A life cycle assessment comparison of materials for a tidal stream turbine blade

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ABSTRACT

Electricity generated from tidal streams via underwater turbines has significantly lower greenhouse gas emissions than fossil-fuel derived electricity. However, tidal stream turbine blades are conventionally manufactured from non-recyclable reinforced polymer composite materials. Tidal stream capacity is forecast to be over 1GW by 2030, which using current methods will ultimately produce around 6000 tonnes of non-recyclable blade waste. This waste is currently disposed of in landfill or incinerated, both of which have greenhouse gas and human health impacts. To address a growing waste management problem, this high-level study considers for the first time a range of conventional and bio-based materials, manufacturing methods, and end-of-life treatments to determine the blade materials and designs likely to have low environmental impact. A finite element model is used to develop material cases and Life Cycle Assessment is used to study the impacts of each over a 'cradle to dock, dock to grave' scope. The impact of material choices on cost and modifications to the wider turbine are considered. Compared to a glass fibre composite turbine blade, steel blades are around 2.5 times heavier, and incur additional environmental impact due to upgrades required to the wider turbine. Carbon fibre composite blades weigh less than glass fibre, but cause greenhouse 80% greater gas emissions, and human and ecosystem health risks, so are also not recommended. The best environmental performance of the cases considered was a flax fibre composite. This material offers greenhouse gas emissions around 50% lower than glass fibre materials when manufactured using conventional epoxy resin, and around 40% lower when manufactured using recyclable epoxy resin, which also enables the reuse of the fibre and may further reduce environmental impact. Initial results suggest that the cost of these materials is similar to or lower than conventional composite materials.

1. Introduction

Tidal stream energy is a promising resource which has substantial prospect to contribute to the low carbon energy generation portfolio. The global tidal stream energy resource is difficult to estimate, and not necessarily representative of the practically extractable resource, but is widely estimated to be of the order of 120 GW. A recent study highlighted the potential of tidal stream energy to supply 11% of UK electricity demand [1]. Numerous advantages of tidal stream energy include predictability of tidal cycles, avoiding intermittency problems associated with other renewable energy technologies, avoidance of visual impact, and potential to bring income to coastal areas. The use of turbines to extract this energy and generate electricity results in greenhouse gas emissions of 10 to 35 gCO_2e/kWh [2], compared with combined cycle gas turbine emissions of over 400 gCO_2e/kWh. As illustrated in Fig. 1, onshore and offshore wind turbines are reported to have emissions of 7 and 11 gCO_2e/kWh respectively [3], solar

photovoltaic systems around 50 gCO_2e/kWh and nuclear around 12 gCO_2e/kWh [4].

However, though tidal stream energy offers electricity generation with lower greenhouse gas emissions than conventional sources, the manufacture, transport, installation, use and decommissioning of the required equipment all cause environmental impacts. One impact of particular recent interest in the wind and tidal energy sectors is waste production and the number of blades which require disposal as turbines reach the end of their lives [9]. At present these blades are manufactured from composite materials (commonly glass fibre-reinforced polymers, GFRP) which cannot be recycled, and are disposed of in landfill or by incineration. Although the volume of waste blades produced in the tidal energy industry is currently small due to the low number of devices deployed, a simple calculation based on the 1GW of installed capacity being targeted by 2030 [10] suggests that around 6000 tonnes of waste (based on 1000 1 MW rated three-blade devices with blade
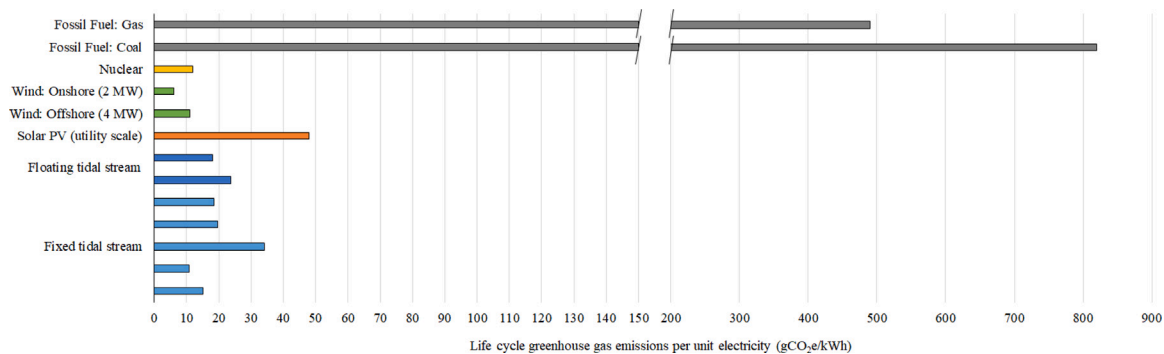
Fig. 1. Greenhouse gas emissions for a range of electricity generation sources. Tidal data from previous studies [2,5–7] [8]. Wind data from previous studies [3]. Solar, nuclear and Fossil fuel data from IPCC [4].

mass of 2 tonnes per blade) will be produced when these devices reach the end of their lives. If capacity continues to increase as planned, this volume of waste will also continue to grow.

Alternatives to non-recyclable composite materials do exist and may offer the potential to reduce waste by allowing reuse and recycling, reduce greenhouse gas emissions, or avoid environmental impacts associated with non-recyclable composite materials. These materials are either recyclable metal such as steel, composite materials made in such a way to allow the resin and fibres to be separated and at least one part to be recycled, and materials which can be disposed of in other ways, such as biodegradation through industrial composting. To date there have been no studies of the environmental impact of recyclable and non-recyclable composites and alternative materials for turbine blades, nor any relevant studies in other industries. This article addresses this knowledge gap by describing a comparative life cycle assessment study of 28 cases covering a range of materials, manufacturing methods and end-of-life treatment methods, in order to understand which materials and treatments offer the potential to reduce the negative impact associated with turbine blades. By understanding this and selecting the correct materials for a turbine blade, it may be possible to improve the net environmental impact of the turbine.

Though tidal stream turbine and wind turbine blades are visually similar and are both commonly manufactured from glass or carbon fibre composites, there are sufficiently significant differences between the structures that environmental assessment is not interchangeable. For the device rated power, tidal stream turbine blades are shorter and generally have much greater material thickness. Tidal stream turbine blades experience a wider variation in loading due to pressure changes with increasing depth during rotation, and are designed to withstand different environmental conditions including pressure, salinity and marine debris. Consequently, blade profiles, structure, and protection differ significantly from wind turbine blades. Tidal turbine blade design has less focus on light weight and greater focus on strength. Results from this study will allow the tidal energy sector to understand the environmental impact of turbine blades manufactured using current methods and materials as well as potential future alternatives. This will allow the sector to make informed decisions on environmental grounds as well as on performance and cost grounds as at present, and stimulate further work on materials, manufacturing and treatment cases with the lowest impact. Minimising the emissions and impacts of electricity generation is a key aspect of developing this renewable energy technology.

The existing body of literature on life cycle assessment of tidal stream turbines is very limited. As identified in a recent review [11], five studies have been published since 2007. Results from these studies give overall life cycle greenhouse gas emissions of between 10.7 and 34.2 gCO_2e/kWh. An unpublished study of floating tidal stream energy also gives a value of 18gCO_2e/kWh [8]. All studies were limited in their scope, and did not study turbine blades in detail, with most assuming a single piece of composite material of appropriate mass. The first life

cycle assessment study of a tidal turbine was undertaken on the Seagen device in 2007 [7]. This study considered only energy use and carbon dioxide emissions, and while one composite manufacturing process was included, no comparison of materials or methods was undertaken, and the blade was considered as a single part. A comparative 2013 study of four turbines [2] assumed glass fibre composite materials were used in each case, and assumed no recycling of blade materials at the end of life, but limited data on manufacturing methods was available and significant assumptions were made. A Swedish study [5] did include some relevant materials data, but only carbon dioxide emissions and energy use were considered, and full manufacturing details were not included. A 2016 review [6] highlighted the lack of high quality studies available, and carried out an assessment of tidal stream energy devices based on the European Commission's Joint Research Centre (JRC) ocean energy database. Here 100% incineration was assumed at the end of life, but the same single material assumption was made for all blade manufacturing processes and all blade materials. The present work was motivated by the absence of any detailed studies of tidal stream turbine blades including accurate manufacturing processes and material data.

2. Methodology

The aim of this work was to consider for the first time the net environmental impact of a range of materials and manufacturing methods for tidal stream turbine blades, whilst also considering practical implications of blade design, in order to determine the blade material , manufacturing method and end-of-life treatment combination with the lowest environmental impact.

Life Cycle Assessment (LCA) was used to estimate the environmental impact of various combinations of material, manufacturing method, and end-of-life disposal across eighteen impact categories. LCA is a method to assess the impacts of a product or process on the environment by considering some or all of the materials, processes, and sub-products required to produce it. The method also evaluates any positive or negative impact of the product in use, and the impact of treatment at the end of the product's life.

The international standard ISO14044 [12] describes four key aspects of an assessment: Goal and Scope, Inventory analysis, Impact assessment and Interpretation.

