much higher axial stiffness (120 GPa) than fiberglass (10 GPa), which is isotropic and uses polyester resin. Under identical loading in FEA, the carbon fiber plate had a 1.8 mm displacement versus 18 mm for the fiberglass plate, and the von Mises stress was 10 times lower. This confirms carbon fiber's superior bending resistance and structural performance. While fiberglass is suitable for less demanding applications, carbon fiber is ideal where high stiffness and strength are critical.

The primary outcome of the FEA analysis is illustrated in **Fig. 2**, where the carbon fiber experiences a uniformly distributed transverse pressure load of 1 MPa applied to the surface on the opposite short edge. The 1 MPa load induces considerable bending stress within the material's linear elastic range. This eliminates the need to examine failure or permanent deformation when analyzing stress and deflection responses.

TABLE I. FEA ANALYSIS OF CARBON FIBER AND FIBERGLASS COMPOSITES[1]

Feature	Carbon Fiber Composite	Fiberglass Composite
Fiber Type	Continuous, aligned carbon fibers	Short, randomly-oriented glass fibers
Matrix Material	Epoxy resin	Polyester resin
Material Behavior	Orthotropic (directional properties)	Isotropic (uniform properties)
Elastic Modulus (Axial)	120 GPa (high stiffness along fiber direction)	10 GPa (significantly lower stiffness)
Elastic Modulus (Transverse)	10 GPa	10 GPa
Poisson's Ratio	0.3	0.2
Modeling Type in FEA	Orthotropic linear elastic material	Isotropic linear elastic material
Geometry Used in FEA	300 x 200 x 3 mm rectangular plate (same for both)	
FEA Mesh Type	Structured quadrilateral, 5 mm element size	
Mesh Quality	Mapped meshing, good aspect ratio (~1:1), ~8 elements across thickness	
Boundary Condition	One short edge fixed (cantilever) all DOFs restricted.	
Loading Condition	1 MPa uniformly distributed transverse pressure on free edge	
Max Displacement at Free End	1.8 mm	18 mm
Max von Mises Stress	24 MPa (at fixed end)	240 MPa (at fixed end)
Bending Behavior	High bending stiffness and low deformation	Low bending stiffness, high deformation
Interpretation of Results	High strength, dimensional stability under bending	Lower performance, more susceptible to bending
Structural Application Suitability	Excellent for high-stiffness/strength needs	Suitable for less demanding applications
Performance Advantage	5–12× greater axial stiffness and strength	Lower mechanical performance
FEA Insight	Confirms the superior performance of aligned carbon fiber composites under bending loads	Demonstrates limitations due to isotropic and lower-stiffness material properties

1. FEA, DOF, GPa, and MPa are the abbreviations of finite element analysis, degree of freedom, gigapascal, and megapascal respectively.

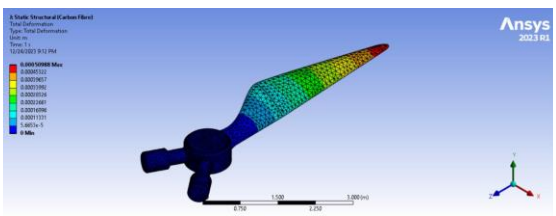

Figure 2: Total Deformation; Carbon fiber.

B. *FEA Result*

The FEA results shown in **Fig. 3** compare the first 100 natural vibration modes and frequencies of a carbon fiber composite structure with those of a similar fiberglass composite structure. The inherent frequencies for the carbon fiber model are significantly higher than those of the fiberglass model across all 100 modes. This indicates that the stiffness and rigidity of the carbon fiber construction are considerably greater than those of the fiberglass structure. The fundamental frequency of carbon fiber in its first natural mode shape is 3.412 Hz, which is more than 50% higher than the fiberglass's frequency of 2.2395 Hz. This significant difference in the lowest natural frequency highlights the superior baseline stiffness that carbon fibers provide compared to fiberglass. Although the frequency ratio between carbon fiber and fiberglass decreases slightly as the modes progress to higher orders, it remains about 30–40% greater for carbon fiber up to mode 100. For example, in mode 50, the fiberglass frequency is 853.65 Hz while the carbon fiber frequency is 1364.9 Hz, representing an increase of nearly 60% for the carbon fiber system.

