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Manufacture of a Wind Turbine Blade

Advanced Processes and Materials (ACMA6000)

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Abstract

This report presents a preliminary study into the materials and manufacturing routes for a next-generation wind turbine blade, sized for a single machine on an upland sheep farm in mid Wales. A three-blade, 3 m rotor was designed at a tip speed ratio of 7 and a 12 m/s rated wind through the Betz optimum, giving 12.0 kW aerodynamic and about 10.2 kW electrical power. Five candidate materials were compared across seven weighted criteria, supported by a raw-material cost build-up and a root stress check under the IEC 61400-2 simplified load model. Blade mass ranged from 70 kg in steel to 14 kg in carbon fibre, and every material cleared the static check with a safety factor above five. Carbon fibre scored highest at 4.20 and glass fibre next at 3.75, but E-glass/epoxy was selected as the better-value blade at 18.8 kg and £162 in material, carbon's small mass saving not justifying over three times the cost. The recommended route is vacuum-assisted resin transfer moulding.

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1 Introduction

Company X has been asked for a preliminary study into a next-generation blade for a small wind turbine, covering design, materials, manufacturing and cost. The duty is a single machine for an upland sheep farm in mid Wales using roughly 20,000 kWh a year. Such businesses can now borrow at 3% fixed against renewable generation under the Welsh Government's Sustainable Agriculture Loan Scheme (Welsh Government, 2026).

Wind supplied a record 30% of UK electricity in 2025 (Department for Energy Security and Net Zero, 2026), and the blade sets how much of that resource a rotor captures. It is also a major driver of lifetime cost, since fatigue, bond-line defects and leading-edge erosion drive blade failure and repair (Mishnaevsky et al., 2022). For a farmer with no crane or maintenance contract, durability outweighs marginal efficiency.

The report covers four tasks: literature research and geometry, material selection, manufacturing routes and defects, and raw material cost. The design point used throughout is a 3 m rotor radius, three blades, a tip speed ratio of 7 and a rated wind speed of 12 m/s, giving 12.0 kW aerodynamic and approximately 10.2 kW electrical.

2 Literature Review

2.1 Aerodynamic Profiles and Power Coefficient

NACA 4412 carries 4% camber at 40% chord and 12% maximum thickness (Abbott and von Doenhoff, 1959). Camber matters because a turbine blade holds one angle of attack for most of its life, so the section gives lift at low incidence where drag is smallest; a symmetric section needs a larger angle for the same lift and pays for it in drag. The blade here runs at a lift coefficient of 1.05 and about 6° , near best lift-to-drag at the operating Reynolds number of roughly 6×10^5 .

The power coefficient is the share of kinetic energy in the swept area that reaches the shaft. Betz put the ceiling at 0.593, since extracting all of it would stop the flow passing through the disc (Burton et al., 2021). Wake rotation, profile drag and tip losses keep real rotors below this; large machines reach 0.45 to 0.50 and smaller rotors less, so 0.40 was taken as an aerodynamic target.

2.2 Optimal Dimensions and Tip Speed Ratio

Three-blade rotors are normally designed for a tip speed ratio between 6 and 8. Below that band the blades pass through air already recovered from the previous blade, leaving energy in the flow; above it, drag, noise and erosion rise faster than the extra capture justifies (Hansen, 2015). A value of 7 was adopted.

Table 1 sets the rotor against machines already sold into this market. Swept area is a fairer comparison than rated power, which depends on the wind speed a manufacturer quotes and how hard the machine regulates. On that basis the design sits closest to the Britwind H5, at 28.3 m^2 against 23.8 m^2 , both rated at 12 m/s (Britwind, 2025a).

Table1: Benchmark small wind turbines compared with the design developed in this report. Manufacturer data accessed 24 August and 4 September 2026. Bergey annual energy is quoted by the manufacturer at a 5 m/s mean and is therefore omitted from the 6 m/s row.

	This design	Britwind H5 (R9000)	Britwind H11	Bergey Excel 10
Rated power	12.0 kW aero / 10.2 kW elec at 12 m/s	5 kW at 12 m/s	11 kW at 9 m/s	8.9 kW at 11 m/s
Rotor diameter (m)	6.0	5.5	13.1	7.0
Swept area (m²)	28.3	23.8	134.8	38.5
Number of blades	3	3	3	3
Rotor speed (rev/min)	267	200	70	0–400
Cut-in wind speed (m/s)	3.0 (assumed)	3.0	2.5	2.5
Blade material	GFRP (recommended)	GFRP, UV and anti-erosion coated	GFRP, T-bolt root fittings	GFRP (PowerFlex fibreglass)
AEP at 6 m/s mean (kWh)	19,100 (calculated)	13,653	46,692	—

2.3 Material Properties: Metals, Ceramics and Composite

Table 2: Comparison of candidate material classes. Steel and aluminium modulus and density from the Eurocodes (EN 1993-1-1, EN 1999-1-1) with strengths from the product standards (EN 10025-2, EN 755-2); composite properties from Callister and Rethwisch (2018) for continuous aligned fibres at a fibre volume fraction of 0.60; silicon carbide from Vargas-Gonzalez, Speyer and Campbell (2010). Strength is quoted as yield for the metals, flexural for SiC and unidirectional longitudinal tensile for the composites; specific strength is that value divided by density.

Property	Steel S275	Al 6082-T6	SiC	GFRP	CFRP
Density (kg/m ³)	7,850	2,700	3,150	2,100	1,600
Strength (MPa)	275 (yield)	260 (yield)	410–600 (flexural)	1,020 (UD tensile)	1,240 (UD tensile)
Young's modulus (GPa)	210	70	370–490	45	145
Specific strength (kN·m/kg)	35.0	96.3	142.9	485.7	775.0
Fatigue behaviour	m ≈ 3 (welded)	notch sensitive	no endurance limit	m ≈ 10	m ≈ 14
Fracture toughness	high	high	3.4–4.6 MPa·m ^{0.5}	moderate	moderate
Key limitation	mass	notch sensitivity	no crack arrest	recyclability	cost
Source	EN 10025-2; EN 1993-1-1	EN 755-2; EN 1999-1-1	Vargas-Gonzalez, Speyer and Campbell (2010)	Callister and Rethwisch (2018); Mishnaevsky et al. (2017)	Callister and Rethwisch (2018); Mishnaevsky et al. (2017)

Table 2 supports a single argument: a blade is a rotating cantilever, so specific properties, strength and stiffness per unit density, matter more than absolute ones. Every kilogram added raises the gravitational moment reversed once per revolution and the centrifugal load at the root, and both feed into the tower and foundation.

Steel has good absolute strength but poor specific strength. Silicon carbide is stiff and strong, yet its fracture toughness is only around 3.4 to $4.6 \text{ MPa}\cdot\text{m}^{0.5}$ (Vargas-Gonzalez, Speyer and Campbell, 2010), far below what an impact-exposed, cyclically loaded part needs. The composites, quoted along the fibre direction in Table 2, win decisively once density is counted, and hold that lead under fatigue: the S–N exponent is roughly 10 for glass composites against about 3 for welded steel (Mandell and Samborsky, 1997), so allowable stress decays far more slowly with cycle count.

2.4 Environmental Factors and Operating Conditions

Available power scales with the cube of wind speed, so a 10% error in the site wind resource becomes a 33% error in yield. Farm sites compound this: hedgerows, trees and buildings raise turbulence intensity, and gust loading drives fatigue rather than static failure. Rain and airborne particles erode the leading edge over time; across 18 operational wind farms, annual energy production fell by 1.8% on average under medium erosion and by 4.9% on the worst-affected turbine (Law and Koutsos, 2020).

3 Design Specifications

Table 3: Design point parameters.

Parameter	Symbol	Value	Unit
Rotor radius	R	3.0	m
Number of blades	B	3	–
Tip speed ratio	λ	7	–
Rated wind speed	V	12.0	m/s
Air density	ρ	1.225	kg/m ³
Power coefficient	C_p	0.40	–
Drivetrain efficiency	η	0.85	–
Aerofoil section	–	NACA 4412	–
Design lift coefficient	C_L	1.05	–
Angle of attack	α	6	°
Swept area	A	28.3	m ²
Aerodynamic power	P	12.0	kW
Electrical power	–	10.2	kW
Rotational speed	N	267	rev/min
Tip speed	–	84	m/s

Table 3 sets out the design point. The 3 m rotor radius follows from the duty: it gives 28.3 m² of swept area, and at 12 m/s with $C_p = 0.40$ that yields 12.0 kW aerodynamic, or roughly 10.2 kW electrical after drivetrain losses. Against a 6 m/s annual mean and a Rayleigh distribution it returns about 19,100 kWh a year; scaling the Britwind H5's published yield at the same mean gives approximately 16,200

kWh, the difference being the power regulation an idealised curve ignores (Britwind, 2025a). On either basis the farm's 20,000 kWh demand (Appendix E) is 80 to 95% covered.

The swept area sits below the 200 m² threshold in IEC 61400-2, so design loads use the small wind turbine standard and its simplified load model (International Electrotechnical Commission, 2013). The farmer also receives Smart Export Guarantee payments only if the installation is MCS certified (Ofgem, 2025), which itself requires compliance with IEC 61400-2 (MCS Service Company Ltd, 2019); the standard is a condition of being paid, not an academic choice. Tip speed at rated wind is 84 m/s at 267 rev/min, but variable-speed control holds the design tip speed ratio, so at the 6 m/s mean the tip runs at only 42 m/s and rated conditions are reached rarely.