The same blade material, manufacturing and end-of-life combinations were assessed in two additional practical measures: Cost and Structural influence. This combination of LCA results and practical measures were used to identify the blades likely to have the lowest total environmental impact. Key to defining the goal of an LCA is the definition of a functional unit. The functional unit used in this assessment was one turbine blade with a length of 8.85 m from root to tip, from a three bladed horizontal axis tidal stream turbine rated at 1 MW. The blade geometry used is described in Section 2.2. Although the influence of the selection of turbine blade design on the rest of the turbine and structure is considered later, only the turbine blade itself
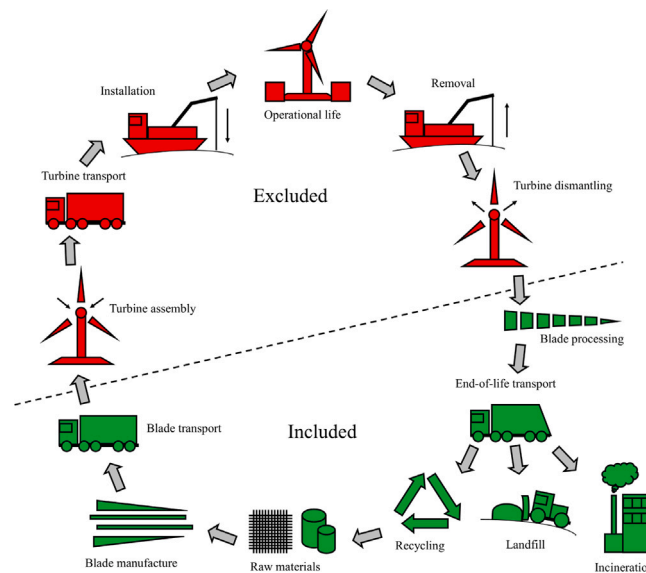
Fig. 2. Life cycle diagram for turbine blade illustrating stages included (green, lower section of diagram) and excluded (red, upper section of diagram). Authors own work.

was considered in the LCA. A total of 28 combinations of materials, manufacturing processes and end-of-life treatment were considered. In all cases a 'cradle to dock; dock to grave' scope was used. The first part of this scope included the manufacture of the turbine blade from raw materials to completed product at the manufacturing site and transport from the manufacturing site to a dock (which was assumed to be 100 km away by road). The use phase of the blade, i.e. the assembly of the turbine, marine transport to site, installation, operational use, maintenance, removal and marine transport to the dock, was not included. The subsequent end-of-life processes, i.e. transport from dock to landfill, incineration, recycling or processing site (again assumed to be a 100 km by road) were again included. A diagram of the life cycle of the turbine blade illustrating the study scope is shown in Fig. 2. The transport and installation phases were not included since this would require a LCA of the entire turbine, which is outside the scope of this study. For the same reason the energy generation of the turbine was not included since this is governed partly by the specification of other parts of the turbine, and partly by installation location, while this study aims to be relevant to any installation site. Finally, energy generation on a given site is governed to a degree by blade geometry, which has been retained between cases to allow direct comparison.

This study was conducted using SimaPro 9.1.1.1 software, using a combination of primary and secondary inventory data sources. Data on manufacturing processes and material selection were provided by tidal stream turbine developers, and material specification data was provided by manufacturers and developers through personal contact, material data sheets and safety information. Literature data was used to provide any data not available through these channels, and life cycle database data from the Ecoinvent v3.6, ELCD (European reference Life Cycle Database) and USLCI (U.S. Life Cycle Inventory) databases were used where literature did not provide a complete picture. Process energy use and emissions data was taken from the same databases and material and process profiles were modified where necessary. Transport data was taken from manufacturer and literature information. End of life treatment data was based on data from manufacturers and literature data, and associated emissions were calculated using modified processes based on database data. A full life cycle inventory data table is given in the supplementary information.

The ReCiPe 2016 Midpoint Hierarchist impact assessment method (version 1.04) was used [13], which gives impact results for the categories required by the Product Environmental Footprint (PEF) methodology [14], as well as in four additional categories.

Table 1
Key specification elements of the generic tidal stream turbine considered in this study.

Parameter	Value
Blade diameter (m)[a]	20
Blade number	3
Pitch control system	Yes
Support structure height (m)[b]	22
Nacelle mass (t)[c]	150
Support structure mass (t)[c]	150
Gravity base mass (t)[c]	400

[a]- Diameter of swept area including blades and hub.

[b]- Support structure height from seabed to centre hub height.

[c]- Corresponds to GFRP blade case.

2.1. Generic turbine design

In order to consider the two defined practical measures (Cost and Structural influence) alongside turbine blade environmental impact results, it was necessary to consider the features of a hypothetical turbine. A generic turbine design was therefore used as a basis for these considerations. The turbine is notional and was envisaged by combining the most common features from an assessment of all deployments to date undertaken in a previous study [15]. The generic turbine was a horizontal-axis device mounted on a steel support structure and fixed to the seabed using gravity base foundations. Key elements of this notional turbine design are given in Table 1. Whilst these features do not directly impact the blade design, they were defined to allow the consideration of LCA results alongside the practical measures. Support structure and foundation data was based on current existing turbine designs, all of which used GFRP blades, so the masses given in Table 1 represent a support structure of suitable strength and stiffness to support blades of this type, and will increase when heavier blades are used, as discussed in Section 4.1.

2.2. Generic blade model

2.2.1. Geometry

To allow direct comparison between turbine blade materials in the LCA study, a generic blade geometry was specified. This design was based on existing turbine blade designs and previous generic blades (particularly the turbine blade designed by NREL [16]). A blade length of 8.85 m was selected through consultation with device manufacturers.
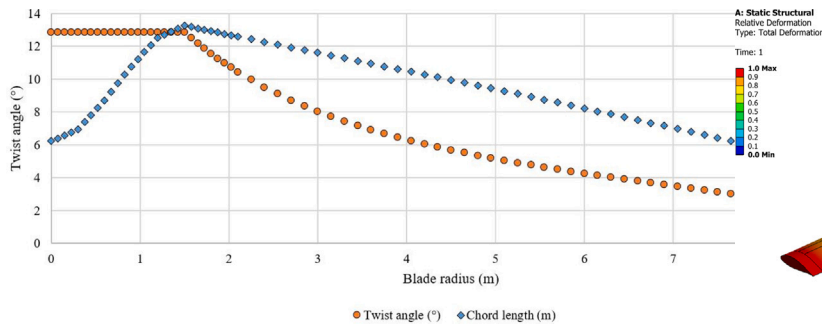
Fig. 5. Deformed result of GFRP blade.

Fig. 3. Generic blade model chord length and twist angle.
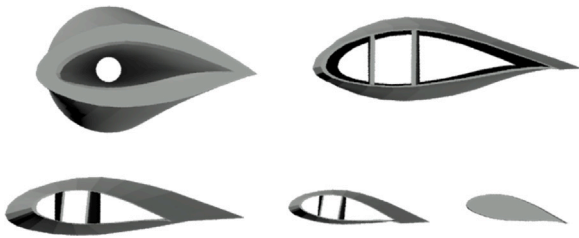

Fig. 4. Blade sections at (top, l-r) 1 m, 3 m, (bottom, l-r) 7 m, 8 m and 8.85 m from root (GFRP material case).

Whilst this specific blade design is not intended for commercial use by any developer, it includes the common features of blade design for a typical commercial three-blade deep water tidal stream turbine with a rated power of 1–2 MW, which represents the largest proportion of devices currently installed or being prepared for installation. The NACA 63-424 profile was used, with 13° twist at the root and 2° twist at the tip. In cases where the manufacturing method and materials required internal supports, two spar webs running along the full length of the blade with a shared spar cap were used. Fig. 3 illustrates the profile of the blade, and blade sections illustrating the shear webs used are shown in Fig. 4, taken from the GFRP case.

2.2.2. Blade structural performance specification

Stiffness of a complex structure like a turbine blade is defined as the product of material Young's Modulus E and second moment of area I. To ensure a fair comparison between materials, it was necessary to determine the material mass required to provide the same level of structural performance in each case. To maintain the same stiffness, the change in E between materials with different properties was compensated by a change in I. In order to ensure the same hydrodynamic performance, the outer surface of the blade geometry remained constant between cases, so the change in I was a change in cross-sectional area, and therefore material thickness. In order to determine the mass required in each material case, a performance baseline was established using the GFRP blade. A finite element model of this baseline blade was produced using AutoCAD 2021 and ANSYS 19.0, using the specification described in Section 2.2. The blade model was subjected to axial and tangential loads corresponding to a flow velocity of 4 m/s, calculated as shown in Eqs. (1) and (2). F_A gives the axial force and F_T the tangential force at the blade tip.

$$F_A = \frac{1}{2} A_A \rho v^2 \tag{1}$$

$$F_T = \frac{1}{2} A_T \rho (v\lambda)^2 \tag{2}$$

Surface areas A_A and A_T were frontal areas as calculated from CAD models based on the blade geometry described in Section 2.2.1.
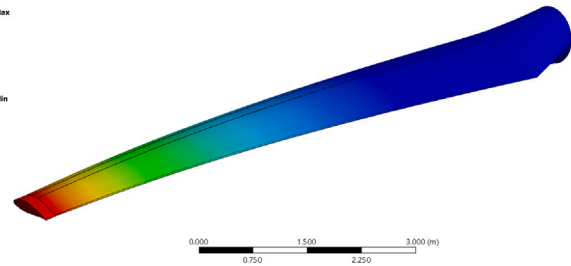
Seawater was assumed to have a density ρ of 1027 kg/m^3, based on the mean annual temperature of 10.5 °C at the European Marine Energy Centre. An extreme flow velocity case (v) of 4 m/s was used. An image of the deformed GFRP blade is illustrated in Fig. 5.

