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Advanced Processes and Materials

Manufacture of Wind turbine blade

ACMA5005

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1 Abstract

Wind energy plays an increasingly important role in reducing carbon emissions within the UK, with wind turbine blade design being critical to improve energy generation efficiencies and ensure long-term reliability. This report presents the conceptual design of a horizontal-axis wind turbine blade intended to offset the average electrical demand of a Welsh wastewater treatment works. Established aerodynamic theory and publicly available airfoil data are applied to define blade geometry, including rotor radius, chord distribution, and taper profile. The NACA 4412 airfoil is selected as a practical profile suitable for feasibility level design. A weighted decision matrix is used to compare candidate blade materials, identifying glass-fibre reinforced polymer (GFRP) as the most appropriate primary material, with selective use of carbon-fibre reinforced polymer (CFRP) in load-critical regions. Manufacturing routes are evaluated, with vacuum infusion identified as the most suitable process for producing 35 m composite blades. The proposed design demonstrates a balanced and practical solution that meets the site's average power demand while maintaining efficiency, durability, and cost-effectiveness.

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3 Introduction

Wind energy is expanding rapidly in the UK as part of the shift away from fossil fuels, and effective blade design is central to converting wind's kinetic energy into reliable, low-cost electricity. This report designs a wind-turbine blade for a conceptual Welsh water treatment works using established aerodynamic theory and standard airfoil profiles. The blade's geometry governs energy capture, while materials and manufacturing choices determine strength, durability, and lifecycle cost. A successful design must balance aerodynamic efficiency with structural performance.

A literature review sets the aerodynamic basis: airfoil selection, lift-to-drag ratio, tip-speed ratio, and expected power coefficient. It then informs design specifications for rotor radius, chord/taper, section stations, and target performance. Materials are selected via a weighted decision matrix, followed by an assessment of manufacturing options. A cost/performance evaluation linking technical choices to lifecycle efficiency and practicality. The objective is to define blade geometry, materials, and manufacturing methods that meet the site's power demand while maximising efficiency and durability at acceptable cost.

4 Literature Review

4.1 Aerodynamic Profiles and Performance

Aerodynamics plays a critical role in wind turbine research and development. In aerodynamics, the design of a flow control mechanism lays the foundation for an efficient power output. In wind turbines, aerodynamic lift on the blades converts the wind's kinetic energy into rotational energy, which is then converted to electrical energy (Maalawi, 2022).

4.1.1 Airfoils

Airfoils are specifically designed cross sections of wings, or blades, that generate lift when air flows around them. The NACA air foil series is a set of standardised airfoil shapes developed by the National Advisory Committee for Aeronautics, the predecessor to the National Aeronautics and Space Administration (NASA) which became widely used in the design of aircraft wings. (Belstein, 1989). These documented airfoil shapes have known aerodynamic properties which include lift, drag, stall behaviour, thickness, camber, etc. As they are documented the numerical data is readily accessible detail data necessary for the application of the airfoils to wing design (Abbot, 1959). There are several series: 4-digit, 5-digit, and 6-series. The numbering encodes features like camber, maximum thickness and position of max thickness.

Modern wind turbine blades often use purpose-designed profiles such as NREL's SERI (S-series) and Wortmann airfoils, which can deliver higher lift-to-drag performance at the low Reynolds numbers typical of turbines and, in the case of SERI, better behaviour under variable inflow and contamination (Hau, 2013). However, these specialised airfoils can be less practical for early-stage feasibility studies due to more complex geometry, tighter manufacturing tolerance sensitivity (especially Wortmann), and limited availability of complete aerodynamic datasets, whereas NACA profiles offer historically validated, publicly accessible data and simple definitions that support repeatable, transparent analysis (Abbott and von Doenhoff, 1959).

For these reasons the NACA 4412 airfoil was chosen because its 4% camber and 12% thickness provide a practical balance of lift, gentle stall behaviour, structural stiffness, and manufacturability, making it a common and reliable choice for small-to-medium wind turbine studies and variable wind conditions (Maalawi, 2022)

4.1.2 NACA 4412

The NACA 4 series airfoils following the naming convention of NACA MPXX

- M is the maximum camber divided by 100. In the example M=4 so the camber is 0.04 or 4% of the chord (Heffley, 2007).
- P is the position of the maximum camber divided by 10. In the example P=4 so the maximum

camber is at 0.4 or 40% of the chord (Heffley, 2007).