3.1 Blade Geometry Derivation

Chord and twist follow the Betz optimum with wake rotation (Burton et al., 2021):

$$\varphi = (2/3) \cdot \arctan(1/\lambda_r)$$

$$c(r) = (8\pi r / B \cdot C_L) \cdot (1 - \cos \varphi)$$

$$\beta = \varphi - \alpha$$

Table 4: Blade geometry at five spanwise stations, derived from the Betz optimum at $C_L = 1.05$ and $\alpha = 6^\circ$.

r/R	r (m)	λ_r	φ (°)	Twist β (°)	Chord c (m)	Max thickness (m)
0.2	0.60	1.40	23.69	17.69	0.4035	0.0484
0.4	1.20	2.80	13.10	7.10	0.2493	0.0299
0.6	1.80	4.20	8.93	2.93	0.1740	0.0209
0.8	2.40	5.60	6.75	0.75	0.1327	0.0159
1.0	3.00	7.00	5.42	-0.58	0.1070	0.0128

Table 4 gives the result at five stations, plotted in Figures 1 and 2. At $C_L = 1.05$ the chord is 0.403 m at $r/R = 0.2$, falling to 0.107 m at the tip, with twist from 17.7° to -0.6° , reproducing the 0.4 m and 0.1 m taper in the brief and confirming the geometry was derived rather than assumed.

The optimum chord is strongly non-linear: a straight taper between the end stations overshoots it by up to 47% near $r/R = 0.6$ (Figure 1). Commercial blades linearise anyway to simplify mould manufacture, so the geometry taken forward is a compromise. Carrying 12% thickness inboard is also structurally thin; in detailed design the inner 20% would transition to a thicker section and a cylindrical root (Britwind, 2025b).

Figure 1: Betz-optimum chord distribution compared with a linear taper, across the five spanwise stations. The optimum chord is strongly non-linear and a straight taper between the root and tip chords overshoots it by up to 47% near $r/R = 0.6$; the linear taper is the manufacturable simplification carried into production. Derived at $C_L = 1.05$ and $\alpha = 6^\circ$ (Appendix A).

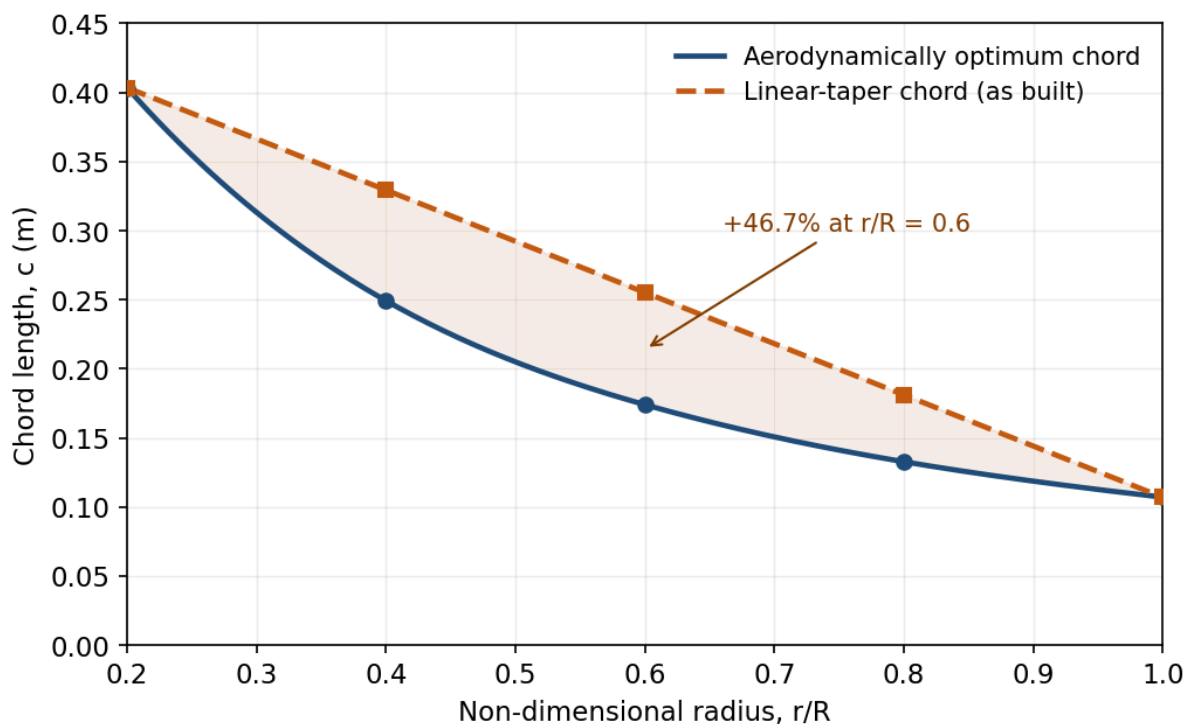
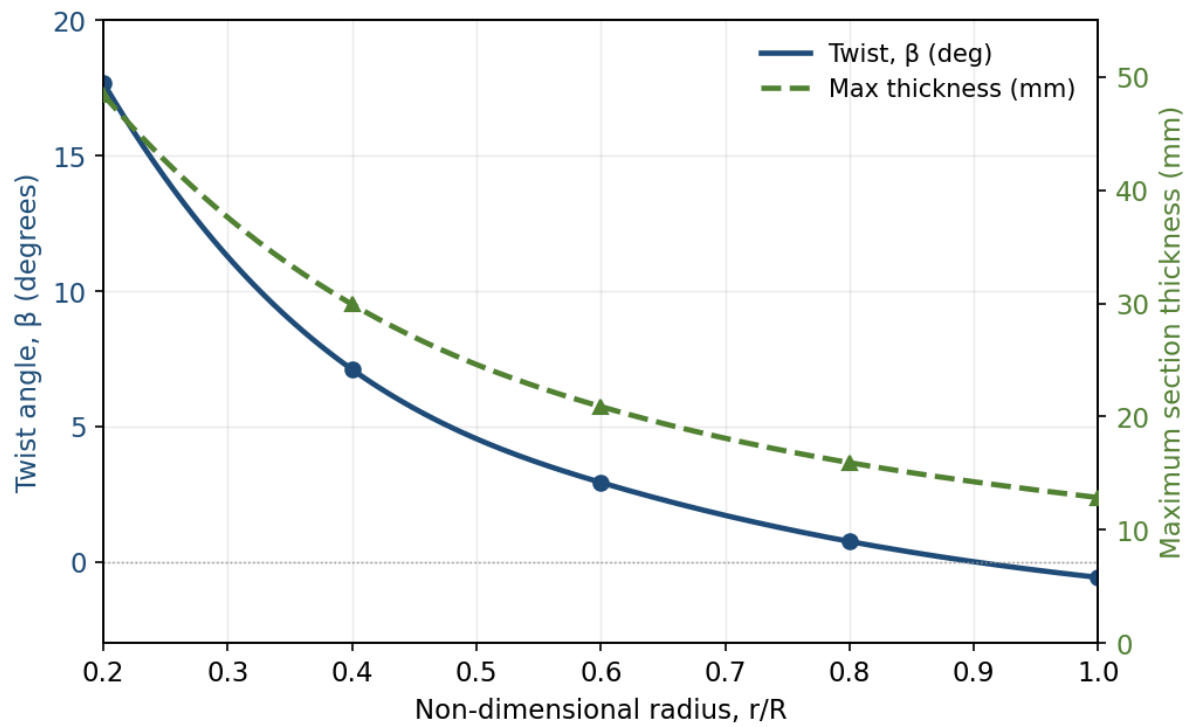


Figure 2: Spanwise distribution of twist and maximum section thickness. Twist falls from 17.7° at $r/R = 0.2$ to -0.6° at the tip, read on the left axis; maximum thickness, at 12% of the local chord, falls from 48.4 mm to 12.8 mm on the right axis. Derived at the Table 3 design point (Appendix A).



4 Material Selection

The blade is a fatigue-critical structural member, so the selection weights favour the properties that decide its service life. Specific strength, specific stiffness and fatigue resistance each carry 0.20; manufacturability, which decides whether a twisted, tapered shell can be moulded at all, carries 0.15; density and raw material cost carry 0.10 each; and recyclability carries 0.05. Each candidate is scored from one to five on every criterion, following the weighted-objective approach to materials selection (Ashby, 2011), and the totals are given in Table 5.

The two composites separate clearly from the metals and the ceramic, scoring 3.75 for GFRP and 4.20 for CFRP against 2.15 to 2.50 for the rest. Steel and aluminium are held back by mass and fatigue; aluminium especially has no true endurance limit and is notch-sensitive, which is disqualifying for a component that sees of the order of a hundred million load cycles. Silicon carbide has the highest specific stiffness of any candidate but is pulled down by its brittleness and by the near-impossibility of moulding a thin, doubly curved shell of this geometry without cracking. Every material clears the static stress check with a safety factor between 5.3 and 15.7, confirming that static strength is not the property that discriminates here; fatigue and mass are.