The resulting applied loads were 88 kN in the axial direction and 22 kN in the tangential direction. During the FE modelling the blade root face was set as a fixed boundary, and material properties were set based on mean material data from previous studies [17,18], as given in Table 2.

With these loads applied, the resulting deflection in the GFRP blade case was recorded. Deflection of the blade tip in the GFRP case was 0.169 m. For each other material case, an iterative process of material thickness change was undertaken until the calculated difference in blade tip deflection between the GFRP blade and the new blade was less than 5%. Material thickness changes were made to the entire blade structure in percentage terms, whilst maintaining the original outer surface volume of the blade.

The calculated material masses for each material case are given in Table 3. Masses given include foam filling and gelcoat, but these were assumed not to have a significant impact on the blade structural performance and were not included in the finite element model. Calculated blade masses are similar to those from other studies (e.g. [18]) for similar materials and blade length. The potential for variation in properties due to manufacturing processes was not considered in these calculations.

2.3. Materials, manufacturing & end of life

Four material categories were considered: Steel, conventional reinforced polymers, recyclable reinforced polymers, and bio-based materials. Three manufacturing methods were applied to conventional and recyclable reinforced polymers (VARTM, Monocoque, and Heated Mould). Material specification, manufacturing methods and end of life treatment are described below, and a summary of the combinations considered is given in Fig. 6.

2.3.1. Steel

Steel blades were used in some early tidal stream turbine blade designs, but their use has diminished, primarily due to the expense of forming complex blade shapes in steel and the large mass of steel blades. To provide a comparison with reinforced polymer materials, steel blades have been included in this study, however it is felt unlikely that steel would be a suitable material for blades significantly longer than the 8.85 m length considered in this study. The steel blade was manufactured entirely from grade 1045 carbon steel sheet, protected by a gelcoat. Steel thickness in the blade shell was between 5.64 mm and 2 mm, and in the box spar between 32 mm and 2 mm. Gelcoat thickness was 0.891 mm in both cases. Polyurethane foam was used in the trailing edge section of the blade, with a thickness between 19 and 34 mm. The total foam mass was 21 kg.

Table 2
Material properties used in the finite element model comparison.

	GFRP	CFRP	Flax composite	Steel
Density (kg/m^3)	1900	1200	1200	7850
Young's Modulus (Pa)	3.5×10^{10}	1.68×10^{11}	4.8×10^{10}	2×10^{11}
Poisson's Ratio	0.3	0.3	0.3	0.3
Ultimate tensile strength (MPa)	900	1900	635	460

Table 3
Calculated blade masses for each material and blade length case.

Blade length (m)	Material	Mass (kg)	Deflection[a]
8.85	GFRP	2530	-
8.85	Hybrid[b]	1703 + 266	3.7%
8.85	CFRP	1024	5.5%
8.85	Bio-based	1489	3.4%
8.85	Steel	5551	4.5%

[a]- % difference to GFRP baseline case deflection.

[b]- Mass in hybrid cases is given as GFRP + CFRP.

The manufacturing method assumed was based on that developed by the 'HyBlade' project [19], and involves folding a shaped steel sheet, laser welding seams and hydroforming using an oil–water mixture. A single central spar provides support in the centre of the 'HyBlade' blade, but here the steel blade incorporated two spar webs as in the relevant composite material cases. The sheet used to form the main blade surfaces was also used to form the leading side spar web, and the trailing side spar web was added as a separate piece and welded to the main structure. At the end of life, steel blades are assumed to be recycled by shredding and adding to blast furnace products to make steel via the Basic Oxygen Steelmaking process.

2.3.2. Conventional reinforced polymers

Three material combinations were considered in this category: Full GFRP, GFRP with CFRP shear webs (known as 'Hybrid'), and full CFRP. For the purposes of manufacturing processes, the unidirectional GFRP material (used for the spar sections of the blade) was assumed to be Vectorply ELT-5500 and the biaxial material (used for the shell section of the blade) Knytex DBM 1708. The CFRP material assumed was Zoltek PX35. The GFRP materials were modelled based on existing data for such materials, with modifications as required to represent these materials. The CFRP material was established for this project, based on existing data for polyacrylonitrile fibres (the precursor material used in the majority of carbon fibre production) and the heat and energy requirements of the stabilisation and carbonisation processes used to manufacture CFRP [20–22]. Impact results for carbon fibre included in this study were found to agree well with previous studies. In all conventional cases, the Glass or Carbon fibres were combined with thermoset epoxy resin to form the composite material, thus forming non-recyclable materials. The epoxy resin assumed here was Araldite 1568, used with Aradur 3489 hardener, which were combined at a ratio of 100:30 resin to hardener. In the two manufacturing cases which require adhesive bonding, the bonding agent assumed was Gurit Spabond 340LV HT [23]. Adhesive is only used in the VARTM and Heated Mould manufacturing methods, since the Monocoque method produces a single-part blade which does not require joining. The mass of adhesive required was calculated based on manufacturer data [23] and an assumed 10 mm diameter bead, which was calculated to give a mass of 397 kg. This is a notably greater mass than estimated by NREL [16], who estimated an adhesive mass of 35.3 kg for a blade of similar length. A sensitivity study was conducted to determine the importance of the mass of adhesive on environmental impact results. Full details are provided in the supplementary information. In the heated mould manufacturing processes, the same glass and carbon fibre materials were used (Vectorply ELT-5500 and Knytex DBM 1708 glass fibres and Zolktek PX35 carbon fibre), this time with powder

epoxy in lieu of the resin used previously. The powder epoxy assumed was based on EireComposites EC-CEP-0016, as studied in previous literature [24,25], though detailed composition data was not available.

Three manufacturing methods were considered in the conventional reinforced polymer cases:

- • 'VARTM': Vacuum-assisted resin transfer moulding (VARTM) is currently the most common method of composite blade manufacture. In this method, the blade is made in parts (upper and lower halves of the blade and the two shear webs), which are bonded together to form the final blade. Parts are made using a mould, into which fibre materials and reinforcing root sections are laid, then covered with a vacuum bag. Resin is pumped between the bag and the fibre, and a vacuum is used to draw the resin into the fibre material. These parts are cured individually, then fitted together and bonded using adhesive, before final trimming and coating. Curing conditions of 8 hours at 80 °C have been assumed for parts made using this method.

- • 'Monocoque': A single-piece blade manufacture technique using the VARTM method has been developed by the manufacturer Airborne [26]. In common with the bonded VARTM method, fibres are laid inside a mould, then a vacuum process is used to draw the resin into the fibres. Again, curing conditions of 8 hours at 80 °C were assumed. This single-piece method allows blades to be manufactured which are stiffer than the bonded VARTM method, and hence eliminates the need for shear webs. Consequently, the hybrid material case was not relevant with this method.

- • 'Heated mould': This method uses heat-activated polyester or epoxy powders instead of the liquid resin used in the two VARTM methods. This method was developed and patented by ÉireComposites [27]. Fibres and powder are placed in a ceramic mould with embedded heating elements, which are used to heat the powder to over 200 °C. This melts the powder and forms the composite material. Each section of the blade structure (the upper and lower halves of the blade, and the two shear webs) can be partially cured, assembled and then fully cured as a single piece. A potential advantage of this method is shorter curing times. Curing conditions of 70 minutes at 170 °C have been assumed for parts made using this method.

The manufacturing process stages for VARTM, Monocoque and Heated mould processes are given in Table 4. The processes have been divided into four key phases (layup, resin, joining, and finishing). Since the monocoque method does not involve joining, no processes are included in this section for this method.

In all cases, 20 30 mm diameter steel root bolts are included, and are assumed to be machined into the blade root. Conventional reinforced polymer blades were assumed to be disposed of at the end of life in landfill or by incineration with heat recovery. In both cases the blades were assumed to be cut into pieces as part of the disposal process, but no separation of the elements of the composite was undertaken. Full details of assumptions made regarding the energy use for end of life treatment of all blade materials, including transport to disposal facilities, are given in the supplementary information.

Table 4
Manufacturing processes for each of the three composite manufacturing methods.

Process	Bonded VARTM	Monocoque VARTM	Heated mould
L1	Outer layer fibre layup	Outer layer fibre layup	Outer layer fibre layup
L2	Root reinforcement installation	Root reinforcement installation	Outer layer powder
L3	Spar cap placement	Foam core placement	Root reinforcement installation
L4	Foam core placement	Inner layer fibre layup	Spar cap placement
L5	Inner layer fibre layup		Foam core placement
L6	Edge flange mould fitting		Inner layer fibre layup
R1	Resin infusion placement	Resin infusion placement	Inner layer powder
R2	Vacuum bag placement	Vacuum bag placement	Mould heating process
R3	Vacuum process	Vacuum process	Curing (70 mins @ 170 °C)
R4	Curing (8 h @ 80 °C)	Curing (8 h @ 80 °C)	
J1	Spar web adhesive		Shear web adhesive
J2	Shear web placement		Shear web placement
J3	Edge adhesive		Edge adhesive
J4	Assembly		Assembly
F1	Perimeter flange trimming	Root face machining	Root face machining
F2	Root face machining	Root bolt installation	Root bolt installation
F3	Root bolt installation	Painting	Painting
F4	Painting		

2.3.3. Recyclable reinforced polymers

In order to create recyclable composite materials, conventional non-recyclable epoxy resin is replaced with a recyclable epoxy resin system based on Recyclamine, a proprietary platform technology comprising of novel polyamines that enable the recycling of epoxy thermoset. The system is a thermoset matrix that cures crosslinks in a similar manner to conventional thermoset epoxy resins, however it can be recycled by low energy solvolysis to recover the epoxy matrix as epoxy thermoplastic which can be re-used and re-purposed. The resin component of epoxy system is synthesised from glycerol-based Epichlorohydrin, reactive diluents based on renewable feedstocks and has 31% bio-based content.