- XX is the thickness divided by 100. In the example XX=12 so the thickness is 0.12 or 12% of the chord (Heffley, 2007).

4.1.2.1 NACA 4412

NACA 4412 is popular with small-scale designs and experiments because of its robust lift at the lower Reynolds numbers typical of small rotors (Ali, 2023).

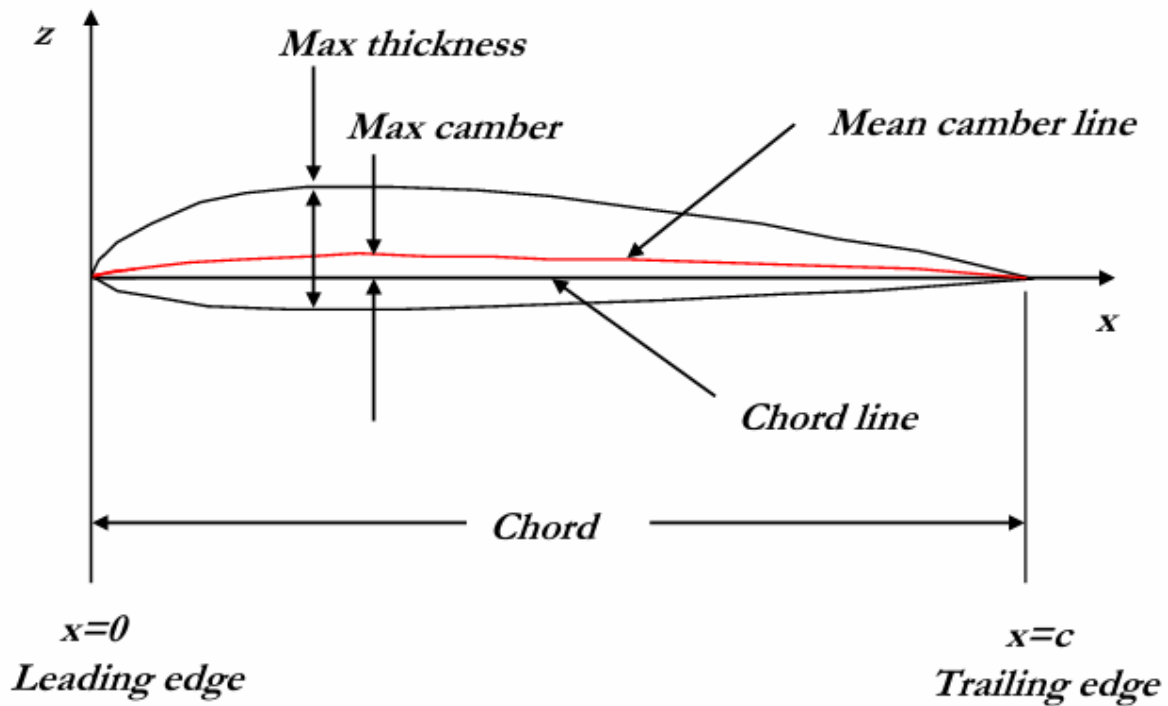


Figure 1 - NACA 4412 Airfoil (Heffley, 2007)

4.1.3 Optimal dimensions for Horizontal Axis Wind Turbines

Horizontal-axis wind turbines (HAWTs) most commonly use three blades because this configuration offers a practical compromise between aerodynamic efficiency, structural loads and dynamics, acoustics, and cost (Schubel, 2012). Compared with two-bladed designs, three-bladed turbines typically achieve similar or higher power coefficients (C_p) at lower tip-speed ratios (Schubel, 2012).

4.1.3.1 Blade Length

Three UK onshore HAWTs show the variance in blade length. The Evance (Britwind) R9000 is rated at 5k and has 2.7m rotor blades, it's suited to "micro-generation" and modest visual impacts. The Vestas V90 is rated at 2-3MW and has 45m rotor blades, is considered a proven medium sized turbine in the UK onshore farms for good energy production for manageable transportation and tower heights. The large Nordex N133/4.8 is rated at 4.8MW with 66.6m rotor blades, has larger components and more costly transport and build requirements but returns higher energy production. As blade sizes increase, as does energy capture and power generation. Although the trade-offs are higher logistical challenges and build costs (Bauer, L. & Matysik, S. 2026).

