Comparative Life Cycle Assessment of tidal stream turbine blades

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Abstract—**Renewable energy allows electricity generation with lower environmental and resource impact than generation from fossil fuels. However, the manufacture, use and ultimate disposal of the equipment used to capture renewable energy has an environmental impact. This impact should be minimised. Most tidal turbine blades are currently manufactured from glass or carbon fibre reinforced polymers. Such blades cannot be recycled at the end of their life, and are disposed of in landfill or by incineration. As the tidal energy industry grows, the volume of non-recyclable waste is a potential problem. Here we consider the environmental impact of ten combinations of material and disposal method for tidal stream turbine blades, including recyclable options.**

Our findings suggest that:

- **Glass fibre blades have greenhouse gas emissions of around 15,500 kgCO_2e for the scope considered, and a significant environmental impact in all impact categories.**
- **Steel blades are heavy and have greater material and manufacturing greenhouse gas emissions than glass fibre blades, but these are partly offset by recycling.**
- **Carbon fibre blades have the greatest impact of the cases considered in greenhouse gas, human toxicity, and marine toxicity. The impact is particularly large when disposed of in landfill.**
- **Composite materials using flax fibre and recyclable resin may have lower impact (26% lower greenhouse gas emissions than glass fibre), provided they are treated correctly after use. These materials may also offer the potential for lower cost blades in future.**

Index Terms—**Carbon footprint, Cost, Environmental impact, Life Cycle Assessment, Tidal turbine blades**

I. Introduction

DESPITE a short temporary reduction due to the COVID-19 pandemic, long term global electricity demand continues to rise. Demand is forecast to continue to grow at 3% or more per year [1]. As demand increases and governments work towards achieving targets for renewable energy generation, demand for tidal stream energy is expected to rise. Meeting this demand will require the manufacture, installation and operation of a significant number of new tidal stream turbines.

Electricity produced from tidal stream energy has lower greenhouse gas emissions per unit than fossil fuel generation, but as with all renewable energy sources, the manufacture of the extractor itself causes environmental impacts. These impacts are caused by raw materials, manufacturing processes, transport, installation, operation and decomissioning. One area of particular recent concern is waste production and disposal due to turbine blades [2] [3]. In the wind turbine industry, concern is growing over the number of turbine blades which require disposal as turbines reach the end of their lives. 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 1GW of installed capacity by 2030 suggests that around 6000 tonnes of blade waste will be produced when these devices reach the end of their lives. Alternatives to non-recyclable composite turbine blades do exist and have been considered in a few cases [4] [5] [6], for both tidal and wind turbines. These materials are either recyclable metal such as steel, recyclable composite materials which allow the resin and fibres to be separated and recycled, or materials which can be disposed of in other ways, such as biodegredation through industrial composting.

As tidal stream energy moves to reduce the cost of energy and allow competition with more established renewable energy technologies, a competitive advantage, can be achieved by understanding the environmental impact of critical parts like blades. If these factors are considered and design decisions are made at the current prototype stage, tidal stream energy may be able to achieve lower environmental impacts than other renewable electricity sources.

A. Aim

In this work, we aim to consider for the first time the net environmental impact of a range of materials and disposal methods for tidal stream turbine blades. We also consider material cost, in order to determine blade material and design combinations which reduce environmental impact from curent levels without increasing cost.

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II. Methodology

A. Generic blade model

To allow direct comparison between turbine blade materials, we used a generic blade design and geometry. This design was based largely on the turbine blade designed by NREL [7]. After consultation with device developers, a blade length of 8.85m was selected. In all material cases, blades included 21kg of polyurethane foam in the trailing edge section, the outer surface of the blade was protected by a gelcoat and alklyd-based paint, and 20 off 30mm diameter steel bolts were fitted to the root face.

1) Geometry: The NACA 63-424 profile was used, with 13° twist at the root and 2° twist at the tip. Two shear webs run along the full length of the blade with a shared spar cap. Blade sections illustrating the shear webs used are shown in Fig. 1, taken from the GFRP case.