In this case, Epotec YDL5557 resin and Epotec THR9357 hardener, both manufactured by Aditya Birla Chemicals [28] were used in place of the conventional epoxy resin described in the previous section. The resin and hardener were assumed to be combined at a ratio of 100:27 resin to hardener by weight, as recommended by the manufacturer.

The Epotec products are suitable for use with both glass and carbon fibres, and the same three combinations as used for conventional reinforced polymers (GFRP, Hybrid, CFRP) were again considered. At the end of life, material recovery is achieved through the use of two recovery solutions. First, a 25% acetic acid solution is used to cleave the composite. The solution is heated to and maintained at 80 °C. In this case, 12 h at this temperature has been assumed. After this time the fibre material can be recovered. The first solution is then neutralised with a 5% sodium hydroxide solution. The recovery solution is then filtered, neutralised and coagulated to recover the cleaved epoxy matrix as an epoxy thermoplastic polymer. After use, the recovery solution is neutralised with caustic soda and to leave a non-acidic effluent. The recovered fibre offers around 90% of the strength and stiffness of the original fibre, so may not be suitable for reuse in high performance products such as turbine blades. However, this fibre can be incorporated in other products where strength and stiffness are less critical, so in glass fibre and carbon fibre cases it was assumed that this recovered fibre is reused elsewhere (and that the fibres used in the recyclable reinforced polymer cases are always virgin fibres). Each 1 kg of recovered fibre was credited in the LCA with the avoidance of 0.5 kg of virgin fibres. This may be a conservative estimate. The 10% reduction in strength is due to distortion in fibre alignment. Through controlled recycling and re-sizing of the product, it may be possible to reduce the drop in strength and enable reuse in higher performance products.

The volume of recovery solution required for a turbine blade was calculated based on a hypothetical tank with dimensions 5% larger than the blade in each direction, giving 5.84 m³ of recovery solution. This is believed to be a reasonable estimate, since although the blade is unlikely to be treated with recovery solution in a single piece and therefore more solution may be used around the root sections than has been accounted for here, tip sections of the blade could be recovered using a lower volume of solution than has been assumed here. The first recovery solution can be reused depending on its pH level, and is commonly reused once (i.e. used twice). This case has been initially assumed in the LCA, but to account for this uncertainty, a sensitivity study was carried out to understand the impact of the number of uses of the first recovery solution on the overall impact of the recovery solution and therefore the recyclable resin product.

2.3.4. Bio-based reinforced polymers

Two bio-based reinforced polymer materials were considered. Both were manufactured using the same manufacturing method, but have different end of life treatment methods. The fibre material in both cases was based on a non-crimp biaxial flax fabric material called Amplitex 5008, manufactured by BComp, which manufacturer data [29] and previous studies [17] suggest offers comparable stiffness to glass fibre fabrics. In both cases, a conventional VARTM reinforced polymer manufacturing method was followed, using only the flax based fibre material (i.e. there was no hybrid case), incorporating shear webs, and bonded using Gurit Spabond 340LV HT. In the first case, this fibre was used with conventional epoxy resin and hardener as in the conventional reinforced polymers. In a second case, the same fibre material was used with the Recyclamine system resin and hardener as used in the recyclable cases. In the first case, the fibre material is bio-based, but the end product is not recyclable or biodegradable, so was assumed to be disposed of by landfill or incineration. In the second case, the resin can be cleaved through the use of the recovery solution and recycled, as in the recyclable reinforced polymer case, while the recovered flax fibre material was assumed to be disposed of by biodegradation by industrial composting. It may be possible to reuse the flax fibre, but at the time of this study no information on the performance of recovered flax fibres is available, so it has been assumed that these fibres would be disposed of by industrial composting.

3. Results

Results are presented in this section for a series of comparative cases, comparing material type, manufacturing methods and end-of-life treatment for conventional polymers, and comparison between conventional, recycled and bio-based materials.
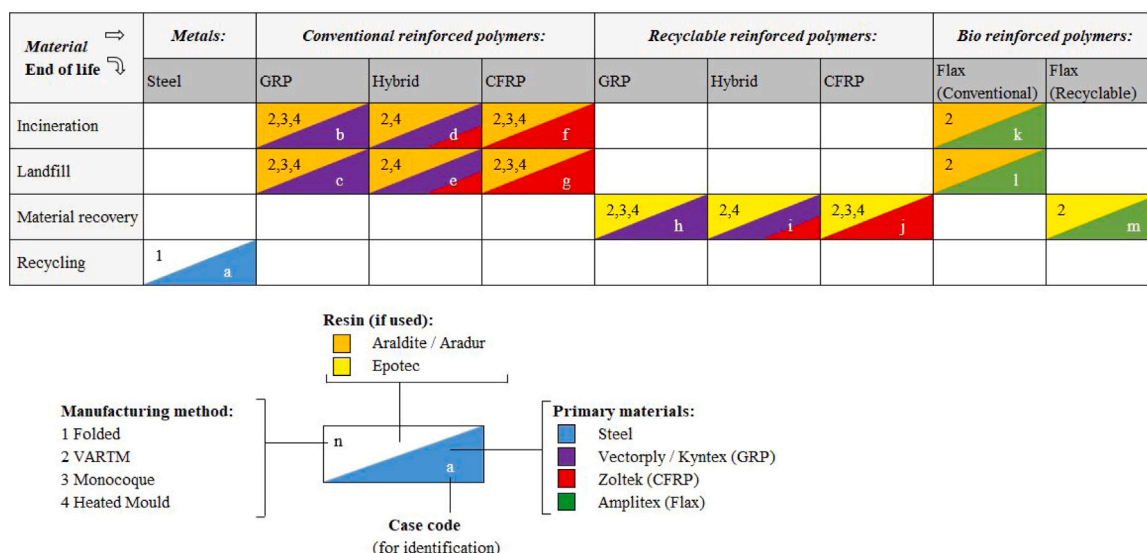
Fig. 6. Summary of material, manufacturing and end of life cases considered in this study (top) and key to cases (bottom). Where present in a cell, top left colours indicate resin type and lower right colours indicate fibre or main material. Numbers indicate manufacturing methods applied to each case, and letters are a code for reference in results.

Table 5
Percentage uncertainty applied by material and impact category, as calculated in sensitivity studies.

Impact category	Steel	Conventional & Bio-based composites[a]	Recyclable composites
Global warming	+21/-21	+13/-13	+57/-17
Stratospheric ozone depletion	+23/-23	+4/-4	+44/-14
Ionizing radiation	+24/-24	+1/-1	+52/-17
Ozone formation (human health)	+18/-18	+24/-24	+60/-19
Fine particulate matter formation	+17/-17	+14/-14	+56/-19
Ozone formation (terrestrial)	+18/-18	+24/-24	+61/-20
Terrestrial acidification	+18/-18	+16/-16	+60/-20
Freshwater eutrophication	+14/-14	+3/-3	+53/-18
Marine eutrophication	+17/-17	+3/-3	+45/-15
Terrestrial ecotoxicity	+10/-10	+5/-5	+59/-20
Freshwater ecotoxicity	+14/-14	+10/-10	+58/-19
Marine ecotoxicity	+14/-14	+11/-11	+58/-19
Human carcinogenic toxicity	+13/-13	+10/-10	+54/-18
Human non-carcinogenic toxicity	+11/-11	+10/-10	+59/-19
Land use	+16/-16	+2/-2	+58/-19
Mineral resource scarcity	+11/-11	+3/-3	+62/-21
Fossil resource scarcity	+24/-24	+13/-13	+74/-23
Water consumption	+24/-24	+22/-22	+56/-19

[a]- Since the uncertainty is due to adhesive, monocoque manufacturing method is excluded.

3.1. Uncertainty in results

Due to the nature of LCA, in common with any modelling process, results cannot ever be a direct representation of reality. The assumptions used in this study have been described in Section 2, and sensitivity analyses have been used to determine the uncertainty in various results sections. Uncertainty is shown on all charts presented in this section. Table 5 gives a summary of the uncertainty applied to each material case in each impact category, resulting from sensitivity analyses (described in full in supplementary information).

3.2. Life cycle assessment results

Results are presented as comparisons between material types, manufacturing methods, end of life treatment, and the use of recyclable or bio-based composite materials. Results are presented in four key impact categories throughout. The cases selected (Greenhouse gas emissions, land use, water consumption, and human toxicity) are commonly highlighted as key categories, however full results are included in the supplementary information, and results are discussed across all impact categories.

3.2.1. Material comparison

The turbine blade with the lowest life cycle greenhouse gas emissions is the bio-based fibre blade with conventional epoxy resin and incineration at the end-of-life, with total emissions for the life cycle stages considered of 9714 $kgCO_2e$ per blade. The same case with landfill at end-of-life had emissions of 10,001 $kgCO_2e$ (2% greater than the incineration case), and the same case with recyclable epoxy resin and recycling and biodegradation at end-of-life had emissions of 11,298 $kgCO_2e$ (16% greater than the incineration case). Greenhouse gas emission results for a selection of combinations of manufacturing method, material and end-of-life treatment are shown in Fig. 7.