Between the two composites CFRP scores marginally higher, almost entirely on specific stiffness, and that margin does not earn its cost. Carbon's only real advantage at this rotor size is a further mass reduction, from 18.8 kg to 14.3 kg, too small to cascade into a lighter tower, bearings or generator; against that, its raw material cost is more than three times higher, roughly £1,625 per rotor against £487. E-glass/epoxy is therefore selected as the better-value choice, capturing the fatigue and mass benefits of a composite at under a third of the cost, and this matches commercial practice, as all three benchmark machines use glass-fibre blades. The chosen laminate is to be produced by vacuum-assisted resin transfer moulding, the route developed in the following section.

Table 5: Weighted decision matrix for blade material selection. Each material is scored from 1 (poor) to 5 (excellent) against each criterion; the weighted total is the sum of score × weight.

Criterion	Weight	Steel S275	Al 6082-T6	SiC	GFRP	CFRP
Specific strength	0.20	1	2	2	4	5
Specific stiffness	0.20	2	2	5	2	4
Fatigue resistance	0.20	2	1	1	4	5
Density (mass)	0.10	1	3	2	4	5
Raw material cost	0.10	5	5	1	5	2
Manufacturability	0.15	2	3	1	5	4
Recyclability	0.05	5	5	2	2	2
Weighted total	1.00	2.15	2.50	2.15	3.75	4.20

5 Exploration of Manufacturing Routes

Table 6: Candidate manufacturing routes for the E-glass/epoxy blade shell. Fibre volume fraction and void content are typical ranges for each process.

Route	Typical fibre volume fraction	Typical void content	Capital and tooling	Fit to a 3 m twisted, tapered shell
Wet hand lay-up	0.30–0.40	3–5%	Low: open mould	Feasible; quality operator-dependent
VARTM (selected)	≈0.50	1–2%	Moderate: mould, vacuum pump, consumables	Industry practice for blade shells
Prepreg + autoclave	0.55–0.60	<1%	High: autoclave, frozen storage	Feasible; capital unjustified for one machine
Pultrusion	≈0.60	Low	Die and haul-off line	Unsuitable: constant section only, no twist or taper
Filament winding	0.50–0.60	Low	Mandrel and winder	Unsuitable: convex surfaces of revolution only

5.1 Metals — Casting and Extrusion

Extrusion is efficient but produces a constant cross-section, so it can form a straight spar but not a twisted, tapered aerofoil: the die profile is fixed. Casting can form complex shapes, but sand casting is too coarse and warp-prone for a thin three-metre shell, and investment casting holds finer detail only at a cost and size a single farm machine cannot bear. Both leave porosity and inclusions that concentrate at the thick root, where bending stress is highest, and act as fatigue initiation sites. The mass penalty settles it regardless: the same blade in steel would weigh roughly 70 kg against 19 kg for the composite (Section 6).

5.2 Ceramics — Sintering and Additive Manufacturing

The ceramic route runs from powder preparation through green-body forming, binder burnout and sintering. Sintering densifies the part but with substantial, uneven linear shrinkage of the order of 15 to 20%, making dimensional control of a three-metre

aerofoil impractical and inviting warping and cracking (Callister and Rethwisch, 2018). Additive manufacturing can form complex ceramic geometries, but only at small scale and still requires sintering. The decisive objection is property rather than process: a fracture toughness of 3.4 to 4.6 MPa·m^{0.5} (Vargas-Gonzalez, Speyer and Campbell, 2010) leaves no crack tolerance in a part under fully reversed cyclic loading, where one undetected flaw propagates to failure. Setting the route out properly is what lets it be ruled out with confidence.

5.3 Polymer Composites — Vacuum Infusion and RTM

VARTM is the selected route. Its chain is mould preparation and gelcoat, dry fabric and core layup, vacuum bagging, a leak and vacuum-drop check, resin infusion under vacuum, cure, demoulding, bonding of the two half-shells, and finishing; resin infusion is one of the two technologies the industry relies on (Brøndsted, Lilholt and Lystrup, 2005). Resin transfer moulding would give a better finish on both faces and lower VOC emissions, but its matched tooling costs far more than a single-sided infusion mould and is not justified at this volume. The characteristic defects each have a procedural fix: dry spots, controlled by a rehearsed flow-media layout and a pre-infusion vacuum-drop test; voids, by resin degassing and a stable vacuum; fibre wrinkles at the root radius, by debulking; and bond-line gaps, by a controlled adhesive gap and ultrasonic inspection, since bond-line flaws recur throughout the blade failure record (Mishnaevsky et al., 2022).

6 Cost Evaluation

Table 7: Raw material cost comparison across the five candidate materials. Published UK small-quantity supplier and stockholder prices, ex VAT, accessed 27 August 2026. Steel: S275 plate £800–1,020/t, midpoint used; aluminium taken at the same source's four to six times steel per kilogram, midpoint (Mixdesigncalc, 2026). GFRP: 290 g/m² E-glass woven roving at £1.90/m² (published 144+ metre trade tier; one rotor requires about 150 linear metres) and IN2 epoxy infusion resin at £14.12/kg (32.5 kg kit), combined at mass fractions 0.73 fibre / 0.27 matrix from the Table 2 laminate (Easy Composites, 2026a; 2026b). CFRP: 650 g/m² twill carbon at £32.00 per linear metre (£49.23/kg) with the same resin at 0.68 / 0.32 (Easy Composites, 2026c). Sintered SiC components are quoted per part (Highland Refractory, 2026); raw grain trades near \$2/kg (Henan Superior Abrasives, 2022) and £30/kg is an indicative figure for a finished part. Masses from the constant-thickness shell model; machining, tooling and process consumables excluded.

Material	Unit cost (£/kg)	Blade mass (kg)	Cost per blade (£)	Cost per rotor, 3 blades (£)
Structural steel S275	0.91	70.3	63.94	191.83
Aluminium 6082-T6	4.55	24.2	109.97	329.90
SiC (sintered)	30.00 (indicative)	28.2	845.91	2,537.72
GFRP (E-glass/epoxy)	8.63	18.8	162.23	486.68
CFRP (standard modulus)	37.82	14.3	541.67	1,625.00

A one-off machine buys at small-quantity prices, so Table 7 uses published UK supplier and stockholder figures, ex VAT, August 2026, applied to the calculated blade masses. Structural steel plate trades at £800 to £1,020 per tonne, taken as £0.91/kg, and aluminium at four to six times that per kilogram (Mixdesigncalc, 2026); at 70.3 kg and 24.2 kg the metal blades cost roughly £64 and £110 in material. The chosen laminate is costed from its constituents: woven E-glass at £1.90 per square metre in rotor quantities and epoxy infusion resin at £14.12 per kilogram in the 32.5 kg kit (Easy Composites, 2026a; 2026b), combined at the Table 7 mass fractions to £8.63/kg, giving £162 for the 18.8 kg blade and £487 for the rotor. Carbon fabric from the same supplier costs £49.23/kg even in its cheapest structural weight (Easy Composites, 2026c), so a CFRP blade reaches £542, over three times the glass

figure, confirming the Section 4 judgement. Sintered silicon carbide is not sold by the kilogram: finished components are quoted per part (Highland Refractory, 2026), raw grain trades near \$2/kg (Henan Superior Abrasives, 2022), and the indicative £30/kg used here still leaves it the costliest blade at £846. Cost therefore confirms rather than drives the selection: the metals are cheapest but fail for reasons no price can cure, while glass fibre delivers composite performance for under £500 of rotor material.

7 Mechanical Properties Analysis

Table 8: Root stress and static safety factor for the five candidate materials. Stresses are evaluated at the blade root under the rated-operation load case, with the IEC 61400-2 simplified-load partial factor of 1.35 applied (International Electrotechnical Commission, 2013). Root bending stress follows from the flapwise root moment of 1,478 N·m per blade and is identical for all materials because the shell geometry and 6 mm wall thickness are held constant; centrifugal stress scales with blade mass; combined stress is the direct superposition of the two at the root. Design strength is yield for the metals, a conservative multiaxial laminate value for the composites (below the unidirectional strengths in Table 2, which apply only to fully aligned fibres), and flexural strength for SiC. Safety factor is design strength divided by combined stress. Values as computed in the workbook.

Material	Root bending stress (MPa)	Centrifugal stress (MPa)	Combined stress (MPa)	Design strength (MPa)	Safety factor
Structural steel S275	34.7	16.8	51.5	275	5.3
Aluminium 6082-T6	34.7	5.8	40.5	260	6.4
SiC (sintered)	34.7	6.7	41.4	450	10.9
GFRP (E-glass/epoxy)	34.7	4.5	39.2	300	7.7
CFRP (standard modulus)	34.7	3.4	38.1	600	15.7

The blade is checked at the root, where bending and centrifugal load peak. Flapwise bending from the rated rotor thrust gives a root moment of 1,478 N·m per blade, and the IEC 61400-2 simplified load model applies a partial load factor of 1.35 (International Electrotechnical Commission, 2013). With shell geometry and wall thickness held constant across the five candidates, this bending stress is 34.7 MPa for every material. So the same figure runs down every row of Table 8; the material cannot alter what the aerodynamics and the section have fixed.