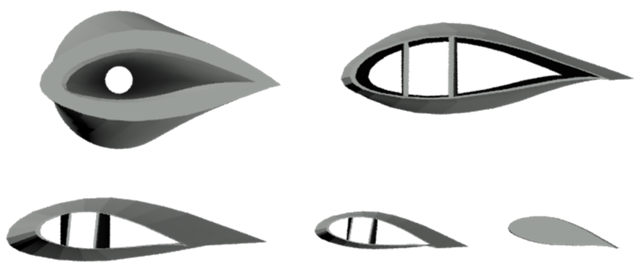

Fig. 1. Blade sections at (top, l-r) 1m, 3m, (bottom, l-r) 7m, 8m and 8.85m from root (GFRP material case)

2) Blade structural performance specification: To ensure a fair comparison between materials, we used a finite element model (constructed using AutoCAD 2021 and ANSYS 19.0) to determine the required material thickness to deliver equivalent stiffness to the GFRP base case and blade specification described in Section II-A. We calculated axial and tangential loads corresponding to a maximum load design flow velocity (v) of 4m/s, calculated as shown in Equations (1) and (2). F_A gives the axial force and F_T the tangential force at the blade tip.

$$F_{\mathrm{A}} = \frac{1}{2} A_{\mathrm{A}} \rho v^2 \tag{1}$$

$$F_{\mathrm{T}} = \frac{1}{2} A_{\mathrm{T}} \rho (v\lambda)^2 \tag{2}$$

Surface areas A_A and A_T were frontal areas as calculated from the CAD model. We assumed a tip speed ratio λ of 4 and seawater density ρ of 1027kg/m^3 (based on the mean annual temperature of 10.5°C at the European Marine Energy Centre). This gave loads of 88kN in the axial direction and 22kN in the tangential direction. An image of the deformed GFRP blade is shown in Fig. 2.

TABLE I
Material properties used in the finite element model comparison

	GFRP	CFRP	Flax RP	Steel
Density (kg/m^3)	1900	1200	1200	7850
Young's Modulus (Pa)	3.5x10^{10}	1.68x10^{11}	4.8x10^{10}	2x10^{11}
Poissons Ratio	0.3	0.3	0.3	0.3
Tensile strength (MPa)	900	1900	635	460

TABLE II
Material properties used in the finite element model comparison

Blade length (m)	Material	Mass (kg)	Deflection[a]
8.85	GFRP	2530	-
8.85	CFRP	1024	5.5%
8.85	Flax RP	1489	3.4%
8.85	Steel	5551	4.5%

[a] % difference to GFRP baseline case deflection.

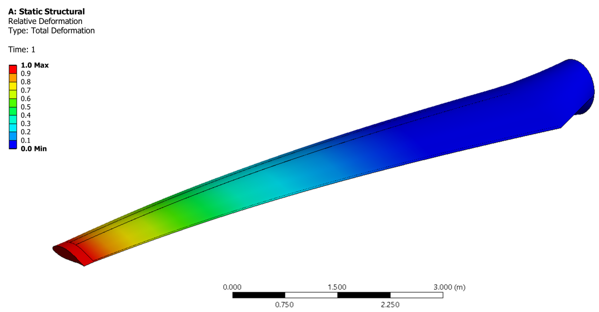

Fig. 2. Deformed result of GFRP blade

Material properties were set based on material data from previous studies [8] [9], as given in Table II-A2. For each 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 proportionally to the entire blade structure, whilst maintaining the original outer surface volume of the blade.

The calculated mass for each material case is given in Table II-A2. Masses given include foam filling, gelcoat and paint, 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. [9]) for similar materials and blade length. The potential for variation in properties due to manufacturing processes was not considered in these calculations.

B. Case studies

We developed LCA models for seven material cases:

1) Steel
2) Glass fibre with non-recyclable epoxy resin*
3) Carbon fibre with non-recyclable epoxy resin*
4) Flax fibre with non-recyclable epoxy resin*
5) Glass fibre with recyclable epoxy resin

6) Carbon fibre with recyclable epoxy resin
7) Flax fibre with recyclable epoxy resin

For steel we considered recycling to be the only viable end-of-life treatment. For reinforced polymers, we calculated the impact of landfill and incineration disposal for the cases with epoxy resin, and for the cases with recyclable resin we assumed the resin would always be recycled, and the fibre reused in the glass and carbon fibre cases, and disposed of via industrial composting in the flax fibre case. This gave a total of ten life cycle cases.