The low emissions of the bio-based cases are largely due to the lower impact of the raw materials, in comparison to carbon fibre for example, which has high materials and end-of-life emissions. The recyclable epoxy resin system used in the recyclable and compostable cases does have a higher manufacturing energy than non-recyclable epoxy resin, due to the additional requirement of the recovery solution, but this is compensated by the advantage of being able to recycle recovered polymer at the end of the product life.

The highest greenhouse gas emission case across all 28 options considered was the carbon fibre blade made with powder epoxy using
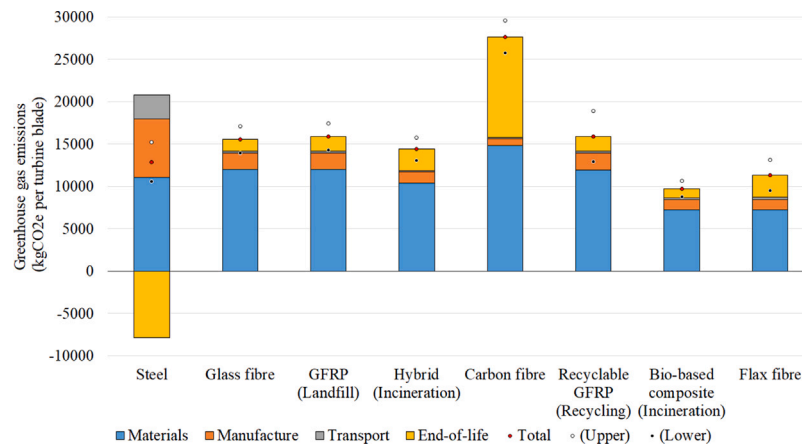
Fig. 7. Comparative results for Greenhouse gas emissions impact category, for a single blade across 8 material and end-of-life treatment options. Manufacturing method is VARTM in all composite material cases. Red dots indicate net value including emissions and avoided emissions where relevant. White dots indicate upper uncertainty bound, black dots indicate lower uncertainty bound.
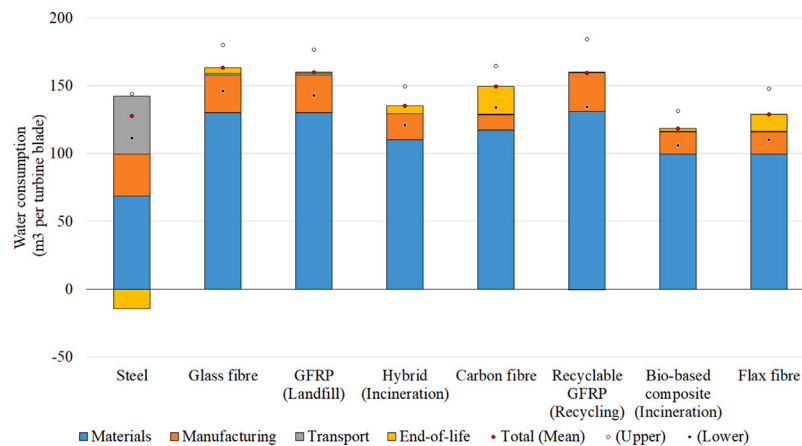

Fig. 8. Comparative results for water consumption emissions impact category, for a single blade across 8 material and end-of-life treatment options. Manufacturing method is VARTM in all composite material cases unless stated. Red dots indicate net value including emissions and avoided emissions where relevant. White dots indicate upper uncertainty bound, black dots indicate lower uncertainty bound.

the heated mould method and incinerated at the end-of-life. The heated mould method is more heat energy-intensive than the VARTM or Monocoque manufacturing methods due to higher curing temperatures, but the greater impact of powder resin when compared to liquid resins is the main driver of the difference in impact. Furthermore, the incineration of carbon fibre releases a significant amount of carbon dioxide, resulting in total emissions for the life cycle stages considered of 30,918 $kgCO_2e$ per blade. This is greater than the 27,653 $kgCO_2e$ per blade for the VARTM carbon fibre blade with incineration shown in Fig. 7 (the powder epoxy case is not shown in this figure).

The greatest water use occurs in cases manufactured using the heated mould method. This is driven by high water use in the powder epoxy, which contributes over 75% of total water use in some cases. The production of titanium dioxide and other chemical ingredients used in the powder epoxy add significantly to the water usage of the product, giving resin in this form a greater water footprint than in the liquid form. The lowest water usage is seen in lightweight blades made using the monocoque or VARTM method, as in Fig. 8. The lowest total water usage for the life cycle cases considered was 75 m^3 per blade, in the monocoque carbon fibre blade with recyclable epoxy and landfill end-of-life treatment.

As Fig. 9 shows, the cases with the greatest impact on land use are those using bio-based fibre materials and recyclable resin. Blade mass has a significant impact on land use, since the area of land required for cultivation is driven by the amount of product required. In the bio-based fibre product cases, 98% of land use associated with the fibre

crop is derived directly from crop growth, with the remainder made up of numerous small contributions from products used in the manufacture (for example timber burned in downstream processes).

In the recyclable GFRP case, 28% of total land use is attributable to processes related to the manufacture and use of the resin. When recyclable resin is used, the recovered product at the end-of-life results in a credit. This is due to the recycled polymer produced, and the avoided land use for raw material cultivation in the virgin products which it replaces.

This study has assumed that when bio-based fibres and recyclable resin are used together, the recovered fibres are disposed of by biodegradation through industrial composting. It may also be possible to reduce overall impact by limiting virgin fibre use through the recovery and reuse of fibre. This will be discussed in Section 3.3, but due to the uncertainty in this process it has not been considered as a separate case.

Human toxicity presented here (see Fig. 10) is a combination of two impact categories: non-carcinogenics and carcinogenics. In all cases, carcinogenic impacts are much lower than non-carcinogenic impacts. In nearly all cases, carcinogenic impacts make up less than 4% of the total impact, apart from in the steel case where the figure is 13%. The case with the largest human toxicity impact is the carbon fibre blade with landfill end-of-life treatment. Here the impact is the sum of impacts from the manufacture of Polyacrylonitrile fibres, and emissions to groundwater through leachate from landfill. In the carbon fibre
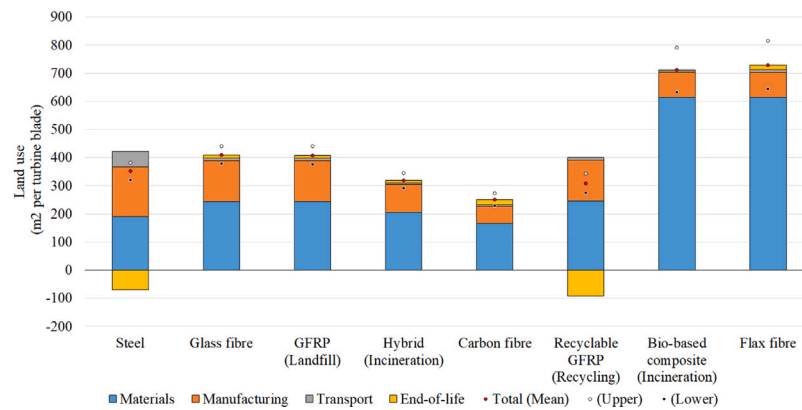
Fig. 9. Comparative results for land use impact category, for a single blade across 8 material and end-of-life treatment options. Manufacturing method is VARTM in all composite material cases. Red dots indicate net value including emissions and avoided emissions where relevant. White dots indicate upper uncertainty bound, black dots indicate lower uncertainty bound.
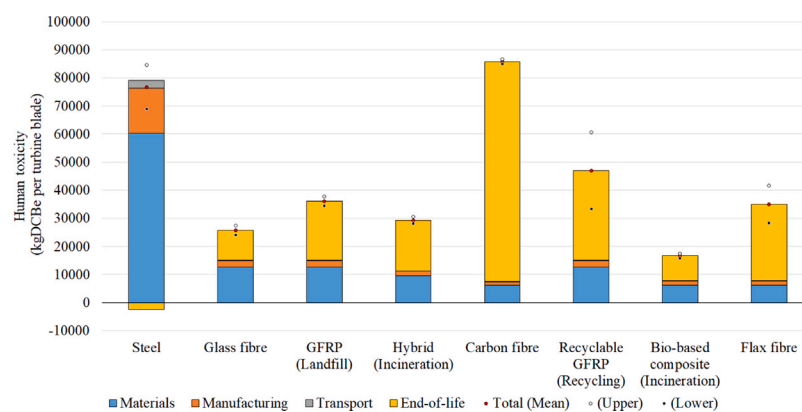

Fig. 10. Comparative results for human toxicity impact categories, for a single blade across 8 material and end-of-life treatment options. Manufacturing method is VARTM in all composite material cases. Red dots indicate net value including emissions and avoided emissions where relevant. White dots indicate upper uncertainty bound, black dots indicate lower uncertainty bound.

blade case, sulfidic leachate is particularly high (contributing around 43% of total toxicity). The lowest overall human toxicity impacts were from the bio-based blade using non-recyclable resin and end-of-life incineration. In general, landfill was found to produce greater toxicity impact than incineration. Using recyclable resin was found to avoid the toxicity impacts associated with landfill, but to introduce some minor toxicity impacts related to the recovery solution. These effects are largely attributable to the manufacture of the acetic acid used in the solution. Acetic acid has low toxicity, but nonetheless some impact does occur.

