

Manufacture of Wind Turbine Blade

Advanced Processes and Materials – ACMA6000

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Abstract

This report presents a preliminary design study for a next-generation wind turbine blade focused on maximising energy efficiency while minimising weight and maintenance costs. A literature review was conducted to identify optimal aerodynamic profiles, blade geometries, and operating parameters such as tip speed ratio and lift-to-drag ratio. Based on these findings, a tapered blade design using the NACA 4412 aerofoil was developed and analysed across multiple spanwise sections. Material selection was performed using a weighted decision matrix comparing metals, ceramics, and polymer composites, with fibre-reinforced polymers identified as the most suitable due to their superior strength-to-weight ratio and fatigue resistance. Manufacturing routes, including vacuum infusion and resin transfer moulding, were evaluated in terms of scalability, defects, and cost. The results indicate that polymer composite blades manufactured using vacuum-based processes provide the most effective balance of performance, durability, and economic feasibility for modern wind turbine applications.

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1. Introduction

The demand for renewable energy systems has driven significant advancements in wind turbine technology, with blade design playing a critical role in overall system efficiency. Wind turbine blades must achieve a balance between aerodynamic performance, structural integrity, and cost-effectiveness while operating under highly variable environmental conditions. As blade size increases to improve energy capture, challenges related to material selection, fatigue resistance, and manufacturing complexity become increasingly significant.

This report presents a preliminary design study for a next-generation wind turbine blade, focusing on optimising aerodynamic performance while minimising weight and maintenance costs. The study integrates aerodynamic theory, material selection, manufacturing considerations, and cost evaluation to determine a suitable blade design and production approach.

The methodology is divided into four key areas. First, a literature review is conducted to identify optimal blade geometries, aerodynamic profiles, and critical design parameters such as lift-to-drag ratio and tip speed ratio. Second, a design specification is developed using aerodynamic and geometric calculations to define blade shape and performance characteristics. Third, material candidates including metals, ceramics, and polymer-based composites are evaluated using a weighted decision matrix. Finally, manufacturing routes and associated costs are analysed to determine the most feasible production method.

The outcome of this report is a justified recommendation for the most suitable material and manufacturing process for wind turbine blade production, supported by engineering analysis and industry-relevant considerations.

2.Literature Review

Wind turbine blade performance is primarily governed by aerodynamic efficiency, which is influenced by blade geometry, aerofoil selection, and operating conditions. Modern horizontal-axis wind turbines typically utilise three-bladed configurations with tapered and twisted geometries to optimise energy capture across the rotor span (Burton, et al., 2011).

A key parameter in blade design is the tip speed ratio (TSR), defined as the ratio between blade tip speed and incoming wind speed. Optimal TSR values for large-scale turbines generally lie between 6 and 8, as this range provides a balance between aerodynamic efficiency and structural loading (Hau, 2013). Operating outside this range results in increased drag losses at low TSR or excessive centrifugal and bending stresses at high TSR.

Blade geometry typically incorporates a tapered chord distribution, where the chord length decreases from root to tip. This design approach ensures structural strength at the root, where bending moments are highest, while reducing drag and improving aerodynamic efficiency towards the blade tip (Manwell, et al., 2010). For small to medium-scale blades, chord lengths may vary linearly from approximately 0.4 m at the root to 0.1 m at the tip, depending on rotor size and application.

Aerofoil selection is critical for achieving high lift-to-drag ratios, which directly influence the power coefficient (C_p). The NACA 4412 aerofoil is widely used in wind turbine blade design due to its favourable lift characteristics and stable performance across a range of angles of attack (Abbot & Doenhoff, 1959). In practice, wind turbines achieve C_p values below 0.4 due to aerodynamic, mechanical, and electrical losses, despite the theoretical Betz limit of 0.593 (Burton, et al., 2011).

In addition to aerodynamic performance, structural considerations are essential. Wind turbine blades are subjected to cyclic and stochastic loading caused by wind variability, making fatigue resistance a critical design requirement (Sutherland, 1999). Materials must therefore exhibit high fatigue strength, sufficient stiffness, and low density to minimise gravitational and inertial loads.

Environmental factors also significantly influence blade performance. Variations in wind speed, turbulence intensity, and environmental exposure can lead to fluctuating

loads and material degradation over time. Blades must therefore be designed to withstand harsh operating conditions, including temperature variations, moisture exposure, and ultraviolet radiation (Ashwill, 2009).