Only the centrifugal term separates them, and that comes down to mass. A heavier blade throws more weight outward, so steel adds 16.8 MPa against carbon fibre's

3.4 MPa. That share is small beside bending, so the combined root stress barely moves, from 38.1 MPa for CFRP to 51.5 MPa for steel.

Every material clears this with a wide margin. The safety factors in Table 8 run from 5.3 for steel to 15.7 for carbon fibre, taken against yield for the metals and a conservative multiaxial laminate strength for the composites rather than the unidirectional values in Table 2. Silicon carbide shows a factor near 11 and was still ruled out earlier, because for a brittle ceramic it is fracture toughness under cyclic load that decides survival.

The site's 6 m/s annual mean wind places the turbine in the lowest small wind class, Class IV, with a reference wind speed of 30 m/s (International Electrotechnical Commission, 2013). Full certification would add the extreme parked-wind case, beyond this report's scope, but within the modelled load all five blades survive comfortably.

8 Comparative Analysis

Table 9: Comparative synthesis of the five candidate materials across the four evaluation axes. Draws together the property, manufacturing, defect and environmental findings of Sections 4 to 7 rather than repeating them. GFRP is the selected material; end-of-life recyclability, the composites' one weakness, is carried forward as the strongest candidate for further work.

Material	Mechanical properties	Productivity	Manufacturing defects	HSE and end-of-life
Structural steel S275	High absolute strength but low specific strength; welded fatigue exponent $m \approx 3$	Extrusion gives a constant section; casting a thin shell warps	Porosity and inclusions concentrate at the root	Fully recyclable; heavy
Aluminium 6082-T6	Light but notch-sensitive, with no true endurance limit	Extrusion constant-section only; no twist or taper	Inclusions	Fully recyclable
SiC (sintered)	Highest specific stiffness, but fracture toughness 3.4–4.6 MPa·m ^{0.5} and no crack arrest	Sintering shrinks 15–20%; a thin aerofoil is impractical	Shrinkage cracking and warping	Inert, but high embodied energy
GFRP (E-glass/epoxy) — selected	High specific strength; fatigue exponent $m \approx 10$	Vacuum infusion proven for blade shells; moderate tooling	Voids, dry spots and bond-line gaps, all procedurally controlled	Styrene/isocyanate handling; poor recyclability
CFRP (standard modulus)	Best specific strength and stiffness; $m \approx 14$	Vacuum infusion, but fibre cost about three times glass	As GFRP, controllable	Styrene/isocyanate handling; poor recyclability

Sections 4 to 7 each ranked the materials on one axis; Table 9 draws them together, and the interest is where they disagree.

On mechanical fit the composites lead outright, holding the highest specific strength and a fatigue decay far slower than welded steel over the hundred million cycles a

blade sees. Silicon carbide is the sharpest conflict: the highest specific stiffness of any candidate sits alongside the lowest fracture toughness, and in a cyclically loaded part toughness wins, so the stiffness is wasted.

Manufacturing points the same way. Extrusion cannot form a twisted taper, casting a thin three-metre shell warps, and sintering a ceramic that size is impractical; only vacuum infusion is proven for blade shells at a tooling cost one machine can carry. Defects divide the same way: casting porosity and sintering cracks are inherent, while infusion's voids, dry spots and bond-line gaps each have a procedural fix.

Health, safety and environment is the one axis where the composite is weakest. Liquid infusion exposes operators to styrene and isocyanates at layup, and a cured thermoset has no clean recycling route, where steel and aluminium are fully recyclable. That is a real weakness, but it is a disposal problem twenty years out rather than a structural one, and it does not outweigh the fatigue, mass and manufacturability case. Glass fibre stays the selection, with carbon set aside on cost.

9 Blade Drawing

Figure 3 shows the blade in plan, tapering from a 403.5 mm root chord to a 107.0 mm tip across the 3 m radius, with the five stations marked. Figures 4 to 8 give the section at each, from $r/R = 0.2$ to 1.0, drawn as a true-shape NACA 4412 profile scaled to its chord and dimensioned for chord, maximum thickness and its 30% chord position. The twist at each station about the quarter-chord axis is listed alongside.

Figure 3: Blade planform at 1:6, showing the five spanwise stations A–A to E–E at 600, 1,200, 1,800, 2,400 and 3,000 mm from the rotor axis, the 2,400 mm aerodynamic span, and the indicative root mounting stub.

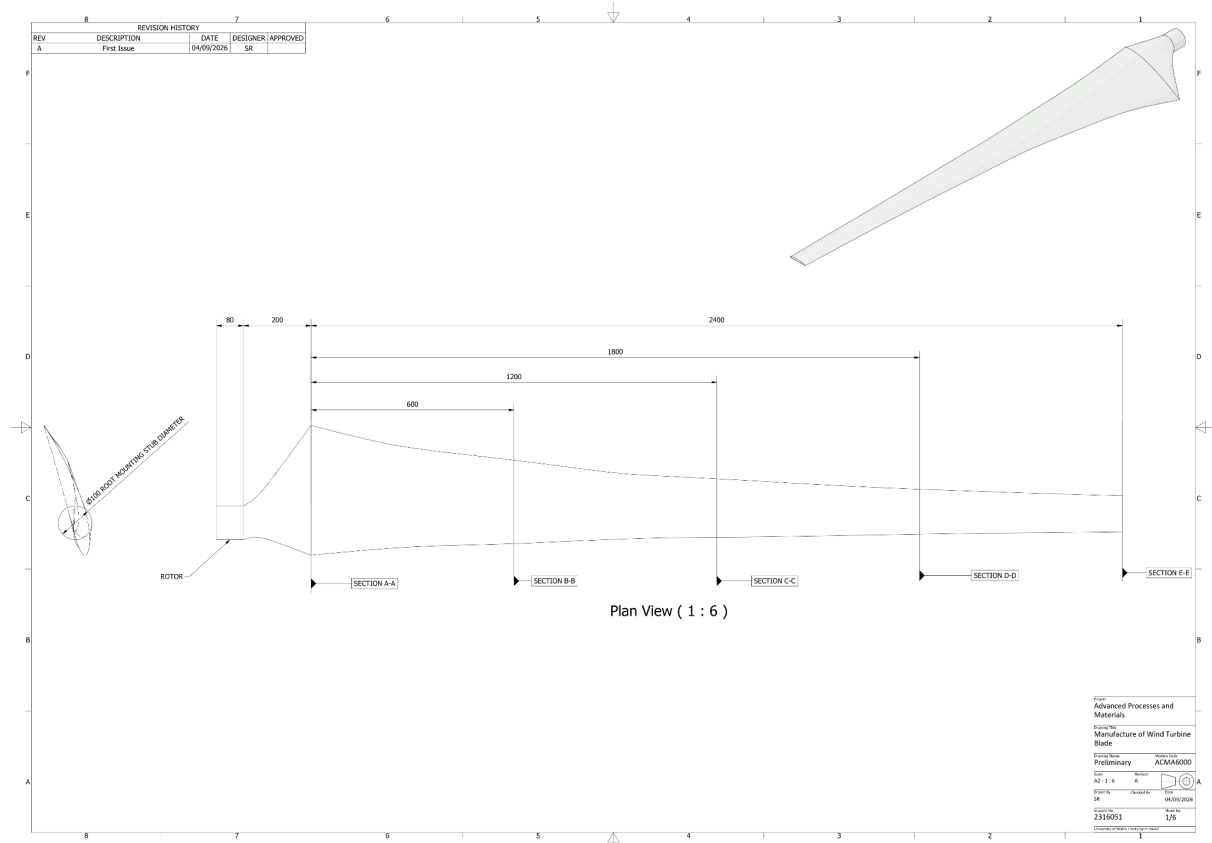


Figure 5: Section B-B at $r/R = 0.4$ (1.5:1). Chord 249.3 mm, maximum thickness 29.9 mm at 74.8 mm from the leading edge.