3.2.2. Conventional composites: Material selection

This section compares the relative environmental impact of glass fibre, carbon fibre and hybrid composites, while manufacturing methods and end-of-life treatment are considered in the following sections.

The relative masses of the GFRP, Hybrid and CFRP blades are 2530 kg, 1969 kg and 1024 kg respectively. Despite lower mass, the CFRP blade has the greatest environmental impact in eleven of eighteen impact categories. In impact categories related to ozone , the impact of the CFRP blade is in some cases over 2.5 times greater than either of the other two materials. The comparison shown in Fig. 11 highlights the higher impacts of the CFRP blade on human toxicity and greenhouse gas emissions. As discussed above, human toxicity impacts are driven by the impact of polyacrylonitrile fibres in the manufacture and end-of-life stages. Greenhouse gas emissions of carbon fibre epoxy composite material were calculated to be 37.6 $kgCO_2$/kg, compared to 2.67 $kgCO_2$/kg for glass fibre composite. Both values are similar to those calculated by others (34.5 $kgCO_2$/kg and 2.5 $kgCO_2$/kg

respectively [30] and 38.9 $kgCO_2$/kg and 2.16 $kgCO_2$/kg [22]), so even the significant weight reduction in the CFRP blade does not offset the overall increased emissions.

In both human toxicity and greenhouse gas emissions categories, the CFRP blade has the greatest impact of all cases considered, which increases further if the heated mould method is used. However, the CFRP blade has comparable water consumption to the GFRP and Hybrid cases, and lower land use impact. The GFRP and Hybrid impacts are similar in all impact categories due to the small amount of glass fibre replaced by carbon fibre in the Hybrid case.

3.2.3. Conventional composites: Manufacturing method

Three manufacturing methods were considered for conventional composites. Vacuum-assisted resin transfer moulding (VARTM) is currently the most commonly used method of manufacturing large parts such as turbine blades, and is widely used in the wind energy industry. The major difference between the processes is that the Monocoque method involves the manufacture of the whole blade as a single unit, and therefore uses no adhesive or perimeter trimming processes. On the whole, the difference in impact between the VARTM and Monocoque processes is relatively small, since the adhesive and perimeter trimming process both make only minor contributions to the overall impact. There are more significant differences between the Heated Mould method of manufacture and the two vacuum processes. The Heated Mould method uses powder resin, which has a greater environmental burden than liquid resin. The exact composition of the powder epoxy proposed for use in tidal turbine blade projects was not available for use in this study, so these results should be treated as an initial estimate, but
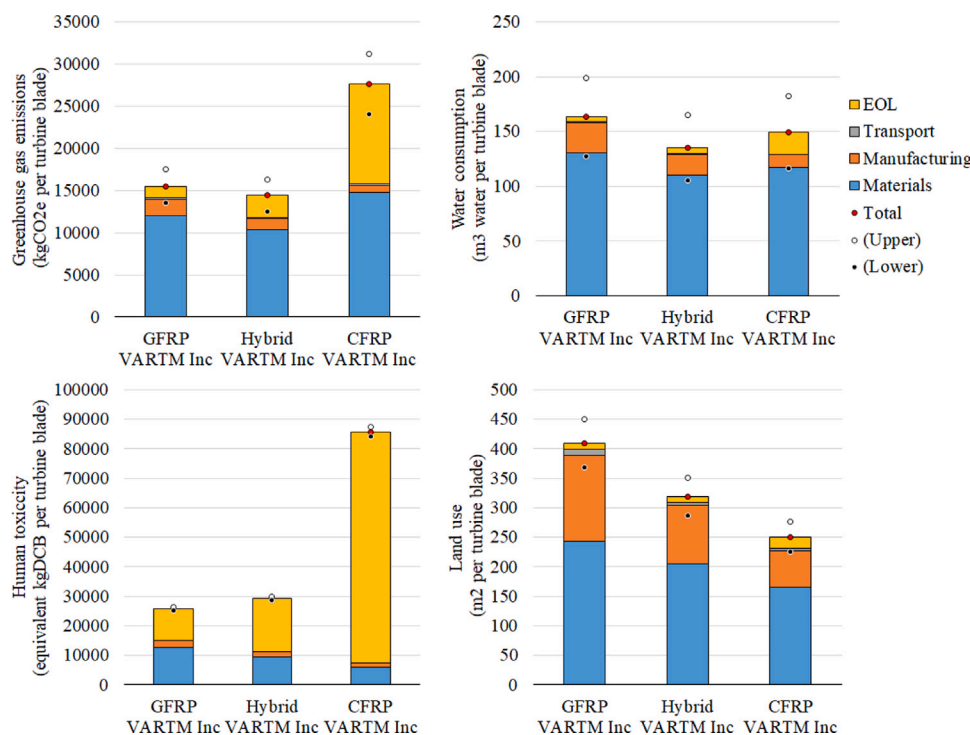
Fig. 11. Comparison in four impact categories of life cycle impacts of a turbine blade manufactured from Glass fibre (GFRP, left), hybrid (centre), and Carbon fibre (CFRP, right), assuming manufacture by the VARTM process and incineration end of life treatment.

the addition of products such as titanium dioxide to create powder resin will only increase environmental impacts. Based on the available data, the Heated Mould blade does have lower energy use than either vacuum method, but it has greater environmental impact in fifteen of eighteen impact categories. The Heated Mould method produces particularly high levels of particulate matter and ozone formation related to the manufacture of the powder resin and inclusion of ingredients such as titanium dioxide (see Fig. 12).

Based on the LCA results, the Monocoque or VARTM methods are preferable to the Heated Mould method, and the Monocoque method is slightly preferable to the VARTM method. However, practical considerations such as the equipment and facility size required to manufacture monocoque blades must be considered, as well as the significance of the powder resin used in the Heated Mould case. Since the powder drives a large proportion of the impacts of this method, its formulation should be carefully considered. If these impacts can be avoided by the removal of some ingredients, the Heated Mould method may become a less environmentally damaging option.

3.2.4. Conventional composites: End of life treatment

Two types of end-of-life treatment were considered in the conventional composites case: Incineration and landfill. The results across four impact categories show that end-of-life treatment makes a relatively small contribution to greenhouse gas emissions (9% in the incineration case and 11% in the landfill case), and a small contribution in the water consumption (2.5% and 0.5%) and land use (2% in both cases) categories. The human toxicity impact is much greater in both cases, and is relatively greater in the landfill case (42% of total in the incineration case and 59% of total in the landfill case). The cause of the greater impact in the landfill case is due to the potential for leakage of metals into water (primarily Zinc, but also Lead, Mercury and Arsenic). For the same reason, landfill also has a greater impact on marine eutrophication, where end-of-life treatment by landfill causes over sixty times greater end-of-life impact than the incineration option. This is the largest difference in impact between the two cases by a

significant margin, and is due to the risks of landfill runoff and nitrogen release (see Fig. 13).

In general, differences between end-of-life options are relatively small, since end-of-life treatment makes up less than 10% of impact in twelve of eighteen impact categories. However, end-of-life is significant in toxicity and eutrophication categories, where the impact of the landfill option is more significant than the incineration option. The only exception to this is the increased stratospheric ozone emissions from the incineration option.

3.2.5. Recyclable & bio-based composites

Two alternatives to steel or conventional reinforced polymers were considered: Recyclable resin and bio-based fibres. The Epotec recyclable epoxy resin is a direct replacement for conventional non-recyclable epoxy resin and allows the separation of fibre and resin at the end of life, thus allowing the reuse of the former and the recycling, re-use or re-purposing of the latter as a thermoplastic, allowing value to be recovered. Recycling rates and assumptions used have been discussed in Section 2.3.3. Bio-based fibres such as the flax fibre considered here are an alternative to glass or carbon fibre. These fibres can be treated in the same way as conventional fibres, with either conventional non-recyclable or recyclable epoxy resin, allowing them to be separated and the fibre biodegraded at end-of-life using industrial composting. Fig. 14 shows four blade material cases: A conventional GFRP blade, incinerated at end-of-life ("GFRP"); a blade using recyclable resin and glass fibre, where the resin is recycled and the fibre reused at end-of-life ("Recyclable GFRP"), a Flax fibre blade with conventional epoxy resin, incinerated at end-of-life ("Flax"), and a flax fibre blade with recyclable resin, where resin is recycled and fibre composted at end-of-life ("Recyclable Flax").