4.1.3.2 Tip Speed Ratios

Tip Speed Ratio (TSR) is the ratio of the blade tip speed to the incoming wind speed. It is an important design variable for understanding efficiency and noise. If the TSR is too low, the blades have more drag. If the TSR is too high, the tips outrun the useful flow input which leads to higher aerodynamic noise (Manwell, J.F., et al, 2009). Burton et al. (2021) stated turbines are more disturbing to look at the faster they rotate which offers an additional social visual aspect to ensure the TSR of the design isn't too high. Most HAWT operate at tip speed ratios between 6 and 8 (Manwell, J.F., et al, 2009).

4.1.3.3 And Taper Profiles

Burton et al. (2021) describe the typical HAWT tapered profile as a thick, wide root for stiffness and increased fatigue lifespan with a maximum chord located commonly around 20–30% of span. The blade profile steadily narrows and untwists towards the tip. This taper profile reduces tip losses and weight and keeps each section of the rotor blade operating at more favourable angles of attack (Manwell, J.F., et al, 2009).

4.2 Material Properties

Composites such as GFRP (Glass-Fiber Reinforced Polymer) and CFRP (Carbon-Fiber Reinforced Polymer) dominate HAWT blade structure because they deliver far higher specific stiffness and strength when compared with metals. This enables long, stiff but lightweight structure designs with better fatigue resistance (Burton et al., 2021).

In contrast, metals such as aluminium and steel increase mass and root bending loads and are less

favourable in long-span fatigue, so they're confined to inserts and fixings (Manwell et al., 2009). Ceramics offer high compressive strength but brittle tensile behaviour making them more suitable to erosion resistant coatings (Hau, 2013).

4.3 Blade Design and Optimal Dimensions

4.3.1 Design Parameters

Using Pen-y-bont Waste Water treatment works as an example of a medium sized sewage treatment works. The site operates at an average flow of approximately 600 L/s, with a maximum treatment capacity of 1,650 L/s and the ability to pass storm flows of up to 3,000 L/s. Based on an feasibility estimate of energy consumption of 0.4 kWh per m³ of inlet flow, the average electrical demand at 600 L/s is estimated to be approximately 0.86 MW, rising to around 2.4 MW at maximum treatment capacity. On this basis, a wind turbine will be sized to target an average electrical output of approximately 0.9 MW, offsetting the average operational demand.

4.3.2 Turbines Design based on Required Power

The wind turbine power equation can be used to calculate the swept area requirement of the wind turbine; this can be used in turn to calculate the rotor length required.

$$P = \frac{1}{2} \times \rho \times A \times v^3 \times C_p$$

P = Power Output (Watts), ρ = Air Density (kg/m³), A = Swept area of the rotor (m²), v = wind speed (m/s) and C_p = Efficiency Coefficient of wind turbine.

With the power output in required to average at 0.9MW. Pen-Y-Bont treatment works average annual wind speed is proposed as 10m/s for this study. The air density is approximately 1.225 kg/m³ typically near the coast. The efficiency coefficient will use 0.4. The area swept is what we are looking to isolate so we can understand the required blade lengths.

As the swept area of the rotor in this study is equal to 3676 m² the corresponding calculation, $A = \pi \times r^2$, for the radius of the proposed rotor is 34.2m which will be rounded up to 35m to account for a lower efficiency coefficient.