C. Material cases

We considered seven material combinations: Glass-fibre reinforced polymer (GFRP) with epoxy resin, as used by the majority of tidal and wind turbine device developers, Carbon-fibre reinforced polymer (CFRP) with epoxy resin, folded and formed Steel, Flax reinforced polymer with epoxy resin, and glass fibre, carbon fibre and flax fibre with recyclable resin. A number of manufacturing methods were considered for reinforced polymers, but here we only present results for blades manufactured using vacuum-assisted resin transfer moulding (VARTM), which is the most commonly used process [10]. This process involves pumping resin into a bag placed over the prepared fibre material, then using a vacuum to draw the resin into the fibre before curing. We assumed curing conditions of 8 hours at 80°C.

Literature and database LCIA data for GFRP materials was widely available. CFRP data was not as widely available, and the CFRP material model was developed from polyacrlylonitrile fibres (the precursor material used in the majority of carbon fibre production) and energy requirements of the stabalisation and carbonisation processes from literature [11] [12] [13]. Impact results for carbon fibre included in this study were found to agree well with previous studies.

Turbine blades are commonly manufactured in parts and joined using adhesive. Here we assumed the most commonly-used bonding agent, SpaBond 340LV HT [14]. This bonding agent is an epoxy resin and styrene based adhesive, so impact data was taken from a combination of these products. We calculated an adhesive mass of 397kg per blade, based on a 10mm diameter bead.

The manufacturing method assumed for steel was based on that developed by the 'HyBlade' project [6], and involves folding a shaped steel sheet, laser welding seams and hydroforming using an oil-water mixture. 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 laser welded to the main structure. At the end of life, steel blades were assumed to be recycled by shredding and adding to blast furnace products to make steel via the Basic Oxygen Steelmaking process.

In the recyclable resin cases, epoxy resin was replaced with the same mass of a thermoplastic resin which can be extracted from the composite material at the end of life. Here we used data from Adita Birla Chemicals [15]. 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 extract thermoplastic solution. The solution is then heated to and maintained at 80°C. On the manufaturer's advice, we assumed 12 hours at this temperature, after which 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, allowing the recovered resin to be rinsed, removed as a thermoplastic and recycled. We assumed that the thermoplastic resin would be recycled. 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 reused where strength and stiffness are less critical, so we assumed that this recovered fibre is reused elsewhere and that 1 kg of recovered fibre avoids the use of 0.5 kg of virgin fibre. We calculated the volume of recovery solution based on a hypothetical tank with dimensions 5% larger than the blade.

Finally, the flax reinforced polymer was assumed to be used in the same way as glass and carbon fibres in the manufacturing phase. At the end-of-life, flax fibres infused with epoxy resin cannot be recycled, so are disposed of in the same way as GFRP and CFRP. Flax fibres infused with recyclable resin can be extracted and we assumed that these fibres would be disposed of by biodegredation by industrial composting, as recommended by the manufacturer.

D. Life Cycle Assessment

Life Cycle Assessment (LCA) is a method used to assess the impact of a product or process on the environment by considering some or all of the materials, processes, and sub-products required to produce it. Resource and energy use in the materials and processes required throughout the life cycle are ascertained and combined to give data on the total impact of the complete product. Impact is not limited to greenhouse gas emissions (commonly called CO_2 footprint), and also includes categories such as land use, water use and human toxicity among many others.

In this study we used LCA to estimate the environmental impact of various combinations of material and end-of-life disposal in the manufacture of a tidal stream turbine blade, across eighteen impact categories. As in any model-based method, assumptions must be made to simplify reality to a level at which it can be simulated, which must be borne in mind when interpreting the results. This study was undertaken in accordance with ISO 14044 [16]. As defined by the standard, an assessment consists of four key parts: Goal and Scope, Inventory analysis, Impact assessment and Interpretation.