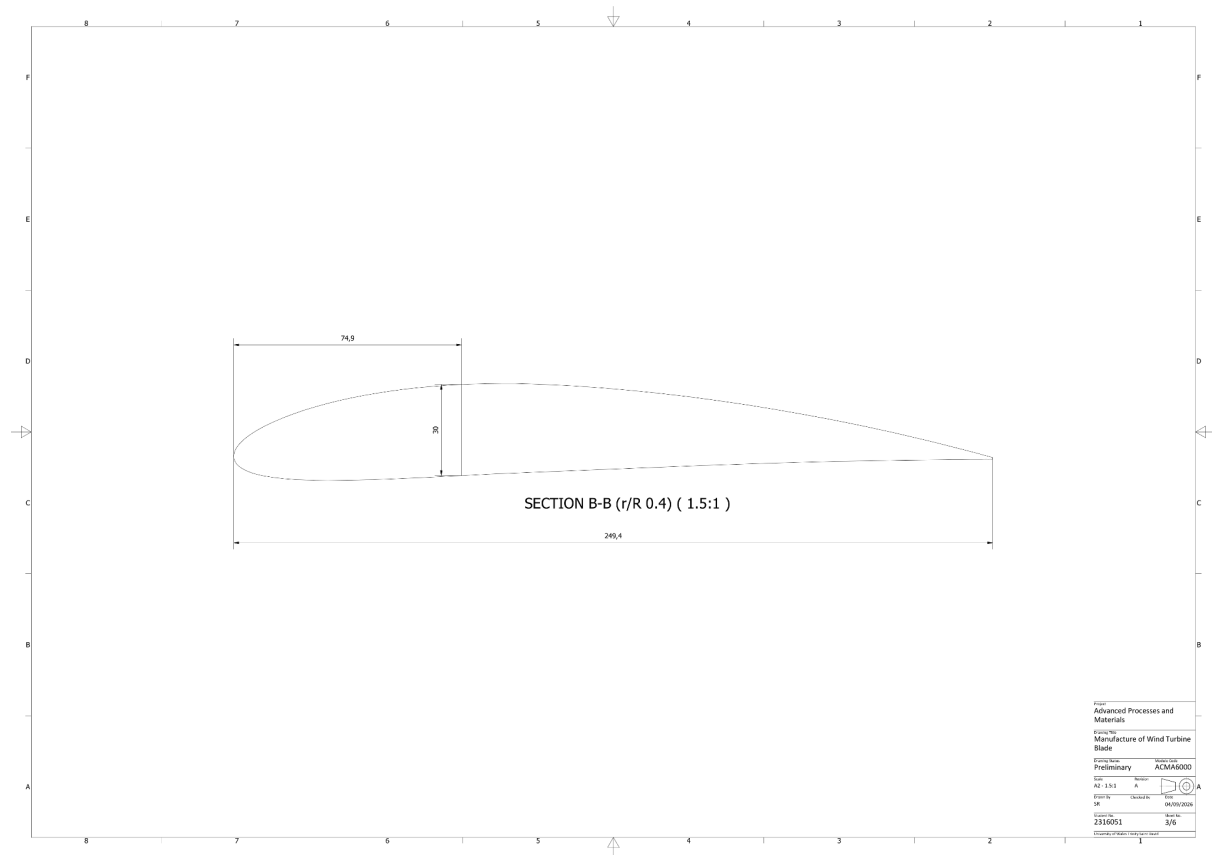


Figure 6: Section C–C at $r/R = 0.6$ (2:1). Chord 174.0 mm, maximum thickness 20.9 mm at 52.2 mm from the leading edge.

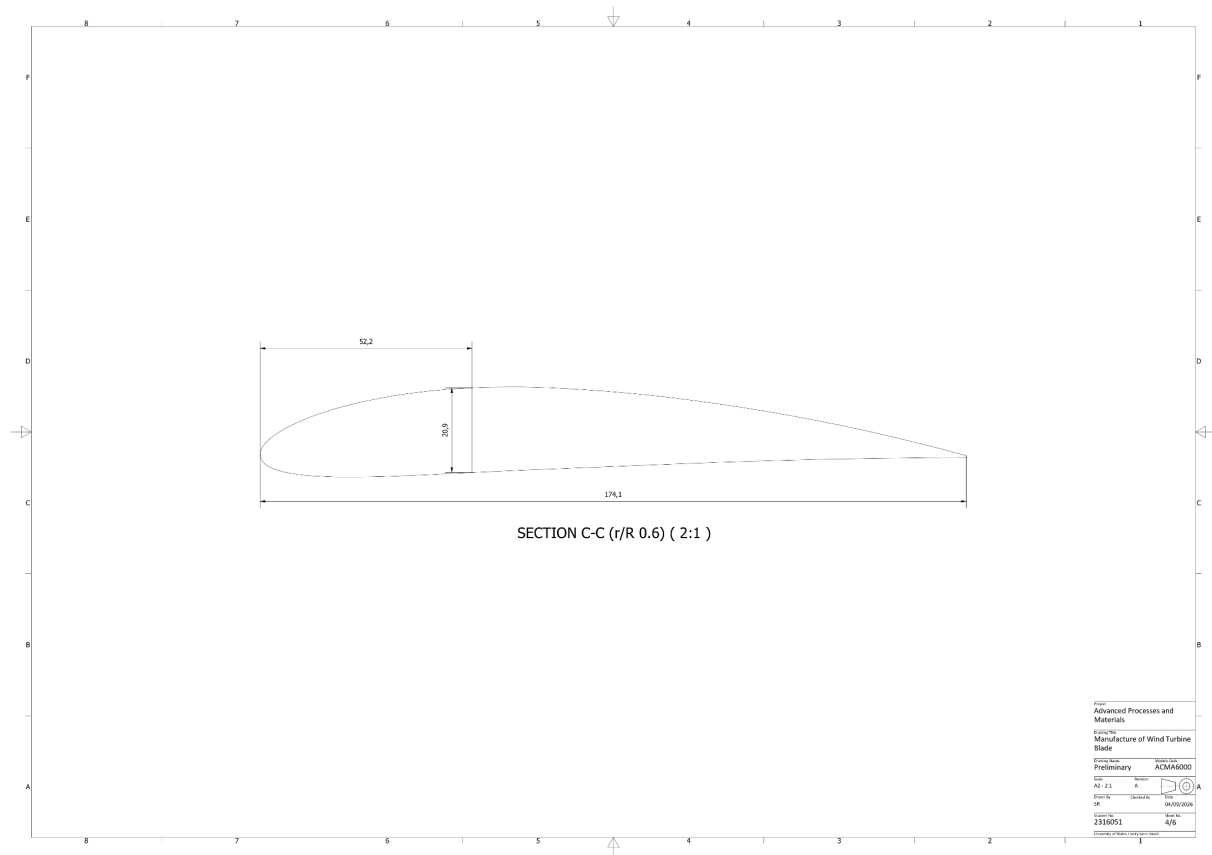


Figure 7: Section D-D at $r/R = 0.8$ (2.5:1). Chord 132.7 mm, maximum thickness 15.9 mm at 39.8 mm from the leading edge.

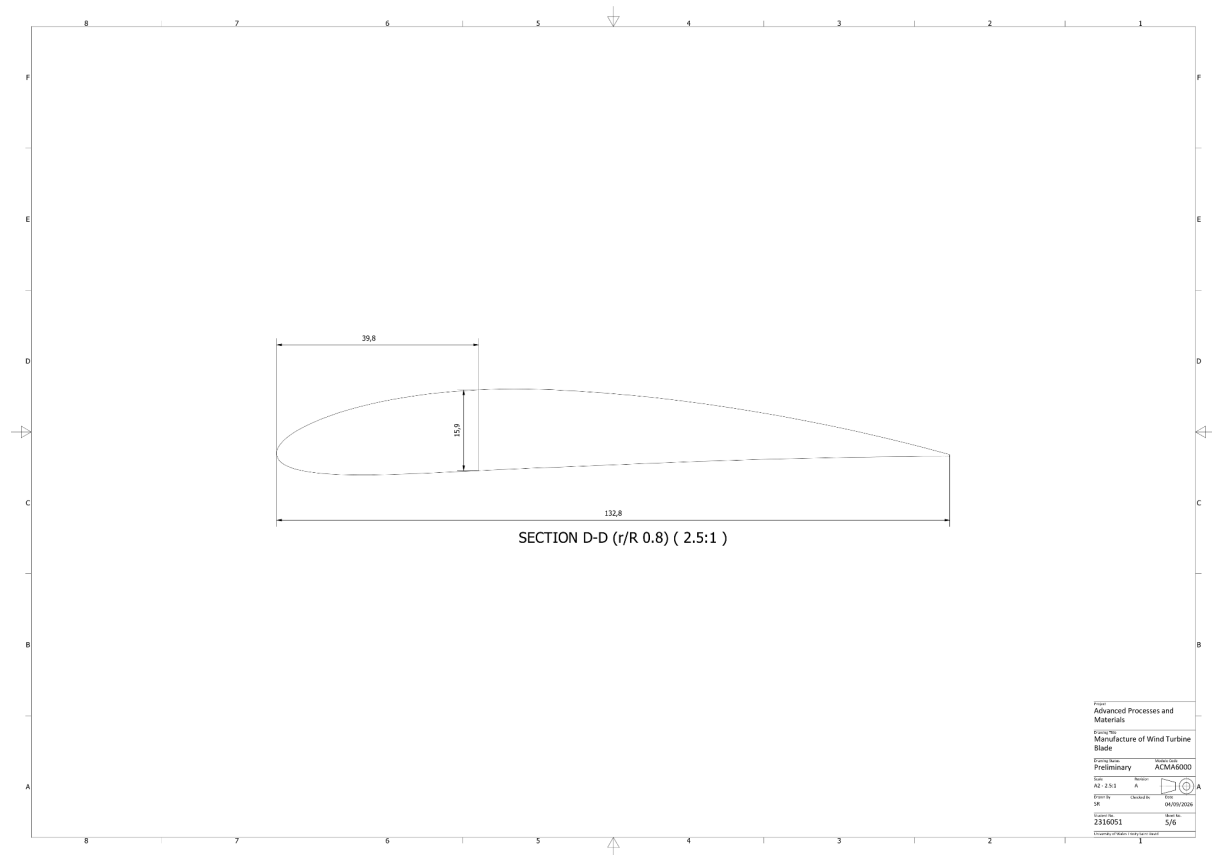
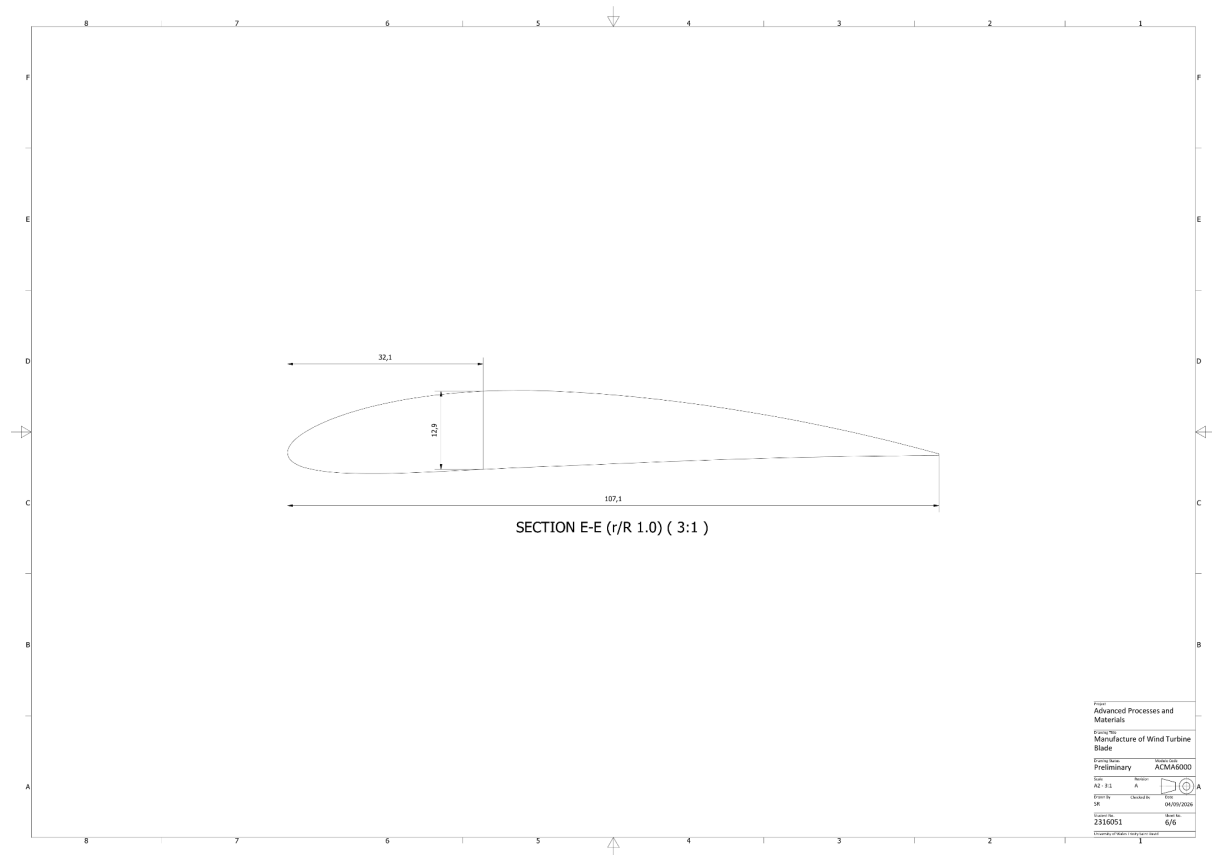