In general, carbon fiber composites demonstrate significantly elevated natural frequencies, which can be attributed to the stiffness and high elastic modulus of the aligned carbon fibers in the direction of loading. The long, continuous carbon fibers provide exceptionally high axial stiffness and rigidity, enhancing the overall structural stiffness of the composite component. In contrast, fiberglass composites possess considerably lower stiffness because of their short, randomly oriented fibers. The carbon fibers maintain their superior stiffness throughout the entire frequency range being examined, as indicated by the consistent frequency differences across all 100 vibration modes. Additionally, the carbon fiber composite exhibits higher damping qualities in comparison to the more viscoelastic fiberglass material, along with its increased rigidity. The heightened structural stiffness and dampening capacity of the carbon fiber composite lead to reduced vibration amplitudes and noise. Ultimately, our modal analysis quantitatively demonstrates that, relative to fiberglass composites, carbon fiber composites provide much better stiffness, dimensional stability, and vibration response due to their enhanced natural frequencies.

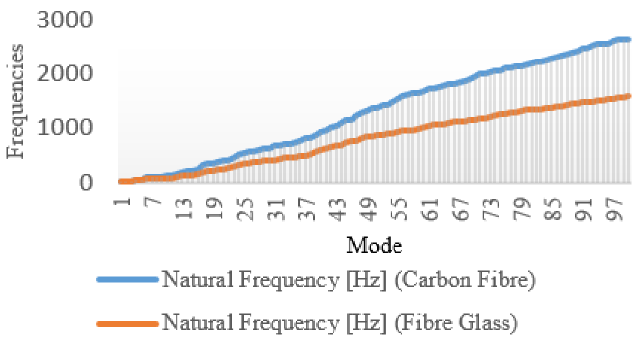

Figure 3. Mode shapes of Carbon fiber vs. Glass fiber

C. *CFD Analysis*

The blade geometry was based on a hybrid airfoil design incorporating NREL S818 (root), S827 (mid), and S828 (tip) profiles to optimize aerodynamic performance along the span. These airfoils were selected for their low drag and high lift characteristics. The following is the CFD analysis of the airfoil design used in the blade modeling, which focused on evaluating the aerodynamic performance of a wind turbine blade using a hybrid airfoil design (NACA series with NREL S818, S827, and S828 profiles). Simulations were conducted in ANSYS at a constant Reynolds number of 822,000 and wind speed of 10 m/s, examining angles of attack from 8° to 12°. The blade's lift and drag behavior was assessed using a 2D steady-state Spalart-Allmaras turbulence model. Detailed mesh refinement and realistic boundary conditions replicated wind tunnel settings. Results, as shown in **Table II**, included force coefficients, pressure contours, and streamlines, providing insights into optimal airfoil performance across blade regions and angle of attack (AOA) ranges.

TABLE II. CBD ANALYSIS OF CARBON FIBER AND FIBERGLASS COMPOSITES[2]

Feature	**CFD Analysis – Airfoil Blade Design**
Airfoil Type	NACA 4-digit series (infused with NREL S818–root, S827–mid, S828–tip)
Purpose of Design	Maximize lift and minimize drag across different blade regions.
Simulation Tool	ANSYS CFD (2D steady-state simulation)
Simulation Objective	Evaluate Cl and Cd for different AOA
Reynolds Number	822,000 (constant)
Wind Speed	10 m/s (constant)
Air Density	1.225 kg/m³
Kinematic Viscosity	1.789×10^{-5} kg/m·s
AOA Range Studied	8° to 12° in 0.5° increments
Number of AOA Simulations	9 individual cases (incremental changes in AOA)
Computational Domain	Rectangular wind tunnel model with airfoil centered inside
Boundary Conditions	- Inlet: Velocity inlet - Outlet: Pressure outlet - Walls: No-slip (top, bottom, and side)
Mesh Type	- Tetrahedral elements in far field - Refined inflation layers near airfoil surface for boundary layer resolution
Turbulence Model	Spalart-Allmaras RANS model
Solver Type	Steady-state, 2D
Data Output	- Velocity streamlines - Pressure contours - Force coefficients (Cl and Cd)
Result Interpretation	- Captured aerodynamic behavior before and after stall - Enabled detailed comparison of lift and drag across AOA range
Design Insight	Demonstrated best practices in simulating high-performance airfoils. Optimized airfoil distribution across the blade for varying aerodynamic loads
Practical Relevance	Simulates realistic wind tunnel conditions to assess blade efficiency under varying AOA
Feature	CFD Analysis – Airfoil Blade Design
Airfoil Type	NACA 4-digit series (infused with NREL S818–root, S827–mid, S828–tip)