1) Goal & Scope: A functional unit defines the unit of comparison between cases in an LCA study. We selected one 8.85m turbine blade as our functional unit. The blade design was based on a three bladed horizontal axis tidal stream turbine rated at 1 MW (blade geometry is described in Section II-A). Only the turbine blade itself was considered in the LCA. A total of 28 combinations of materials, manufacturing processes and end-of-life treatment were considered. A 'cradle to dock; dock to grave' scope was used, including the manufacture of the turbine blade from raw materials, 100km road transport to a hypothetical dock, and the same distance at the end of life to landfill, incineration, recycling or processing site. The use phase of the blade (including the assembly of the turbine, marine transport to site, installation, operational use, maintenance, removal and marine transport to the dock) was not included. The turbine blade life cycle with included and excluded parts is shown in Fig. 3. Though there will be small differences between the blade material cases in the areas excluded from this study, the major differences in impact are expected to be due to materials, manufacturing and end-of-life treatment.

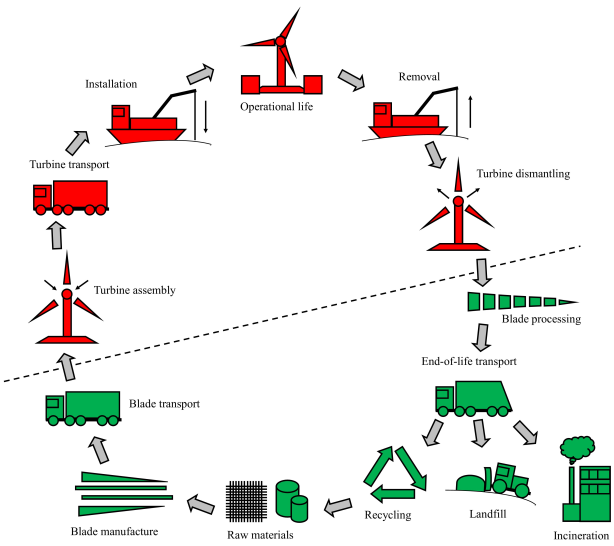

Fig. 3. Life cycle diagram for turbine blade illustrating stages included (green) and excluded (red)

2) Inventory Analysis: Inventory Analysis is the process of understanding the inputs and outputs of each process in the LCA model. We used SimaPro 9.1.1.1 software and a combination of primary and secondary inventory data sources. We used literature or manufacturer data wherever possible, and life cycle database data from the Ecoinvent v3.6, ELCD (European reference Life Cycle Database) and USLCI (U.S. Life Cycle Inventory) databases where literature did not provide a complete picture.

Energy use and emissions data for manufacturing, transport and end-of-life treatment was taken from the same databases and material and process profiles were modified where necessary.

3) Impact Assessment and Interpretation: The Life Cycle Impact Assessment (LCIA) quantifies the impact of each stage of the life cycle, using a series of impact categories. We used the fourteen categories recommended by the Product Environmental Footprint (PEF) methodology [17]. We used the ReCiPe 2016 Midpoint Heirarchist (version 1.04) impact assessment method [18], which gives impact results for the categories required by the PEF method as well as in four additional categories. Interpretation was carried out to the standards defined by ISO14044 and the PEF method.

III. Results

For the ten material combinations considered, we produced impact results across the eighteen impact categories of the ReCiPe 2016 Midpoint impact assessment method, which incorporates the fourteen impact categories recommended by the PEF LCIA method. The impact categories assessed were:

- Global warming potential
- Stratospheric ozone depletion
- Ionizing radiation
- Ozone formation (human health impact)
- Fine particulate matter formation
- Ozone formation (terrestrial exosystem impact)
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Human toxicity (carcinogenic)
- Human toxicity (non-carcinogenic)
- Land use
- Mineral resource depletion
- Fossil resource depletion
- Water consumption

A. Overall results

In order to consider results in a single metric, we ranked each case by calculating the number of impact categories in which it was the worst performer. Though this method does not consider the size of the difference in impact between cases, it gives a general overall view of which cases have significant negative impacts across the full range of LCIA impact categories. This calculation showed that:

- Steel performed worst in five categories
- Glass fibre performed worst in four categories
- Carbon fibre performed worst in nine categories
- Flax fibre did not perform worst in any categories

Carbon fibre cases performed worst in fossil resource depletion, in ozone formation categories when incinerated, and in some ecological (marine and freshwater ecotoxicity) and human health (non-carcinogenic toxicity) categories. Glass fibre performed worst in the water consumption categories. Steel performed worst in the mineral resource depletion, human carcinogenic toxicity, terrestrial ecotoxicity, freshwater eutrophication and particulate matter categories.