Figure 8: Section E–E at $r/R = 1.0$ (3:1). Chord 107.0 mm, maximum thickness 12.8 mm at 32.1 mm from the leading edge.



10 Conclusions and Recommendations

10.1 Conclusions

The study set a 3 m, three-blade rotor at a tip speed ratio of 7 and a 12 m/s rated wind, with chord and twist from the Betz optimum, giving 12.0 kW aerodynamic and about 10.2 kW electrical power, enough to cover the farm's annual demand at the site mean. Across seven weighted criteria, carbon fibre scored highest at 4.20 and glass fibre next at 3.75, but E-glass/epoxy was selected as the better-value blade, carbon's small mass saving not justifying more than three times the material cost. The chosen blade weighs 18.8 kg at £162 in material, carries a root safety factor of 7.7, and is to be made by vacuum-assisted resin transfer moulding.

10.2 Recommendations

Before manufacture, Company X should validate the root joint by finite-element analysis, since the hub interface was treated here only as an indicative mounting, and confirm the laminate's fatigue life through a coupon test programme rather than resting on the simplified load model. A leading-edge protection strategy, tape or coating, should be specified from the outset, given erosion's measured effect on yield. The clearest research gap is end-of-life: a thermoset glass laminate has no clean recycling route, the weakness conceded in the comparison, so recyclable resins and fibre recovery are where further work would most help.

11 References

Abbott, I.H. and von Doenhoff, A.E. (1959) Theory of wing sections: including a summary of airfoil data. New York: Dover Publications.

Ashby, M.F. (2011) Materials selection in mechanical design. 4th edn. Oxford: Butterworth-Heinemann.

Bergey Windpower Co. (2013) Bergey Excel 10 specification sheet. Norman, OK: Bergey Windpower Co. Available at:

https://www.bergey.com/wp-content/uploads/excel-10-spec-sheet_2013.pdf

(Accessed: 24 August 2026).

British Standards Institution (2005) BS EN 1993-1-1:2005 Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings. London: British Standards Institution.

British Standards Institution (2007) BS EN 1999-1-1:2007 Eurocode 9: Design of aluminium structures. Part 1-1: General structural rules. London: British Standards Institution.

British Standards Institution (2019) BS EN 10025-2:2019 Hot rolled products of structural steels. Part 2: Technical delivery conditions for non-alloy structural steels. London: British Standards Institution.

British Standards Institution (2025) BS EN 755-2:2025 Aluminium and aluminium alloys. Extruded rod/bar, tube and profiles. Part 2: Mechanical properties. London: British Standards Institution.

Britwind (2025a) H5 (R9000) 5kW horizontal axis wind turbine. Stroud: Britwind Ltd. Available at:

<https://www.britwind.co.uk/products/h5-r9000-5kw-horizontal-axis-wind-turbine/>

(Accessed: 4 September 2026).

Britwind (2025b) H11 11kW horizontal axis wind turbine. Stroud: Britwind Ltd. Available at:

<https://www.britwind.co.uk/products/h11-11kw-horizontal-axis-wind-turbine/>

(Accessed: 4 September 2026).

Brøndsted, P., Lilholt, H. and Lystrup, Aa. (2005) 'Composite materials for wind power turbine blades', Annual Review of Materials Research, 35, pp. 505–538. Available at: <https://doi.org/10.1146/annurev.matsci.35.100303.110641>

Burton, T., Jenkins, N., Sharpe, D., Bossanyi, E. and Graham, M. (2021) Wind energy handbook. 3rd edn. Chichester: John Wiley & Sons.

Callister, W.D. and Rethwisch, D.G. (2018) Materials science and engineering: an introduction. 10th edn. Hoboken, NJ: John Wiley & Sons.

Department for Energy Security and Net Zero (2026) Energy trends: March 2026. London: Department for Energy Security and Net Zero. Available at: https://assets.publishing.service.gov.uk/media/69cd13595cf899414a0bc618/Energy_Trends_March_2026.pdf (Accessed: 24 August 2026).

Easy Composites Ltd (2026a) 290g plain weave woven glass cloth (1000mm). Stoke-on-Trent: Easy Composites Ltd. Available at: <https://www.easycomposites.co.uk/290g-woven-roving-glass-cloth> (Accessed: 27 August 2026).

Easy Composites Ltd (2026b) Vacuum infusion resins. Stoke-on-Trent: Easy Composites Ltd. Available at: <https://www.easycomposites.co.uk/infusion-resins> (Accessed: 27 August 2026).

Easy Composites Ltd (2026c) Carbon fibre weights, weaves, k-counts and formats explained. Stoke-on-Trent: Easy Composites Ltd. Available at: <https://www.easycomposites.co.uk/learning/carbon-fibre-cloth-explained> (Accessed: 27 August 2026).

Hansen, M.O.L. (2015) Aerodynamics of wind turbines. 3rd edn. Abingdon: Routledge.

Henan Superior Abrasives (2022) How much does silicon carbide cost per ton? Available at: <https://www.silicon-carbides.com/blog/how-much-does-silicon-carbide-cost-per-ton.html> (Accessed: 27 August 2026).

Highland Refractory (2026) Silicon carbide ceramic plate pricelist: B2B cost analysis. Available at:

<https://www.hilandrefractory.com/silicon-carbide-ceramic-plate-pricelist-b2b-cost-analysis.html> (Accessed: 27 August 2026).

International Electrotechnical Commission (2013) IEC 61400-2:2013 Wind turbines – Part 2: Small wind turbines. 3rd edn. Geneva: International Electrotechnical Commission.

Law, H. and Koutsos, V. (2020) 'Leading edge erosion of wind turbines: effect of solid airborne particles and rain on operational wind farms', *Wind Energy*, 23(10), pp. 1955–1965.

Mandell, J.F. and Samborsky, D.D. (1997) DOE/MSU composite material fatigue database. Albuquerque, NM: Sandia National Laboratories.

MCS Service Company Ltd (2019) MCS 006: Small wind turbine product certification scheme requirements. Issue 3.0. Daresbury: MCS Service Company Ltd.