4.3.3 Blade Section Parameters

Table 1 - NACA 4412 Profile 35m Blade Section Parameters

r/R	Radius r (m)	Chord c (m)	Max thickness (12% c, m)	Max camber (4% c, m)	Camber pos. (x/c)	Thickness pos. (x/c)
0.20	7.0	2.80	0.34	0.11	0.40	0.30
0.40	14.0	2.20	0.26	0.09	0.40	0.30
0.60	21.0	1.60	0.19	0.06	0.40	0.30
0.80	28.0	1.10	0.13	0.04	0.40	0.30
1.00	35.0	0.70	0.08	0.03	0.40	0.30

4.3.4 Blade Profiles

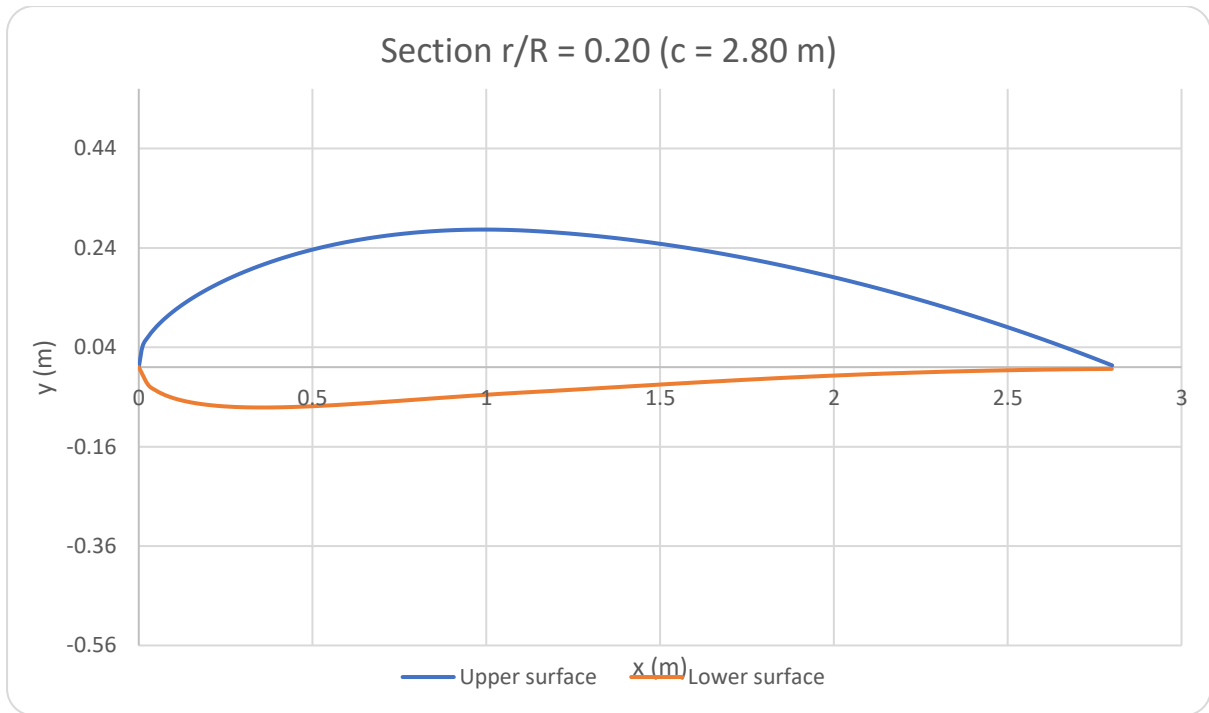


Figure 2 - NACA4412 35m Blade Profile Section 0.2

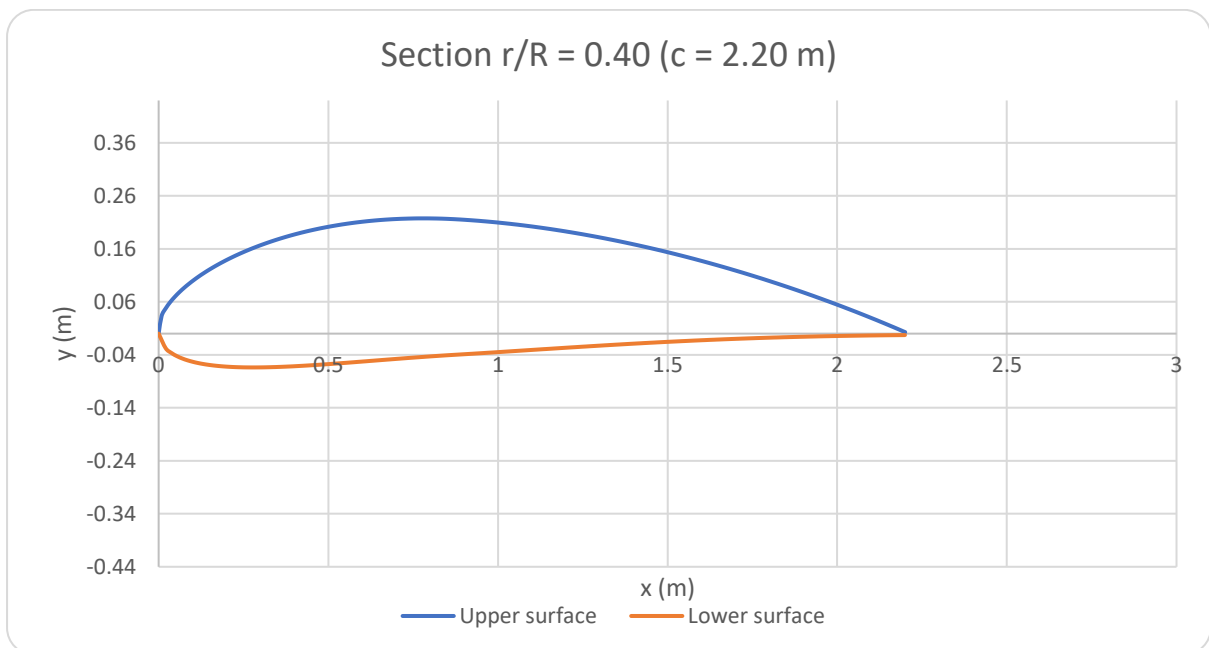


Figure 3 - NACA4412 35m Blade Profile Section 0.4

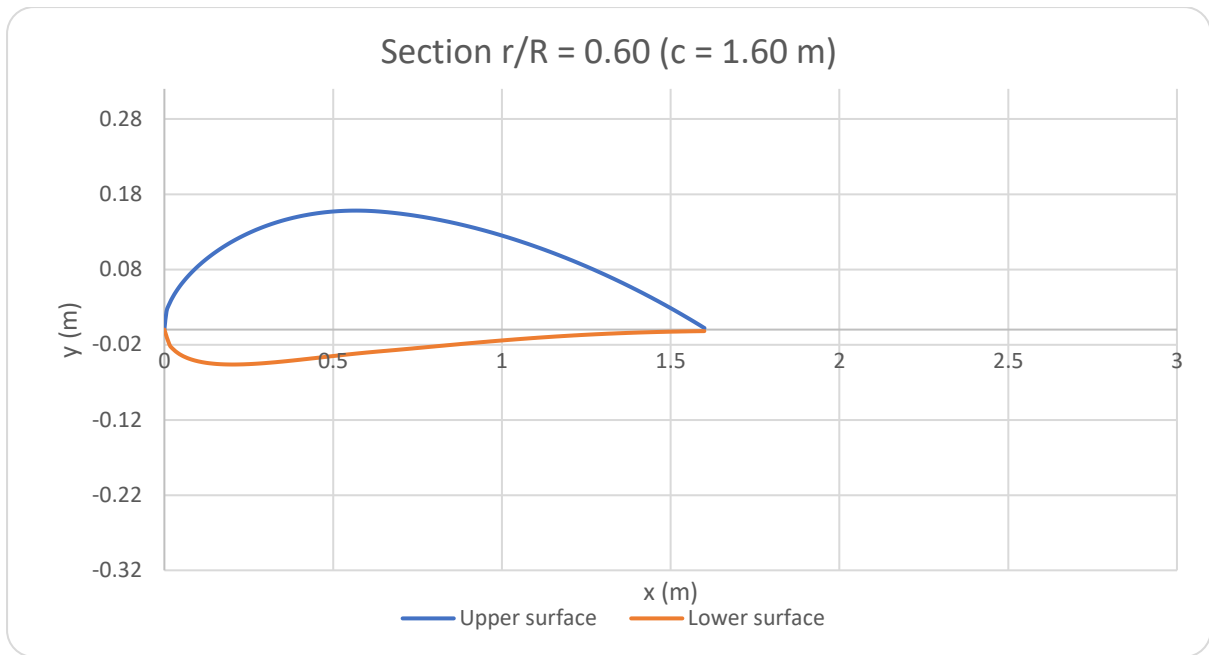


Figure 4 - NACA4412 35m Blade Profile Section 0.6

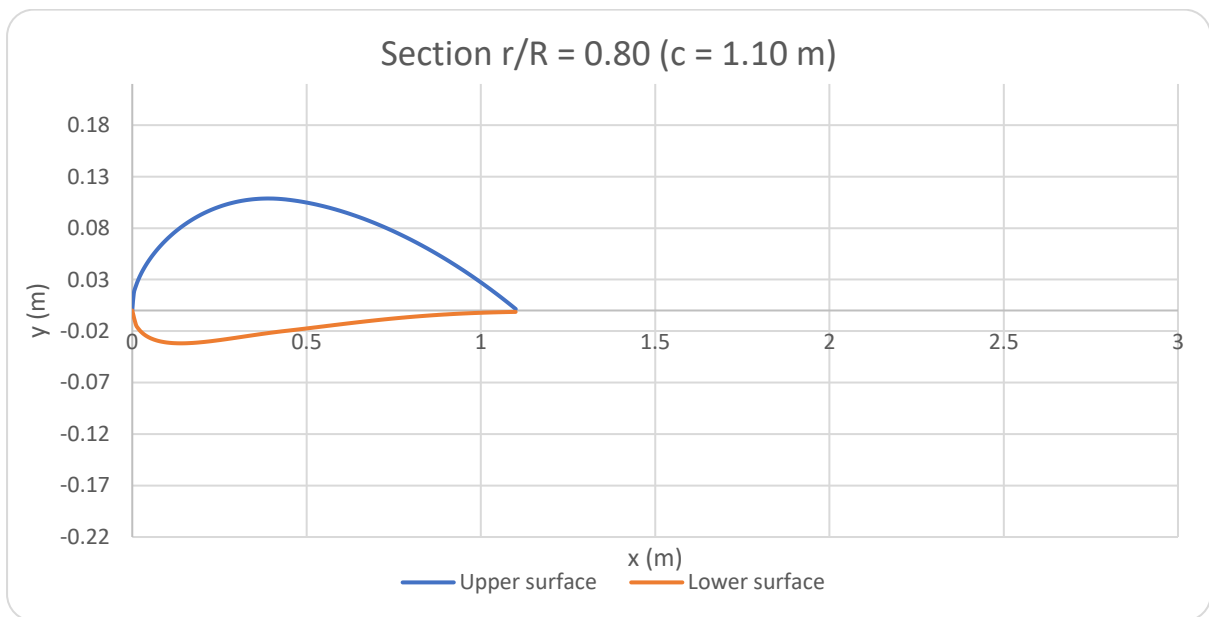


Figure 5 - NACA4412 35m Blade Profile Section 0.8

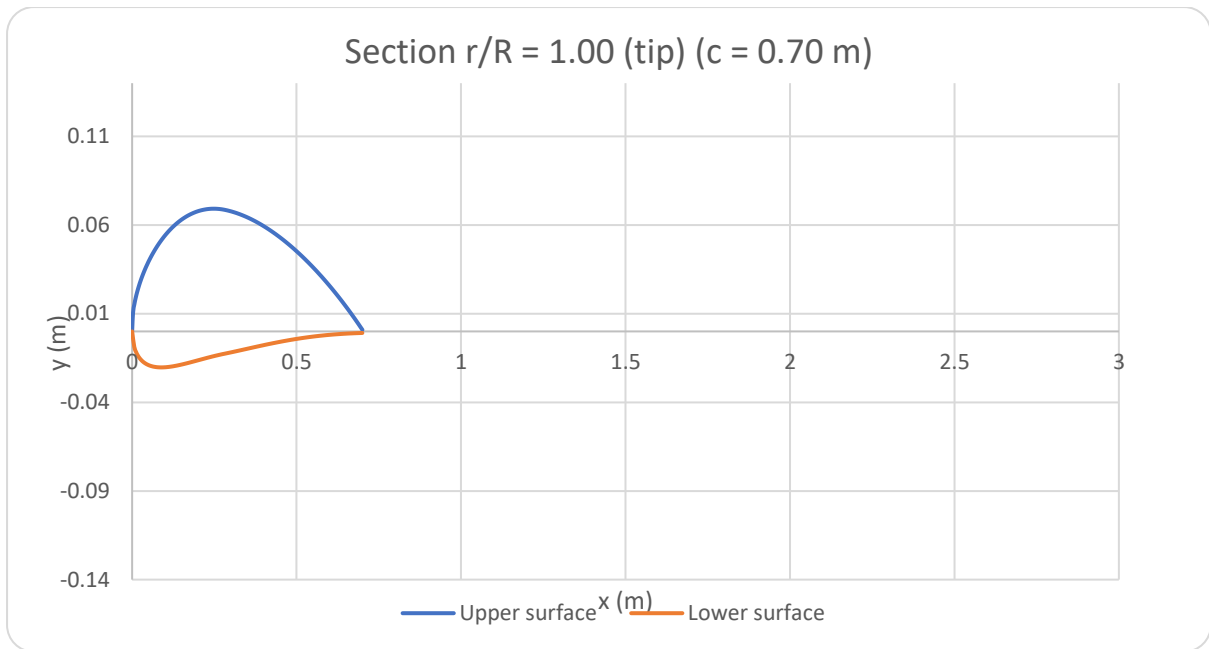


Figure 6 - NACA4412 35m Blade Profile Section 1.0

5 Materials Selection