Material selection plays a crucial role in achieving the desired balance between performance and durability. Metals such as steel and aluminium offer high strength but are generally unsuitable due to their high density, which increases structural loads and reduces efficiency (Ashby, 2011). Ceramics provide excellent stiffness and thermal resistance but are limited by their brittleness and low fracture toughness. In contrast, polymer-based composites, such as glass fibre-reinforced polymers (GFRP) and carbon fibre-reinforced polymers (CFRP), offer an optimal combination of low density, high strength, and excellent fatigue resistance, making them the preferred materials in modern wind turbine blade manufacturing (Gibson, 2016).

3.Design Specifications

The blade design was developed based on aerodynamic principles identified in the literature, with the objective of maximising energy capture while maintaining structural integrity and manufacturability. A horizontal-axis wind turbine configuration with three blades was assumed, as this represents the most efficient and widely adopted design for modern systems (Burton, et al., 2011).

A design wind speed of 10 m/s was selected as a representative operating condition for small to medium-scale turbines. Based on this, a tip speed ratio (TSR) of 7 was chosen to achieve an optimal balance between aerodynamic efficiency and mechanical loading (Hau, 2013). The corresponding blade tip speed is therefore given by:

$$v_{tip} = \lambda \cdot V = 7 \times 10 = 70 \text{ m/s}$$

A rotor radius of 1 m was selected to ensure manageable blade size for modelling and analysis. This results in an angular velocity:

$$\omega = \frac{v_{tip}}{R} = \frac{70}{1} = 70 \text{ rad/s}$$

The blade geometry was defined using a tapered chord distribution to balance structural and aerodynamic requirements. A larger chord length at the root provides strength to resist bending moments, while a reduced chord at the tip minimises drag. A linear taper was adopted, with chord length decreasing from 0.4 m at the root to 0.1 m at the tip.

To analyse the variation in blade geometry, the span was divided into five sections based on nondimensional radius (r/R):

r/R	Radius (m)	Chord Length (m)
0.2	0.2	0.34
0.4	0.4	0.28
0.6	0.6	0.22
0.8	0.8	0.16
1.0	1.0	0.10

Figure 1: Tapered chord distribution

The NACA 4412 aerofoil was selected for all sections due to its high lift coefficient and stable aerodynamic behaviour across a range of operating conditions (Abbot & Doenhoff, 1959). The aerofoil has a maximum thickness of 12% of the chord, which provides a suitable compromise between aerodynamic performance and structural stiffness.

The aerodynamic loading on each blade section can be approximated using the lift force equation:

$$L = \frac{1}{2} \rho V^2 C_L A$$

where ρ is air density (1.225 kg/m^3), V is relative wind velocity, C_L is the lift coefficient, and A is the sectional area. This relationship demonstrates that lift increases with both velocity and chord length, justifying the larger chord dimensions near the blade root.

In addition to aerodynamic considerations, structural performance was evaluated through bending stress estimation. The blade experiences maximum bending at the root due to aerodynamic loading, making this region critical in material selection and thickness design. The use of a thicker aerofoil section at the root improves stiffness and reduces the risk of structural failure.

Overall, the selected design combines a moderate rotor size, optimal TSR, tapered geometry, and a proven aerofoil profile to achieve a balance between efficiency, strength, and manufacturability.

4. Material Selection

The selection of a suitable material for wind turbine blades is critical in achieving the required balance between aerodynamic performance, structural integrity, durability, and cost. Blades are subjected to continuous cyclic loading, environmental exposure, and aerodynamic forces, making fatigue resistance and strength-to-weight ratio key design considerations.

Three primary material categories were evaluated: metals, ceramics, and polymer composites. Metals such as aluminium and steel offer high strength and ease of manufacturing but are limited by their high density, which increases gravitational loading and reduces overall efficiency (Ashby, 2011). Ceramics provide excellent stiffness and resistance to environmental degradation; however, their brittle nature and low fracture toughness make them unsuitable for applications involving dynamic loading. Polymer composites, particularly fibre-reinforced polymers, provide a superior combination of low density, high specific strength, and excellent fatigue resistance, making them widely used in modern blade design (Gibson, 2016).

To systematically evaluate these materials, a weighted decision matrix (WDM) was developed. Key performance criteria were identified based on design requirements, including strength-to-weight ratio, fatigue resistance, stiffness, manufacturability, cost, and environmental resistance. Each criterion was assigned a weighting factor between 0 and 1 based on its relative importance, and each material was scored on a scale of 1 to 5.