B. Energy use results

In addition to the LCIA impact categories, we calculated the total energy use in the materials, manufacture, transport and end-of-life treatment for each of the ten cases described in II-B. These results are shown in 4. Carbon fibre with either incineration of landfill at

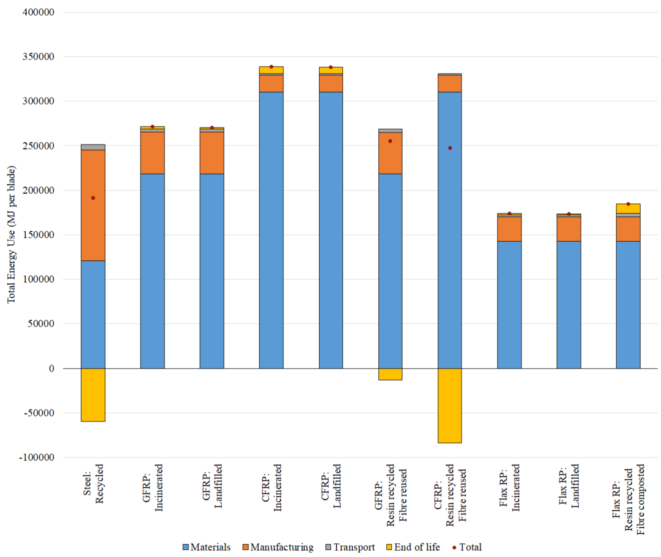

Fig. 4. Life cycle total energy use for ten turbine blade material and treatment cases

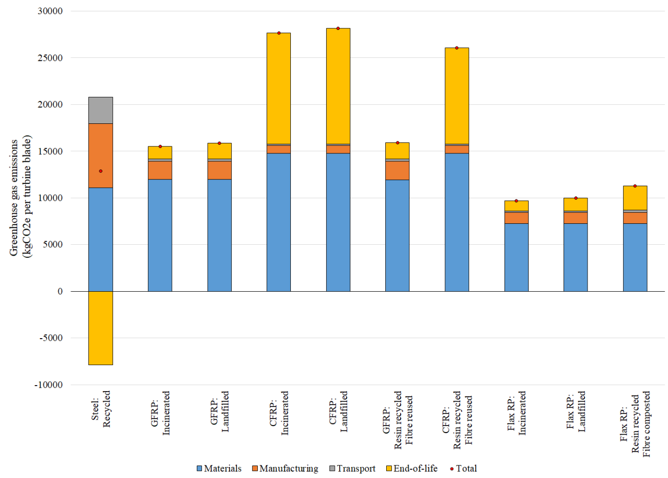

Fig. 5. Life cycle greenhouse gas emissions for ten turbine blade material and treatment cases

end-of-life has the greatest energy use of the cases considered. The incineration case had slightly higher energy use at 338,900MJ per blade. The lowest energy use results were in the Flax reinforced polymer cases, where the landfill and incineration cases both had energy use approximately half of that of the comparable carbon fibre cases. The composted flax fibre case results in 6% greater energy use due to the energy required to recover the flax fibre. Steel and the cases using recyclable epoxy offset energy which would be required to produce virgin materials, so receive an energy use credit at the end of life. This helps reduce the energy use of these materials below the level of the non-recycled equivalent.

C. *Detailed impact category results*

We next studied results in detail for key impact categories. Results are presented here for Greenhouse gas emissions and human toxicity (a combined total of carcinogenic and non-carcinogenic toxicity). These are key impact categories in the assessment of low-carbon electricity generation and material waste management respectively, and are generally regarded as important outputs from LCA modelling. We also present results for marine ecotoxicity and marine eutrophication, which are two important indicators of the potential for environmental damage to the marine environment. Although the impacts considered here are life cycle impacts and are not specifically impacts caused directly by the turbine when placed in the marine environment, marine ecological impacts are likely to be heavily scrutinsed as the tidal energy sector grows. For each blade material and treatment case we grouped sub-category impacts into four categories (raw materials, manufacturing, transport and end-of-life) to allow the identification of the sources of the greatest impact (see Fig. 5 to Fig. 8).