Impacts are similar across the four cases in many categories. In some impact categories, using recyclable epoxy resin with glass fibre increases impact relative to the non-recyclable epoxy resin case, but in many categories this impact is offset by the credit for the avoidance of virgin glass fibre manufacture. The lowest greenhouse gas emissions in this comparison are in the two bio-based fibre cases. Emissions in the
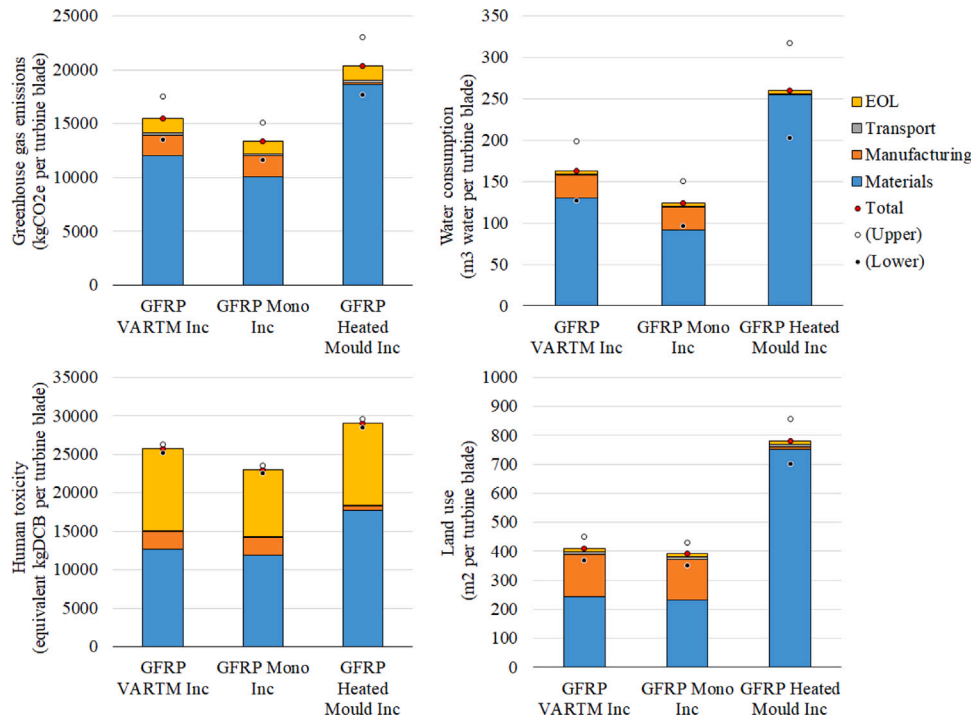
Fig. 12. Comparison in four impact categories of life cycle impacts of a conventional composite GFRP turbine blade manufactured using three manufacturing methods (VARTM (left), Monocoque (centre) and Heated Mould (HM) (right)), assuming incineration at end of life in all cases.
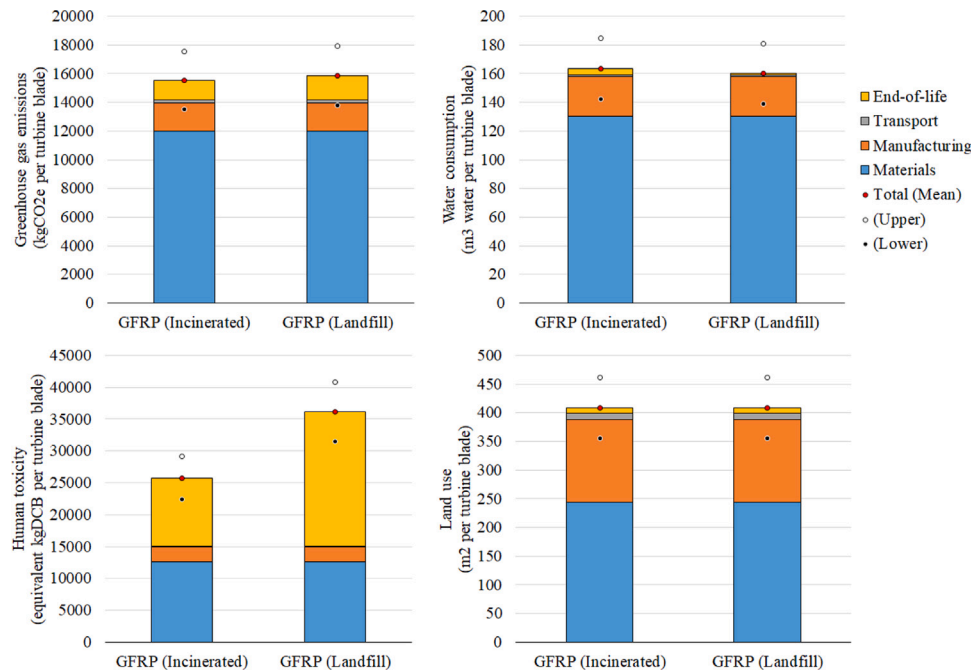

Fig. 13. Comparison in four impact categories of life cycle impacts of a conventional composite GFRP turbine blade manufactured using the VARTM process by incineration (left) and landfill (right) end of life treatment.

flax fibre cases with conventional and recyclable epoxy resin are similar in the material part, but the recyclable epoxy resin case has greater end-of-life treatment emissions, due to the requirement for recovery solution.

3.3. Material recovery

In the same way that using recyclable epoxy resin allows the recovery and reuse of glass fibre, it may be possible to recover and reuse

flax fibre when recyclable epoxy resin is used. Work is ongoing to understand the potential for the recovery and reuse of natural fibres, so this study has assumed that flax fibre would be recovered and biodegraded through industrial composting, but if the product could be recovered and reused (assuming that 1 kg of recovered fibre could replace 0.5 kg of virgin fibre, as in the glass fibre case), land use could be reduced by 31% relative to the biodegradation case. Greenhouse gas emissions, water consumption and human toxicity impacts would all be
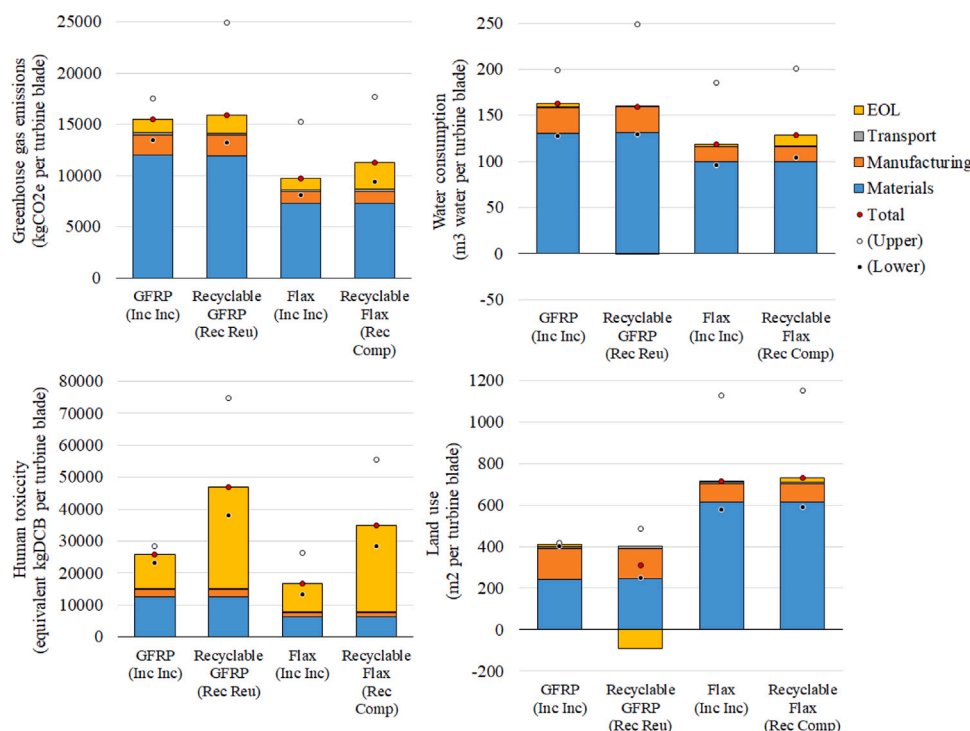
Fig. 14. Comparison in four impact categories of life cycle impacts of a turbine blade manufactured from (l-r) glass fibre with epoxy resin, incinerated at end-of-life; glass fibre with recyclable resin, resin recycled and fibre reused at end-of-life; Flax fibre with epoxy resin, incinerated at end-of-life; and flax fibre with recyclable resin, resin recycled and fibre composted at end-of-life. All manufactured using the VARTM method.

reduced by around 5% relative to the biodegradation case and in this case would have lower GHG emissions than the other cases studied.

4. Discussion

The tidal energy industry is currently at a critical development stage: Prototype installations have proved successful and the sector is attempting to move towards cost of energy levels which allow it to compete with established renewable energy sources. This is a challenge due to the economies of scale enjoyed by established technologies, meaning that cost reduction is key for the tidal sector. In order to minimise environmental impact and ensure that the sector is able to generate energy at an acceptable cost, any proposed changes to turbine blade materials or manufacturing must therefore be constrained by the same cost limits as current designs. This influences choice of materials, but also has wider impacts due to the relationship between blade materials or design and whole turbine design. For example, heavier blades will require other parts of a turbine to be redesigned in order for the complete structure to withstand the subsea environment, which will increase cost.

4.1. Practical measures

In addition to calculated LCA results, two practical measures were established in order to consider impacts outside the scope of the LCA which influence the validity of any recommendations. These are based on a conventional three-blade horizontal axis tidal turbine as described in Section 2.1 and Table 1.

4.1.1. Cost

Though the tidal turbine industry is relatively small, much of the technology required to manufacture blades is based on that of wind turbines. As discussed in Section 1, design parameters and the final products differ between the two sectors, but manufacturing processes

such as VARTM are transferable and are thus well-established despite the youth of the industry.

In the wind turbine industry, material and manufacturing cost is estimated to make up around 40% of total turbine costs [17]. Exact costs are difficult to calculate accurately, but material cost changes are relatively easy to estimate. A series of material cost estimates and the resulting cost of the major component of the blade (i.e. excluding adhesive, foam, gelcoat, paint, and root fixings) are given in Table 6.