Criteria	Weight	Metals	Ceramics	Composites
Strength-to-weight	0.25	2	3	5
Fatigue resistance	0.20	3	1	5
Stiffness	0.15	4	5	4
Manufacturability	0.15	4	2	4
Cost	0.15	3	2	3
Environmental resistance	0.10	3	5	4

Figure 2: Weighted decision matrix

Material	Score
Metals	2.95
Ceramics	2.65
Composites	4.55

Figure 3: Weighted scores

The results of the weighted decision matrix indicate that polymer composites significantly outperform metals and ceramics in overall suitability for wind turbine blade applications. The high score for composites is primarily due to their excellent strength-to-weight ratio and superior fatigue resistance, which are critical for components subjected to cyclic aerodynamic loading.

While metals demonstrate good manufacturability and stiffness, their high density leads to increased structural loads and reduced efficiency. Ceramics, despite their high stiffness and environmental resistance, are unsuitable due to their brittle failure behaviour and poor fatigue performance.

Based on this analysis, fibre-reinforced polymer composites are selected as the most appropriate material for the proposed blade design. These materials provide an optimal balance between mechanical performance, durability, and manufacturability, making them the industry standard for modern wind turbine blades.

5. Manufacturing Routes

The manufacturing process must be capable of producing large, aerodynamically complex structures with high structural integrity and minimal defects. While multiple material classes were considered during material selection, their associated manufacturing routes further influence their suitability for wind turbine blade production.

Metal manufacturing processes such as casting and extrusion are capable of producing structural components; however, they are not well suited to wind turbine blades. Casting is prone to defects including porosity, shrinkage, and residual stresses, while extrusion is limited to uniform cross-sections and cannot accommodate the varying blade geometry. Additionally, the high density of metals results in increased structural loading, reducing overall efficiency.

Ceramic manufacturing methods, including sintering and additive manufacturing, offer high stiffness and environmental resistance but are limited by brittleness and poor impact resistance. Sintering processes are energy-intensive and susceptible to cracking due to thermal gradients, while additive manufacturing is not yet viable for large-scale structural components. These limitations make ceramics unsuitable for dynamic applications such as wind turbine blades.

In contrast, polymer composite manufacturing provides a highly suitable solution due to its ability to produce lightweight, high-strength structures with complex geometries. Two primary processes were evaluated: resin transfer moulding (RTM) and vacuum infusion.

RTM involves placing dry fibre reinforcement within a closed mould and injecting resin under pressure. This process produces high-quality components with good surface finish and controlled fibre distribution. However, it requires expensive tooling and precise process control, increasing production costs.

Vacuum infusion is widely used in wind turbine blade manufacturing due to its scalability and cost-effectiveness. In this process, dry fibres are arranged in a mould and resin is drawn through the material using vacuum pressure. This enables uniform resin distribution and reduces void content compared to manual lay-up

techniques. The process is particularly suitable for large components and requires relatively lower equipment investment.

Potential defects in composite manufacturing include voids, dry spots, and incomplete impregnation, which can negatively impact fatigue performance. However, these issues can be mitigated through controlled resin flow, effective vacuum sealing, and quality assurance procedures.

Overall, polymer composite manufacturing processes offer significant advantages over metals and ceramics in terms of weight, performance, and manufacturability. Among these, vacuum infusion is identified as the most suitable manufacturing method for the proposed blade design due to its balance of cost, scalability, and product quality.

6. Cost Evaluation

The economic feasibility of wind turbine blade production is strongly influenced by both material costs and manufacturing processes. In this study, a comparative cost evaluation was conducted for metals, ceramics, and polymer composites, focusing on raw material costs alongside general production considerations.

Raw material costs vary significantly between the three material categories. Metals such as steel are relatively inexpensive on a per kilogram basis; however, their high density results in greater material usage, increasing overall cost and structural loading. Aluminium offers a lighter alternative but at a higher cost per unit mass. Ceramics generally have moderate raw material costs, but their specialised processing requirements and high rejection rates increase overall production expenses. In contrast, polymer composites such as glass fibre-reinforced polymers (GFRP) provide a balance between cost and performance, while carbon fibre-reinforced polymers (CFRP) offer superior mechanical properties at a significantly higher material cost.

Material Type	Approx. Cost (£/kg)	Key Consideration
Steel	0.5 – 1.5	Low cost, high density
Aluminium	2 – 5	Moderate cost, lighter
Ceramics	5 – 15	Processing cost high
GFRP	3 – 10	Good cost-performance
CFRP	20 – 50	High performance, expensive

Figure 4: Material approx. cost

Manufacturing costs are also a critical factor. Metal processes such as casting require high energy input and extensive finishing operations, increasing labour and equipment costs. Ceramic processing, particularly sintering, is energy-intensive and prone to defects, leading to higher rejection rates and waste. Composite manufacturing methods such as vacuum infusion require relatively low equipment investment and are well suited to large-scale production, reducing labour costs and material waste.