2. AOA, Cd, Cl, CFD, NACA, NREL, and RANS are the abbreviations of angle of attack, drag coefficient, lift coefficient, computational fluid dynamics, national advisory committee for aeronautics airfoils, national renewable energy laboratory, and Reynolds averaged navier stokes, respectively.

D. *CFD Result*

The aerodynamic performance metrics of a wind turbine blade are analyzed below using data at various AOAs, ranging from 8 to 12 degrees. Key outputs examined include pressure distributions, calculated power output, along with lift and drag coefficients (Cl, Cd).

- At 8.5 degrees AOA, the lift coefficient (Cl) initially rises to a peak of 22.74 as AOA increases from 8 to 12 degrees. Following the maximum at 8.5 degrees, Cl progressively declines as the blade begins to stall at higher angles of attack.
- The drag coefficient (Cd) increases from 6.4 at 8 degrees to 9.03 at 12 degrees, nearly in a linear fashion with AOA,

as expected. An increase in Cd signifies higher drag forces due to flow separation.

- With a Cl/Cd ratio of 3.20, optimal aerodynamic efficiency is observed at 8.5 degrees. Since Cd increases more rapidly than Cl, performance deteriorates on either side of this point.
- At lower AOAs, pressure distributions show a relatively uniform suction peak on the blade's upper surface. As AOA rises, the peak suction pressure shifts downstream, indicating the onset of flow separation.
- Significant flow separation and stall are illustrated by a sharp suction pressure spike that occurs farther downstream at 12 degrees AOA, correlating with the reduction in Cl as AOA increases.
- The calculated power output, which is maximized at 8.5 degrees AOA and declines at higher angles due to stall, is closely linked to Cl. It reaches its highest value just below the stall angle.

Fig. 4 below shows the graphical representation of the lift-over-drag coefficient ratio results at different angles.

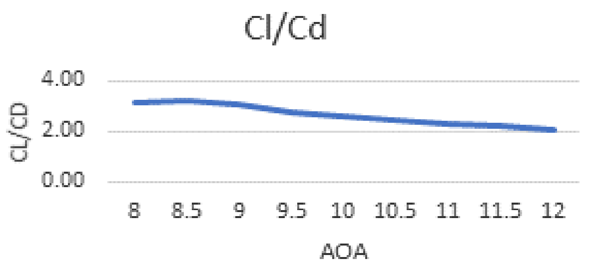

Figure 4. Lift over drags coefficients ratio.

The static pressure values in the CFD simulation, as shown in **Fig. 5**, represents the local pressure exerted by the airflow on the airfoil surface when the wind is moving at 10 m/s for various AOA. As the AOA increases from 8° to 12°, the static pressure gradually rises from 34.9 Pa to 40.7 Pa. This increase indicates that the airfoil is generating more resistance as it presents a steeper surface to the incoming flow. However, even as static pressure increases, lift-to-drag ratio (Cl/Cd) decreases, showing a decline in aerodynamic efficiency beyond the optimal AOA (~8.5°–9°). Essentially, static pressure is a sign of increased aerodynamic loading, and beyond a certain point, it correlates with diminishing returns in performance due to increased drag and the onset of stall behavior.