To determine the most suitable material for the HAWT blade, a Weighted Decision Matrix (WDM) approach is applied. This method allows different candidate materials to be compared objectively against defined criteria, with each weighted according to its relative importance in blade design.

Table 2 - Table of Blade Material Properties

Material	Tensile strength (MPa)	Fatigue resistance (qual.)	Cost ($\approx$ £/kg)	Environmental impacts (summary)
Aluminium alloys	200–600	Moderate (no clear endurance limit; sensitive to surface/mean stress)	3–4	High embodied energy if primary; excellent recyclability ; low corrosion.
Steels	400–1200	Good (endurance limit; robust if protected from corrosion)	1–2	Moderate embodied energy ; high recyclability ; corrosion protection needed.
Ceramics	< 300	Poor in tension / excellent in compression	15–30	Energy-intensive processing; limited recyclability ; used mainly as coatings .
GFRP (glass fibre laminates)	500–1200	Good–very good (damage-tolerant)	5–7	Thermoset recycling difficult ; moderate embodied energy; landfill constraints; long life.
CFRP (carbon fibre laminates)	1500–3500	Very good (especially in tension; compression driven by design)	20–30	High embodied energy (carbon fibre); recycling improving (pyrolysis/solvolyis) but limited scale.

The key evaluation factors are:

- Mechanical properties: tensile strength, fatigue resistance, stiffness
- Environmental impact: recyclability, lifecycle emissions
- Cost: raw material and processing costs
- Ease of manufacturing: scalability, availability of fabrication methods

Table 3 - Weighted Decision Matrix (WDM) for Blade Material Selection

Criteria	Weight	Material									
		Aluminium		Steel		Ceramics		GFRP		CFRP	
		Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Mechanical	0.4	6	2.4	8	3.2	4	1.6	8	3.2	10	4
Environmental	0.2	6	1.2	4	0.8	4	0.8	8	1.6	3	0.6
Cost	0.2	6	1.2	4	0.8	8	1.6	6	1.2	6	1.2
Manufacturing	0.2	8	1.6	6	1.2	3	0.6	8	1.6	8	1.6
Total:			6.4		6		4.6		7.6		7.4

5.1 Results and Recommendation:

Aluminium alloys (6.4): Good balance of properties and manufacturability, but limited stiffness restricts blade length.

Steel (6.0): Strongest among metals but too heavy, reducing aerodynamic and structural efficiency.

Ceramics (4.6): High environmental resistance but brittle and difficult to fabricate into long blades.

GFRP (7.6): Industry standard; offers excellent performance-to-cost ratio, fatigue resistance, and manufacturability.

CFRP (7.4): Superior mechanical performance but penalised by high cost; best used selectively in high-stress zones.

5.2 Conclusion

The results again confirm that polymer composites are the optimal choice. GFRP provides the most practical solution for full blade construction, while CFRP can be applied in load-critical regions to enhance stiffness and reduce weight. This hybrid use ensures an optimal balance of efficiency, durability, and cost-effectiveness.