Mishnaevsky, L., Branner, K., Petersen, H.N., Beauson, J., McGugan, M. and Sørensen, B.F. (2017) 'Materials for wind turbine blades: an overview', *Materials*, 10(11), 1285.

Mishnaevsky, L., Thomsen, K., Beauson, J., McGugan, M., Sørensen, B.F. and Branner, K. (2022) 'Root causes and mechanisms of failure of wind turbine blades: overview', *Materials*, 15(9), 2959.

Mixdesigncalc (2026) S275 steel weight calculator. Available at: <https://mixdesigncalc.co.uk/s275-steel-weight-calculator/> (Accessed: 27 August 2026).

Ofgem (2025) Smart Export Guarantee (SEG). London: Office of Gas and Electricity Markets. Available at: <https://www.ofgem.gov.uk/environmental-and-social-schemes/smart-export-guarantee-seg> (Accessed: 4 September 2026).

Vargas-Gonzalez, L., Speyer, R.F. and Campbell, J. (2010) 'Flexural strength, fracture toughness, and hardness of silicon carbide and boron carbide armor ceramics', *International Journal of Applied Ceramic Technology*, 7(5), pp. 643–651.

Welsh Government (2026) Welsh farms to access low-interest loans for sustainable investment. Cardiff: Welsh Government. Available at:

<https://www.gov.wales/welsh-farms-access-low-interest-loans-sustainable-investment>

(Accessed: 24 August 2026).

12 Appendices

Appendix A — Blade Geometry Calculations

Inputs (Table 3): $R = 3.0$ m, $B = 3$, $\lambda = 7$, $C_L = 1.05$, $\alpha = 6^\circ$, section NACA 4412 (12% thick, maximum thickness at $0.30c$). Chord and twist follow the Betz optimum with wake rotation (Burton et al., 2021):

$$\lambda_r = \lambda \cdot (r/R) \quad \varphi = (2/3) \cdot \arctan(1/\lambda_r) \quad c(r) = [8\pi r / (B \cdot C_L)] \cdot (1 - \cos \varphi) \quad \beta = \varphi - \alpha$$

$$t_{\max} = 0.12c \text{ at } 0.30c$$

Table A1: Blade geometry, station-by-station working.

r/R	r (m)	λ_r	$1/\lambda_r$	$\arctan$ ($1/\lambda_r$) ($^\circ$)	φ ($^\circ$)	$1 - \cos$ φ	$8\pi r / (B \cdot C_L)$ (m)	Chord c (m)	Twist β ($^\circ$)	$t_{\max}$ (m)	Linear-taper c (m)
0.2	0.60	1.40	0.7143	35.538	23.692	0.08428	4.7872	0.4035	17.69	0.0484	0.4035
0.4	1.20	2.80	0.3571	19.654	13.103	0.02603	9.5744	0.2493	7.10	0.0299	0.3294
0.6	1.80	4.20	0.2381	13.392	8.928	0.01212	14.3616	0.1740	2.93	0.0209	0.2552
0.8	2.40	5.60	0.1786	10.125	6.750	0.00693	19.1488	0.1327	0.75	0.0159	0.1811
1.0	3.00	7.00	0.1429	8.130	5.420	0.00447	23.9359	0.1070	-0.58	0.0128	0.1070

The 0.4035 m root and 0.1070 m tip chords reproduce the 0.4 m and 0.1 m taper in the brief. The optimum is non-linear: a straight taper between the end stations overshoots it by 32.1%, 46.7% and 36.5% at $r/R = 0.4$, 0.6 and 0.8 (Figure 1).

Table A2: NACA 4412 aerofoil coordinates, unit chord (source: Abbott and von Doenhoff, 1959, four-digit series equations, $m = 0.04$, $p = 0.40$, $t = 0.12$).

x/c	y_{upper}/c	y_{lower}/c
0.0000	0.0000	0.0000

0.0029	0.0098	-0.0087
0.0117	0.0203	-0.0157
0.0262	0.0313	-0.0212
0.0462	0.0426	-0.0251
0.0716	0.0537	-0.0276
0.1020	0.0644	-0.0288
0.1370	0.0743	-0.0289
0.1763	0.0829	-0.0280
0.2194	0.0900	-0.0263
0.2658	0.0951	-0.0241
0.3149	0.0981	-0.0217
0.3662	0.0988	-0.0194
0.4191	0.0972	-0.0173
0.4729	0.0940	-0.0151
0.5271	0.0893	-0.0129
0.5809	0.0835	-0.0108
0.6338	0.0766	-0.0088
0.6851	0.0690	-0.0070
0.7342	0.0607	-0.0055
0.7806	0.0522	-0.0043

0.8237	0.0435	-0.0034
0.8630	0.0351	-0.0027
0.8980	0.0271	-0.0022
0.9284	0.0198	-0.0018
0.9538	0.0134	-0.0016
0.9738	0.0082	-0.0014
0.9883	0.0044	-0.0013
0.9971	0.0020	-0.0013
1.0000	0.0012	-0.0012

Table A3: Dimension schedule for the Section 9 drawing (millimetres).

Section	r/R	Radius from axis	Chord	Max thickness (0.12c)	Max-thickness position from LE (0.30c)	Twist β (°)
A-A	0.2	600	403.5	48.4	121.0	17.69
B-B	0.4	1200	249.3	29.9	74.8	7.10
C-C	0.6	1800	174.0	20.9	52.2	2.93
D-D	0.8	2400	132.7	15.9	39.8	0.75
E-E	1.0	3000	107.0	12.8	32.1	-0.58

Rotor radius 3,000 mm; aerodynamic span 2,400 mm ($r/R = 0.2$ station to tip). Root mounting ($\varnothing 100$ mm stub, 200 mm blend) is indicative only, outside the aerodynamic design.

Appendix B — Aerodynamic and Structural Calculations

B.1 Design-point aerodynamics.

Swept area $A = \pi R^2 = \pi \times 3.0^2 = 28.27 \text{ m}^2$

Aerodynamic power $P_{\text{aero}} = \frac{1}{2}\rho AV^3 C_p = 0.5 \times 1.225 \times 28.2743 \times 12^3 \times 0.40 = 11.97 \text{ kW}$

Electrical power $P_{\text{elec}} = \eta P_{\text{aero}} = 0.85 \times 11.97 = 10.17 \text{ kW}$

Angular velocity $\omega = \lambda V/R = 7 \times 12 / 3.0 = 28.0 \text{ rad/s}$; $N = 267.4 \text{ rev/min}$; tip speed

$V_{\text{tip}} = 84 \text{ m/s}$

Thrust coefficient $C_T = 4a(1 - a)$ at $a = 1/3 = 0.8889$

Rotor thrust $T = \frac{1}{2}\rho AV^2 C_T = 2217 \text{ N}$

Flapwise root bending moment per blade $M = (T/B)(2R/3) = 1478 \text{ N}\cdot\text{m}$

B.2 Annual energy (Rayleigh distribution).

At a 6.0 m/s annual mean, $p(v) = (2v/c^2) \cdot \exp[-(v/c)^2]$ with $c = 2\bar{V}/\sqrt{\pi} = 6.770 \text{ m/s}$.

Power curve cubic from cut-in (3 m/s) to rated (12 m/s), flat to cut-out (25 m/s).

Integrating gives a capacity factor $CF = 0.214$, so $AEP = 10.17 \times 8760 \times 0.214 = 19,074 \text{ kWh/year}$, against the 19,978 kWh/year schedule (Appendix E), 95.5% coverage.

Table B1: Section and load coefficients (numerical integration of the NACA 4412 profile at the root chord 0.4035 m, wall 0.006 m).

Coefficient	Symbol	Value	Applies as
Enclosed area	k_A	0.0822	$\times c^2$
Perimeter	k_p	2.047	$\times c$
Second moment (shell)	k_I	0.00425	$\times t_w c^3$
Extreme-fibre distance	k_y	0.0722	$\times c$
Mass centroid radius	r_{cg}	1.12 m	—
Partial load factor	γ_f	1.35	—

$I = k_t t_w c^3 = 1.675e-06 \text{ m}^4$; $y = k_y c = 0.0291 \text{ m}$. Bending stress $\sigma_b = \gamma_f My/I = 34.7 \text{ MPa}$ (same for all materials). Centrifugal stress $\sigma_c = \gamma_f m \omega^2 r_{cg} / (k_p c \cdot t_w)$, scaling with blade mass. Combined $\sigma = \sigma_b + \sigma_c$; $SF = \sigma_{design}/\sigma$.

Table B2: Root stress and static safety factor by material.

Material	Mass (kg)	σ_b (MPa)	σ_c (MPa)	σ (MPa)	σ_{design} (MPa)	Basis	SF
Structural steel S275	70.27	34.7	16.8	51.5	275	yield	5.34
Aluminium 6082-T6	24.17	34.7	5.8	40.5	260	0.2% proof	6.42
SiC (sintered)	28.20	34.7	6.7	41.4	450	flexural, mid of 410–600	10.86
GFRP (E-glass/epoxy)	18.80	34.7	4.5	39.2	300	multiaxial laminate	7.65
CFRP (standard modulus)	14.32	34.7	3.4	38.1	600	multiaxial laminate	15.74

Composite design strengths are conservative multiaxial laminate values, below the unidirectional 1,020 and 1,240 MPa of Table 2. SiC's static factor is not its governing criterion; fracture toughness under cyclic load is.