Defect mitigation also contributes to overall cost. Issues such as porosity in metals, cracking in ceramics, and void formation in composites can lead to reduced product

quality and increased rework or rejection. However, composite processes allow for better control of defects through process optimisation, improving production efficiency.

Overall, while some materials such as steel offer lower initial material costs, their increased weight and associated manufacturing limitations reduce their economic viability. Polymer composites, particularly GFRP, provide the most cost-effective solution when both material and manufacturing considerations are accounted for. Therefore, composite materials manufactured using vacuum-based processes offer the best balance between performance and economic feasibility.

7. Mechanical Properties Analysis

The mechanical performance of the wind turbine blade is critical to ensure structural integrity under aerodynamic loading and long-term cyclic operation. Blades are subjected to a combination of bending, torsional, and fatigue loads due to wind forces acting along the span. These loading conditions must be considered when evaluating material suitability.

The primary loading condition on the blade is bending, which is greatest at the root due to the accumulation of aerodynamic forces along the blade length. The bending stress can be approximated using:

$$\sigma = \frac{My}{I}$$

where M is the bending moment, y is the distance from the neutral axis, and I is the second moment of area. This relationship highlights the importance of material stiffness and cross-sectional geometry in resisting deformation.

In addition to bending, the blade experiences torsional loading due to aerodynamic forces acting off the shear centre. Excessive torsional deformation can lead to changes in angle of attack, reducing aerodynamic efficiency and potentially causing structural instability. Therefore, materials with adequate shear stiffness are required to maintain geometric integrity under load.

Fatigue is a dominant failure mode in wind turbine blades due to continuous cyclic loading from fluctuating wind conditions. Materials must be capable of withstanding repeated stress cycles without significant degradation. Polymer composites exhibit excellent fatigue resistance compared to metals, which are more prone to crack initiation and propagation under cyclic loading (Sutherland, 1999).

Material density also plays a critical role in mechanical performance. Lower density materials reduce gravitational loads and bending moments, particularly in larger blades. Polymer composites provide a significant advantage in this regard, offering high strength and stiffness at relatively low weight.

Overall, fibre-reinforced polymer composites demonstrate superior mechanical performance for wind turbine blade applications. Their high strength-to-weight ratio, good stiffness, and excellent fatigue resistance make them well suited to withstand

the combined loading conditions experienced during operation, supporting their selection as the preferred material for the proposed design.

8. Comparative Analysis

A comparative evaluation of the three material classes—metals, ceramics, and polymer composites—highlights clear differences in their suitability for wind turbine blade applications. Metals offer high strength and good manufacturability; however, their high density results in increased structural loading, reducing overall efficiency and increasing operational stresses. This makes them less suitable for large, rotating structures such as turbine blades.

Ceramics provide excellent stiffness and environmental resistance but are limited by their brittle behaviour and low fracture toughness. Their susceptibility to cracking under dynamic loading conditions makes them unsuitable for applications involving cyclic stresses and impact loading.

In contrast, polymer composites demonstrate a superior balance of mechanical and physical properties. Their low density significantly reduces gravitational and inertial loads, while their high strength-to-weight ratio and excellent fatigue resistance make them well suited to withstand cyclic aerodynamic forces. Additionally, composite materials allow for tailored structural properties through fibre orientation, further enhancing performance.

From a manufacturing perspective, composite processes such as vacuum infusion offer scalability, cost-effectiveness, and the ability to produce complex geometries with relatively low defect rates. When combined with favourable mechanical performance and acceptable material costs, polymer composites clearly outperform metals and ceramics in overall suitability.

Therefore, polymer composites are identified as the optimal material choice for wind turbine blade production, supported by both performance and manufacturing considerations.

9. Blade Design and Geometry

The wind turbine blade was designed using a tapered geometry to achieve an optimal balance between aerodynamic efficiency and structural performance. The blade incorporates a linear chord distribution, decreasing from 0.4 m at the root to 0.1 m at the tip, as defined in the design specifications. This tapering reduces aerodynamic drag towards the tip while maintaining sufficient structural strength at the root.

The blade profile is based on the NACA 4412 aerofoil, selected for its favourable lift-to-drag characteristics and stable performance across varying operating conditions. The aerofoil geometry was scaled at multiple spanwise positions corresponding to nondimensional radii (r/R) of 0.2, 0.4, 0.6, 0.8, and 1.0. These sections were used to generate the three-dimensional blade geometry.