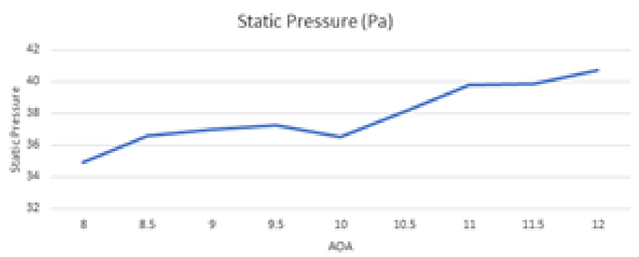

Figure 5. Static pressure

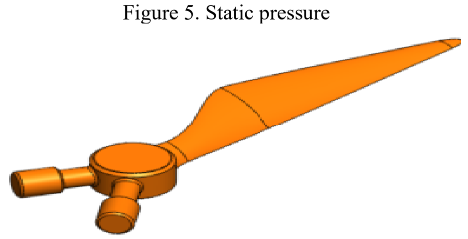

Figure 6. Geometry of the blade generated in SolidWorks

In general, the CFD study generated extensive data to assess how the angle of attack impacts the aerodynamic efficiency of wind turbines. To enhance power generation, this information will help identify the optimal blade pitch angles just before stall. Operating past the stall angle can result in considerable losses in both efficiency and power, as indicated by the simulations. **Fig. 6** shows the geometry of the carbon-fiber blade as generated in SolidWorks.

IV. LIFE CYCLE ANALYSIS

Table III below shows the life cycle analysis of carbon fiber and glass fiber, as used in a single blade.

TABLE III. CARBON FIBER VS GLASS FIBER (SINGLE BLADE)

LCA Metric	Carbon Fiber Blade	Glass Fiber Blade
Carbon Footprint (CO_2e)	28,000 kg	14,000 kg
Total Energy Consumption	480,000 MJ	160,000 MJ
Air Acidification (SO_2e)	54 kg	60 kg
Water Eutrophication Impact	Higher	Lower
Energy-Intensive Processes	High-temp pyrolysis, oxidation	Lower-temp melting
Electricity Source Sensitivity	Affects eutrophication and emissions	Affects SO_2 via fossil fuel use
LCA Metric	Carbon Fiber Blade	Glass Fiber Blade
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Total Energy Consumption	480,000 MJ	160,000 MJ
Air Acidification (SO_2e)	54 kg	60 kg
Water Eutrophication Impact	Higher	Lower
Energy-Intensive Processes	High-temp pyrolysis, oxidation	Lower-temp melting
Electricity Source Sensitivity	Affects eutrophication and emissions	Affects SO_2 via fossil fuel use

While carbon fiber offers performance advantages, it has a significantly higher environmental impact in terms of carbon footprint, energy use, and water eutrophication, with only a slight benefit in air acidification over glass fiber. Further analysis also shows that while the carbon fiber blade provides superior structural performance, its environmental impact is substantially higher, particularly in terms of CO_2 emissions, energy use, and eutrophication of water bodies. The three-blade fiber system presents a more environmentally sustainable option, highlighting a crucial trade-off between technical excellence and ecological responsibility. Moreover, while the concept of a single blade presents benefits such as lighter weight and lower rotational speeds, the existing design entails excessive financial risk because of its unproven reliability and aerodynamic efficiency. To boost trust in the technology, more testing and design revisions would be necessary. **Fig. 7** shows the wind turbine using carbon fiber generated by SolidWorks.

V. CONCLUSION

Comprehensive simulation research evaluates the performance and design of an innovative single-blade carbon-fiber wind turbine using a multidisciplinary approach. To determine the superior stiffness and vibration characteristics of the orthotropic carbon fiber composite blade compared to isotropic fiberglass composites, an in-depth FEA is performed. The FEA quantitatively demonstrates the favorable modal frequency response of aligned carbon fibers, indicating enhanced structural integrity against fatigue and deflection under operating loads.