Appendix C — Cost Calculations

Shell surface area (NACA 4412 section integrated along the span, with root block) = 1.4919 m^2 ; shell volume = area $\times t_w = 1.4919 \times 0.006 = 0.008951 \text{ m}^3$. Blade mass = volume $\times$ density; rotor = 3 blades.

Table C1: Volume-derived blade and rotor mass by material.

Material	Density (kg/m ³)	Blade mass (kg)	Rotor mass (kg)
Structural steel S275	7,850	70.27	210.8

Aluminium 6082-T6	2,700	24.17	72.5
SiC (sintered)	3,150	28.20	84.6
GFRP (E-glass/epoxy)	2,100	18.80	56.4
CFRP (standard modulus)	1,600	14.32	43.0

Unit prices (UK small-quantity prices, ex VAT, accessed 27 August 2026): steel S275 plate £800–1,020/t, midpoint £0.91/kg (Mixdesigncalc, 2026); aluminium 4–6× steel, midpoint £4.55/kg (same source); E-glass 290 g/m² woven roving £1.90/m² at the 144+ m tier → £6.55/kg (Easy Composites, 2026a); IN2 epoxy £14.12/kg, 32.5 kg kit (Easy Composites, 2026b); 650 g/m² carbon twill £32.00/linear m → £49.23/kg (Easy Composites, 2026c); sintered SiC quoted per part (Highland Refractory, 2026), raw grain ≈ \$2/kg (Henan Superior Abrasives, 2022), £30/kg indicative.

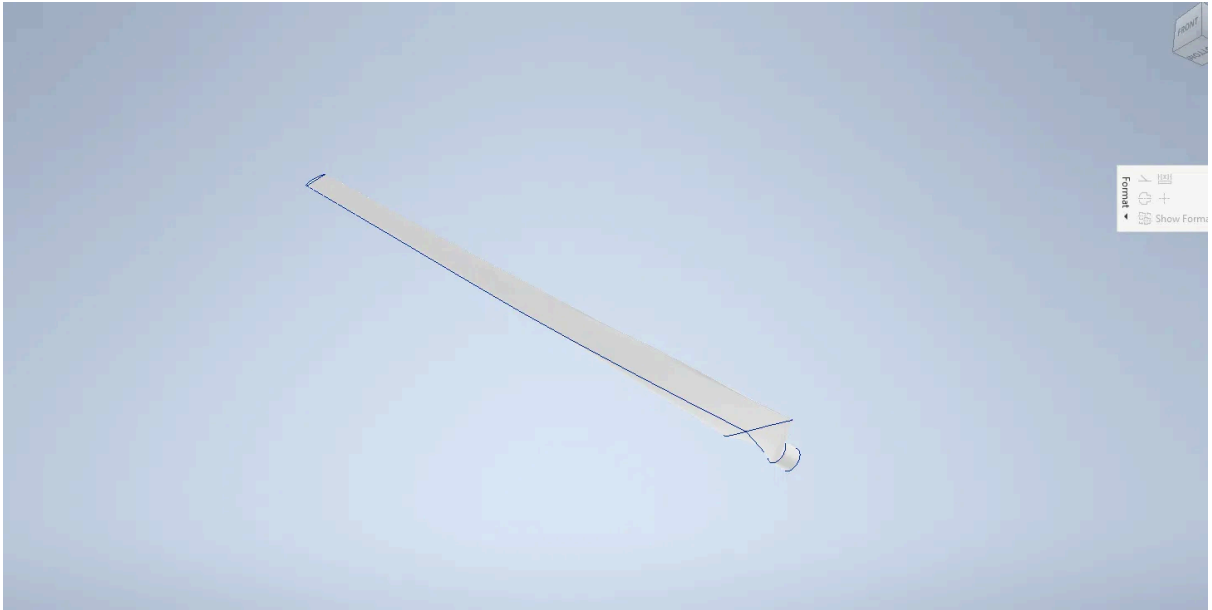
Laminate cost from constituents ($V_f = 0.60$): fibre mass fraction $W_f = V_f \rho_f / \rho_{\text{laminate}}$.
GFRP $W_f = 0.60 \times 2540 / 2100 = 0.726 \rightarrow 0.726 \times 6.55 + 0.274 \times 14.12 = £8.63/\text{kg}$.
CFRP $W_f = 0.60 \times 1800 / 1600 = 0.675 \rightarrow £37.82/\text{kg}$.

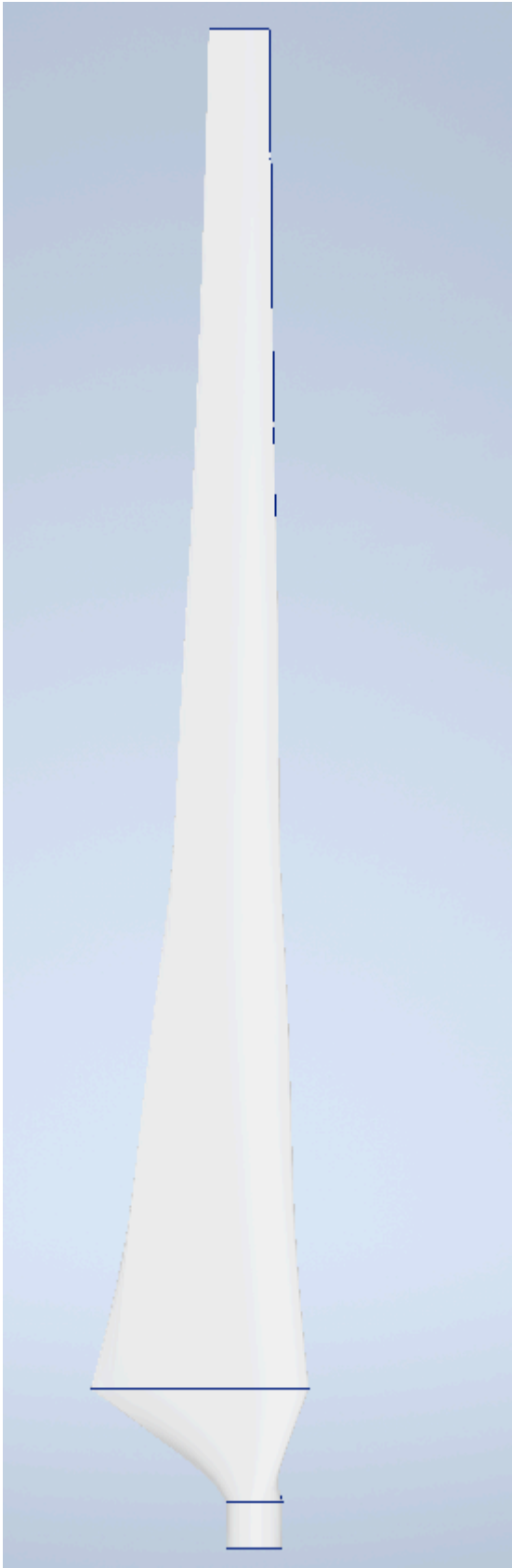
Table C2: Raw material cost build-up (machining, tooling and consumables excluded).

Material	Unit cost (£/kg)	Blade mass (kg)	Cost per blade (£)	Cost per rotor (£)
Structural steel S275	0.91	70.27	63.94	191.83
Aluminium 6082-T6	4.55	24.17	109.97	329.90
SiC (sintered)	30.00	28.20	845.91	2537.72
GFRP (E-glass/epoxy)	8.63	18.80	162.23	486.68
CFRP (standard modulus)	37.82	14.32	541.67	1625.00

Appendix D — CAD Isometric Views







Appendix E – Farm Load Schedule

Indicative annual electricity demand for an upland mixed sheep farm in mid Wales (≈200 ewes plus followers, farmhouse, general-purpose building, workshop). Figures are indicative and should be replaced with metered data where available.

Table E1: Indicative annual electricity demand.

Load	Category	Rated power (W)	Hours/yr	Annual energy (kWh)
Farmhouse general	Dwelling	–	–	4,200
Air source heat pump	Dwelling	–	–	5,000
Yard and building lighting	Livestock	750	1,500	1,125
Borehole and water booster pump	Livestock	1,100	1,500	1,650
Electric fence energisers	Livestock	60	8,760	525.6
Sheep shearing plant	Livestock	700	60	42
Trough de-icers	Livestock	500	700	350
Chest freezers ×2	Storage	–	–	700
Veterinary refrigerator	Storage	–	–	250
Air compressor	Workshop	2,200	300	660
MIG welder	Workshop	4,000	50	200
Pressure washer	Workshop	2,500	150	375

Hand tools and battery charging	Workshop	–	–	400
Hay drying fan	Seasonal	3,000	300	900
Feed mill / grinder-mixer	Seasonal	4,000	150	600
Light commercial vehicle and ATV charging	Transport	–	–	3,000
Total annual demand				19,977.6

Estimated turbine output at the design point 19,074 kWh → 95.5% of annual demand (capacity factor 21.4%, Rayleigh at 6.0 m/s mean). Matching annual totals is not self-sufficiency; without storage, realistic self-consumption is nearer 40–60%, the balance exported under the Smart Export Guarantee.