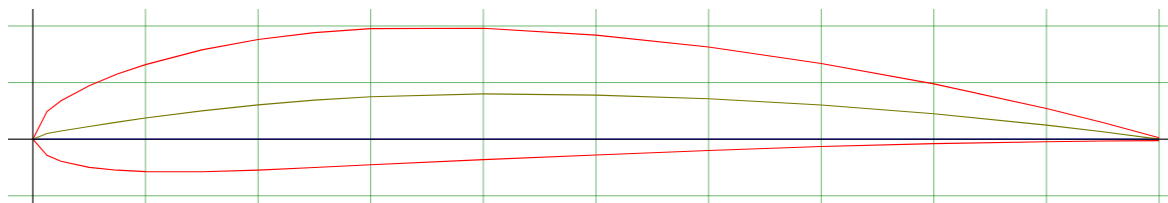


Figure 5: NACA 4412 aerofoil details - geometry

(naca4412-il) NACA 4412
NACA 4412 airfoil
Max thickness 12% at 30% chord.
Max camber 4% at 40% chord
Source [UIUC Airfoil Coordinates Database](#)
[Source dat file](#)
The dat file is in Selig format

Figure 6: NACA 4412 aerofoil details - thickness

A CAD model of the blade was created by lofting between the defined aerofoil sections, producing a smooth and continuous surface. The resulting geometry reflects the aerodynamic and structural requirements identified in earlier sections. Annotated drawings of the blade, including chord lengths and sectional positions, are provided to illustrate the final design.

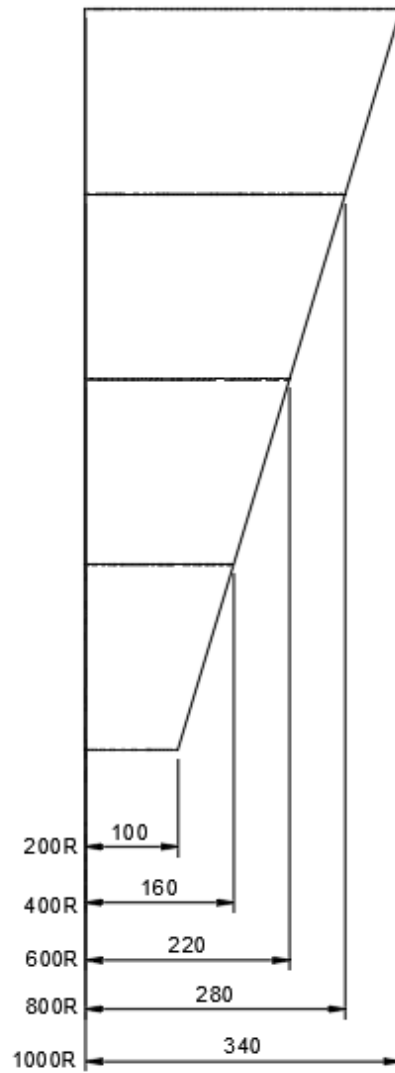


Figure 7: Chord lengths at incremental radius



Figure 8: Blade design - 3D Isometric view

10. Conclusions and Recommendations

This report has presented a preliminary design study for a wind turbine blade, integrating aerodynamic analysis, material selection, manufacturing considerations, and cost evaluation. The findings demonstrate that blade performance is strongly influenced by geometry, aerofoil selection, and operating conditions, with a tapered design and NACA 4412 aerofoil providing an effective balance between aerodynamic efficiency and structural performance.

The material selection process, supported by a weighted decision matrix, identified polymer composites as the most suitable material class. Their high strength-to-weight ratio, excellent fatigue resistance, and low density make them well suited to withstand the cyclic loading conditions experienced by wind turbine blades. In contrast, metals were found to be limited by their high density, while ceramics were unsuitable due to their brittle behaviour.

Manufacturing analysis further reinforced this selection, with vacuum infusion identified as the most appropriate production method. This process offers scalability, cost-effectiveness, and the ability to produce complex geometries with controlled defect levels. Cost evaluation confirmed that composite materials, particularly glass fibre-reinforced polymers, provide the most practical balance between performance and economic feasibility.

It is therefore recommended that wind turbine blades be manufactured using fibre-reinforced polymer composites via vacuum-based processes. Future work should focus on detailed aerodynamic optimisation, structural validation, and experimental testing to further refine the blade design.

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