This comparison, though an estimate, suggests that the cost differential between carbon fibre and glass fibre is negated in total blade cost due to the lower mass of carbon fibre. Steel material costs appear lower than composite materials, though manufacturing cost may be higher. The flax composite material has the lowest estimated cost, though this is also the cost with the greatest uncertainty, since only small amounts of bio-based fibres are currently used in composite applications. While it could be argued that costs will fall as the industry grows, costs may also increase if this application becomes more profitable than other uses of the flax crop. In this case, a higher proportion of the cost of the flax cultivation may be borne by the flax fibre material. This is an issue seen historically in other cases when a waste product becomes a valuable commodity.

Any change to the materials or manufacturing methods of a tidal turbine blade, for example moving from a VARTM to a Monocoque or Heated Mould manufacturing method, may increase cost and expose the developer, investors and supply chain to additional financial risk in the short term due to equipment and training costs, and the loss of a competitive advantage and confidence in product reliability gained

Table 6

Material mass and relative cost estimate of turbine blade (data from [17] [31] [32])

	GFRP/Epoxy	CFRP/Epoxy	Flax/Epoxy	Steel
Mass (kg)	2530	1024	1489	5551
Cost (USD/kg)	2.6	8.2	1.53	0.61
Blade cost (USD)	6552	6589	2278	3369

through experience of the previous technique. Once this short term impact has passed, longer term advantages of the change may be seen. This must be balanced against the relative security of a well-established method, however the adoption of new method or material may allow access to improvements in environmental impact not achievable with current materials. For example, the manufacture of products using non-recyclable GFRP is a large industry and benefits from well-established economies of scale, whereas the manufacture of products using recyclable resins is in its infancy. If this industry grows it is expected that economies of scale and other efficiencies will drive down emissions. Notwithstanding the importance of this as a separate issue, it may also bring financial benefits in future due to regulation of environmental impacts. Developers who are willing to adopt materials and methods with lower environmental impact earlier have time to undergo cost reduction through learning by doing before any such regulations force material or process changes.

The total cost increase due to a change in manufacturing method is complex, but since energy use is a major cost, manufacturing cost can be estimated in relative terms using the LCA model. Greenhouse gas emissions from the manufacturing phase of the life cycle are largely the result of energy use (since all raw materials are included in the materials category), so can therefore be used as a proxy for relative manufacturing cost. This data suggests that the manufacturing of the steel blade is the most costly in energy terms, around 2.5 times greater than any other case. This may offset the relatively low material costs highlighted in Table 6. The lowest manufacturing energy use occurred when the Heated Mould method was used, since although heating is still required, the vacuum pumping energy used in the VARTM and Monocoque methods is not required. This suggests that taking VARTM as a current baseline, a cost saving may be achievable by moving to the Heated Mould method. However, as discussed in Section 3.2.3, the powder resin used in this method may have significant environmental impacts.

4.1.2. Structural influence

Considering a turbine of the type described in Table 1, a change in blade design would be likely to require a number of significant changes to device design. These changes would have downstream impacts on cost and environmental impact, and it is important to consider blade decisions as part of holistic device design in order to avoid unexpected environmental or financial consequences. If a GFRP blade was changed to a Steel blade, the total increase in the mass of the blades would be 8 tonnes, representing approximately a 5% increase in nacelle mass. This would require additional stiffness in the support structure, causing a further increase in total mass. Additional gravity base support may also be required, possibly requiring the use of concrete, which has significant environmental impacts. The additional mass of rotating blades would require additional support in the gearbox, shaft support systems and mechanical brake. Heavier blades would directly impact the pitch control system, which rotates the blades about their central axis between each tide. A quantitative estimate of the additional mass and equipment resulting from an increase in blade mass is outside the scope of this study, but an assessment of a typical device suggests that almost every part of the drive system and support structure would require upgrading to cope with an increase in blade mass. One tonne of additional steel material alone would increase the total device greenhouse gas emissions by 1940 $kgCO_2e$ (15% of the total emissions of a single steel turbine blade).

Similarly, any reduction in blade mass may permit a reduction in support structure mass, or in the materials and manufacturing required in other components, which has the potential to reduce the environmental impact and cost of the device as a whole, and contribute to cost of energy reduction. Only limited data is currently available on the long-term structural performance of bio-based and recyclable composites [33], and the availability of this data will allow the quantification of these potential benefits.

4.2. Comparison with wind energy

A direct comparison between tidal stream energy and wind energy would need to account for differences in material selection, end of life treatment, capacity factor, installation location and numerous further details, but a broad indicative comparison can be made between the environmental impact of the two. Work undertaken in 2018 [34] calculated life cycle emissions for onshore, shallow offshore and deep offshore wind turbines of 5.84, 6.49 and 7.89 gCO_2e/kWh for turbines rated at 2.3 MW. Other studies [35] suggest that the contribution of turbine blades to the total emissions of a wind turbine are of the order of 10%. These values imply approximate emissions of between 0.6 and 0.8 gCO_2e/kWh attributable to wind turbine blades.

Tidal stream turbine blades in this study have emissions between 27,000 and 9000 $kgCO_2e$. Based on generation data from currently operating turbines [15], a 1 MW rated turbine may generate 0.07 TWh over a 20 year lifetime. This suggests blade emissions per unit generation of between 0.77 and 0.26 gCO_2e. These values are similar to or lower than those of wind turbines, and given the relatively early stage of the industry suggest that tidal stream energy has the potential for emissions per unit generation at least as low as those of wind energy. This comparison is indicative however, and a full comparative study is required.

5. Conclusions

The aim of this work was to consider for the first time at this level of detail the net environmental impact of a range of materials for tidal stream turbine blades, whilst also considering practical trade-offs in other parts of a tidal energy device, in order to determine the blade material and , manufacturing method and end-of-life treatment combination likely to have the lowest environmental impact. The following general conclusions can be drawn:

- Glass fibre epoxy composites are currently the most common material choice for tidal turbine blades. In many environmental impact categories, this material represents an average level of performance. In general, steel and carbon fibre composites have greater environmental impacts than glass fibre composites, and bio-based and recyclable products offer lower environmental impacts. Glass fibre composites appear to be one of the most expensive blade materials. This is due to a combination of mass requirement driven by material properties, and high specific material cost.
- All composite materials, when disposed of by depositing in landfill, produce significant ecosystem and human health impacts due the potential for release of metals in landfill runoff and nitrogen release. Incineration of composite materials contributes significantly to stratospheric ozone depletion, but relative to landfill has lower impacts in most other impact categories considered.
- When composite materials are manufactured using powder resin as in the heated mould method, the resin poses environmental risks at the manufacture and end-of-life stages. Powder resin includes additional ingredients such as titanium dioxide, which contribute to high particulate emissions and ozone impacts on human and terrestrial health. Of the methods considered here, the Monocoque method offers slightly lower environmental impacts than the VARTM method, but does require the facility to manufacture the blade as one complete unit.
- Carbon fibre allows turbine blades to be manufactured with a lower mass, which may permit reductions in environmental impact and cost in other parts of the turbine. However, carbon fibre causes greater greenhouse gas emissions per turbine blade than glass fibre, and has particularly high human and ecosystem health risks when deposited in landfill at the end-of-life. Carbon fibre is also the most expensive material option of those considered.

- A Hybrid blade with a high proportion of CFRP would have impacts close to those of a full CFRP blade. As in the full CFRP case, this light weight brings advantages such as reduction of gearbox and structure loads and reduced transport emissions, but these may not be sufficient to offset the significant emissions and environmental impacts associated with blades of this type.

- Steel offers reduced impacts in many categories compared to composite materials, and lower cost than conventional composites, but has significantly higher impact in categories related to terrestrial ecotoxicity and carcinogenic human health impacts, as well as high greenhouse gas emissions. The main disadvantage of steel blade manufacture is the mass, which is expected to drive additional impacts and emissions due to structural upgrades and increased material mass in other areas of the turbine to support the heavy blades. Steel appears unlikely to be a feasible solution for tidal turbine blades as the industry moves to larger devices, but may offer a lower cost alternative to composites for smaller devices.

- Recyclable epoxy resin allows the separation of resin and fibre at end-of-life and the recycling of resin as a thermoplastic. This reduces impacts associated with incineration or landfill and allows fibre and matrix to be reused. The recovery solution required increases material impacts, but the net impact is lower than conventional composite materials, provided the products are treated correctly at end-of-life. If disposed of by landfill or incineration, the net impact relative to conventional composites will increase. Recyclable resin presents a further advantage as the tidal stream energy sector grows, by directing waste away from landfill. This is likely to offer advantages in public perception of the sector as well as any direct environmental benefit.

- Bio-based fibres offer an alternative to carbon or glass fibres. This fibre material offered the lowest greenhouse gas emissions of any considered, and relatively low impacts across all measures. When used in combination with recyclable resin, it may be possible to further reduce impacts by reusing the fibre. Although currently a niche material, material costs do not appear to be as high as glass or carbon fibres, and engineering performance appears comparable.

Whilst individual blade design cases should be considered separately, these findings suggest that bio-based fibres and recyclable resin offer a way to reduce the environmental impact of tidal turbine blade manufacturing. The results show that this may be achievable without increasing cost or causing indirect environmental impacts via other parts of the turbine and that as these technologies develop, costs may be lower than current materials. These findings also suggest that certain combinations of materials, manufacturing methods and end-of-life treatment, such as the incineration of carbon fibre composites, should be actively avoided in order to reduce environmental risk.

CRediT authorship contribution statement

Stuart R.J. Walker: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Philipp R. Thies:** Conceptualisation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.118353.

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