6 Exploration of Manufacturing Routes

The selection of polymer composites (primarily GFRP, with selective use of CFRP in load-critical areas) as the material for HAWT blades requires careful evaluation of appropriate manufacturing methods. The chosen process must balance cost, scalability, quality control, and environmental considerations while producing blades that meet aerodynamic and structural requirements.

6.1 Manufacturing Methods

6.1.1 Vacuum Infusion (VI)

Vacuum infusion involves laying dry fibre reinforcement (glass or carbon fabrics) into a mould, sealing with a vacuum bag, and drawing resin through the laminate under vacuum pressure.

Advantages:

- High fibre volume fraction ($\approx 50\text{--}60\%$), yielding good strength-to-weight ratio.
- Reduced void content compared with hand lay-up.
- Lower labour intensity once mould is prepared.
- Compatible with large structures (scalable to multi-metre blades).

Disadvantages:

- Long cycle times due to resin infusion and curing stages.
- Requires precise control of resin flow to avoid dry spots.
- Relatively high tooling costs for precision moulds.

6.1.2 Resin Transfer Moulding (RTM)

RTM is a closed-mould process in which resin is injected into a pre-shaped fibre preform inside a rigid mould.

Advantages:

- Excellent surface finish and dimensional accuracy.
- Consistent fibre/resin distribution and reduced defects.
- Suitable for automated, repeatable production once tooling is established.

Disadvantages:

- High initial tooling and mould costs.
- Typically limited to small- and medium-sized parts; scaling to 5+ metre blades requires complex multi-part moulds.
- Higher resin injection pressures increase energy demand.

6.2 Conclusion

For 35m HAWT blades, vacuum infusion (VI) offers moderate production costs through simplified tooling and efficient material use. There's a moderate manufacturing time due to slower infusion and curing times but the ease of scalability and abilities to produce curved shells with a lower environment impact makes it the ideal manufacturing process for the turbine blades in comparison with resin transfer moulding.

7 Conclusion and Recommendations

This assignment has demonstrated the design process of a HAWT blade intended to offset the average electrical demand of a medium-sized Welsh wastewater treatment works. Using established aerodynamic theory, publicly available airfoil data, and realistic site assumptions, a clear blade geometry, material selection, and manufacturing route have been defined.

The literature review confirmed that aerodynamic lift is fundamental to turbine performance and that airfoil choice, tip-speed ratio, and blade geometry are key determinants of efficiency. While modern wind turbines often employ bespoke airfoils, the NACA 4412 profile was selected for a feasibility level design. Its moderate camber, thickness, and beneficial stall characteristics provide a robust balance between aerodynamic performance, structural stiffness, and manufacturability, particularly for variable wind conditions.

Based on the site's estimated average electrical demand of approximately 0.9 MW and an assumed mean wind speed of 10 m/s, the wind turbine power equation was applied to determine the required swept area. This resulted in a rotor radius of approximately 35 m, consistent with small to medium onshore wind turbine dimensions. This reduced size would be in keeping with the local environment. A tapered blade with decreasing chord and thickness towards the tip was adopted in line with established HAWT design practice, ensuring reduced tip losses, improved load distribution, and favourable angles of attack along the span.

Material selection using a weighted decision matrix showed that polymer composites significantly outperform metal and ceramic alternatives for wind turbine blade applications. GFRP emerged as the most suitable material due to its favourable strength-to-weight ratio, fatigue resistance, cost-effectiveness, and proven track record in the wind industry. CFRP, while offering superior mechanical performance, was found to be most appropriate for selective use in high stress regions where stiffness and mass reduction are critical. This hybrid approach provides an effective balance between performance and lifecycle cost.

An evaluation of manufacturing routes identified vacuum infusion as the most suitable process for producing the blades. Compared with resin transfer moulding, vacuum infusion offers better scalability for large components, reduced material waste, and lower environmental impact with one of the negative factors being the manufacturing times incurred due to longer curing times. These trade offs are acceptable for this application.

Overall, the proposed blade design represents a technically sound and practical solution capable of meeting the average energy demand of the treatment works while balancing efficiency, durability, manufacturability, and cost.

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