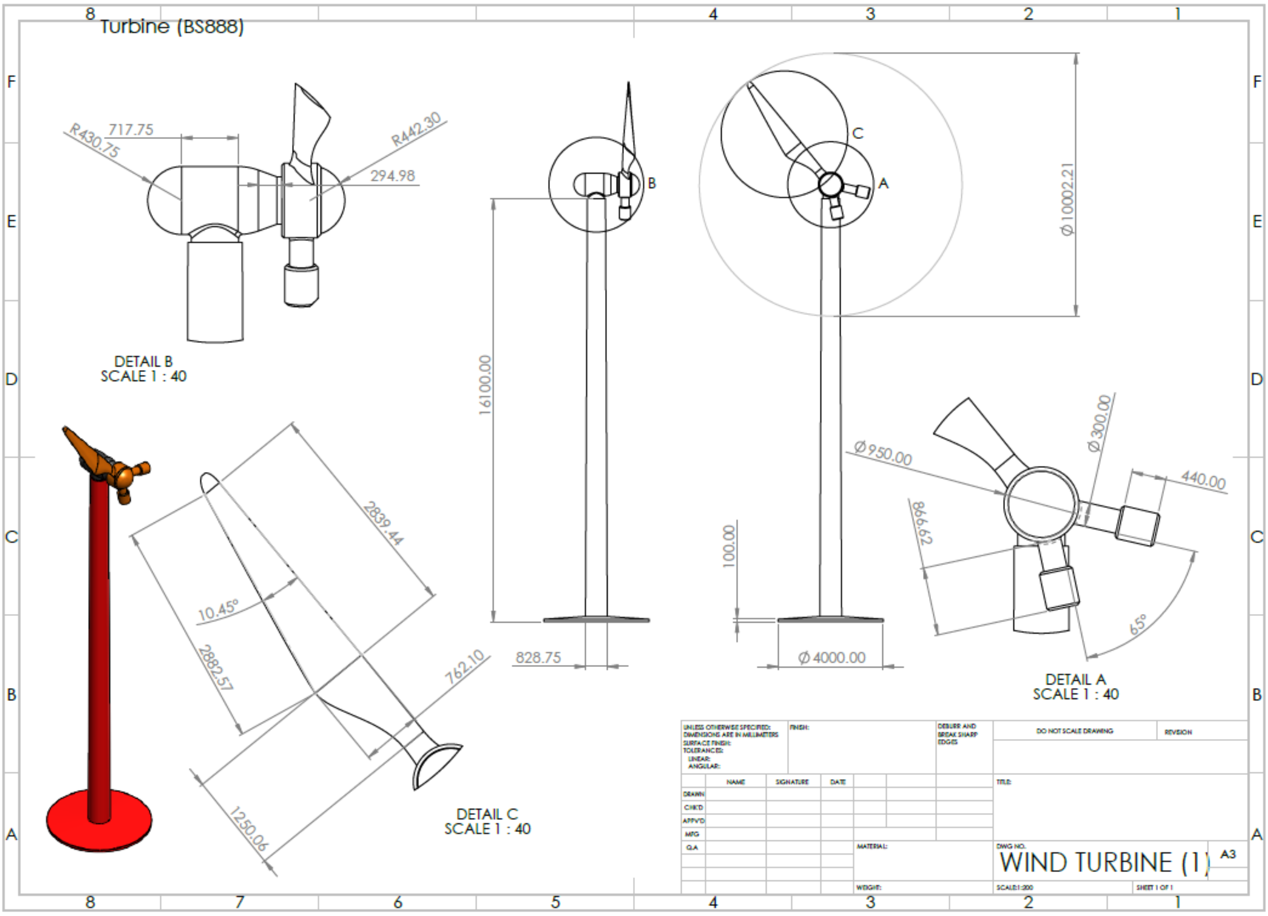

Figure 7. Wind turbines use carbon fiber, generated in SolidWorks.

The complexities of airflow around the turbine blade at various angles of attack are explored through detailed CFD simulations. The models identify the optimal pitch angle just prior to aerodynamic stall, maximizing lift forces and generating the maximum possible power for a specific wind speed. By leveraging precise performance data acquired from thorough CFD modeling, researchers can fine-tune control settings and material configurations for optimal aerodynamic efficiency.

A detailed LCA compares glass fiber and carbon fiber blades. Since carbon fiber is manufactured using relatively energy-demanding, high-temperature processes, the LCA results reveal significantly higher emissions and energy usage during the manufacturing phase. However, the carbon fiber blade results in slightly lower SO_2 equivalent emissions, indicating potential benefits for air quality.

The series of assessments indicates that, despite advantages such as reduced weight, the carbon fiber single blade still faces challenges regarding practical performance, manufacturing readiness, environmental impact, and economic viability. The extensive data provided by the integrated modeling process facilitates further development of the unique design through testing, optimization, and design adjustments. Employing multidisciplinary modeling, the research serves as a virtual prototyping framework for advancing wind turbine technology.

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