The turbine blade with the lowest life cycle greenhouse gas emissions is the flax fibre blade with epoxy resin and incineration at end-of-life, with total emissions for the life cycle stages considered of 9714 kgCO_2e per blade. The landfill flax fibre blade has emissions only 1% greater, and the flax fibre blade with recyclable resin and recycling and composting at the end-of-life have has emissions 16% greater.

The relatively low emissions of the flax cases is largely due to the relatively low impact of the raw materials (in comparison to carbon fibre for example, which has high materials and end-of-life emissions). The use of recyclable epoxy in the recyclable and compostable case does increase manufacturing energy due to the recovery solution, but this is offset by the end-of-life emissions avoided by the recyclability of the recovered thermoplastic.

Regarding the blade materials considered here, the case with the highest greenhouse gas emissions was the CFRP blade. Whether disposed of in landfill, by incineration or recovered through the use of recyclable resin, the carbon fibre blade causes greater CO_2 emissions than any other material case. The use of recyclable resin does significantly improve the impact of the CFRP blade relative to the landfill or incineration options. Despite the lower mass of the CFRP blade, end-of-life treatment by incineration or landfill has a much greater impact in the CFRP case than in the GFRP case. This is due to the high embodied greenhouse gas of the CFRP material. We calculated greenhouse gas emissions of CFRP to be 37.6 kgCO_2/kg, compared to 2.67 kgCO_2/kg for GFRP (similar to results by others [19] [13]).High greenhouse gas emissions from CFRP disposal are largely driven by the ingredients of the fibre material, and particularly the high embodied CO_2 of the polyacrylonitrile fibres which is released as the fibre breaks down in landfill or is incinerated.

Recyclable resin causes a small increase in most impact categories relative to epoxy resin, and a more significant increase in land use , but the avoidance of end-of-life disposal by landfill or incineration provides an offset greater than this impact. However, this does mean that if recyclable resin is used but the product is not recycled, the total impact will be greater than if epoxy resin had been used.

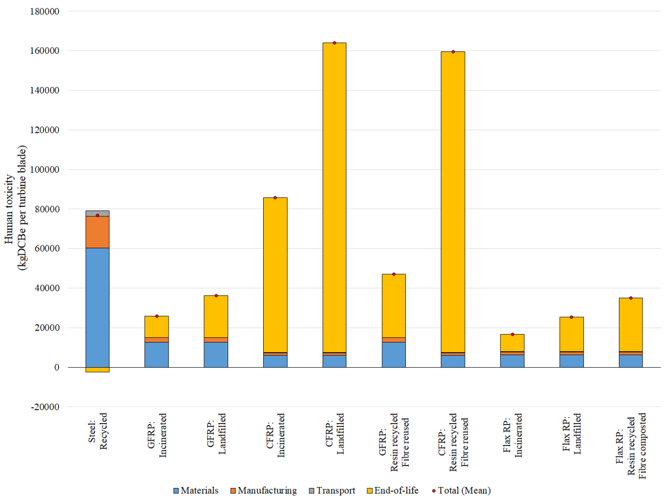

Fig. 6. Life cycle combined human health impacts for ten turbine blade material and treatment cases

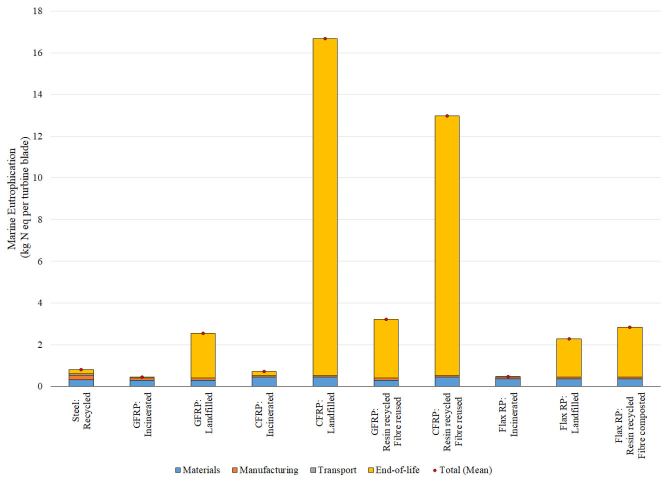

Fig. 7. Life cycle marine eutrophication impact for ten turbine blade material and treatment cases

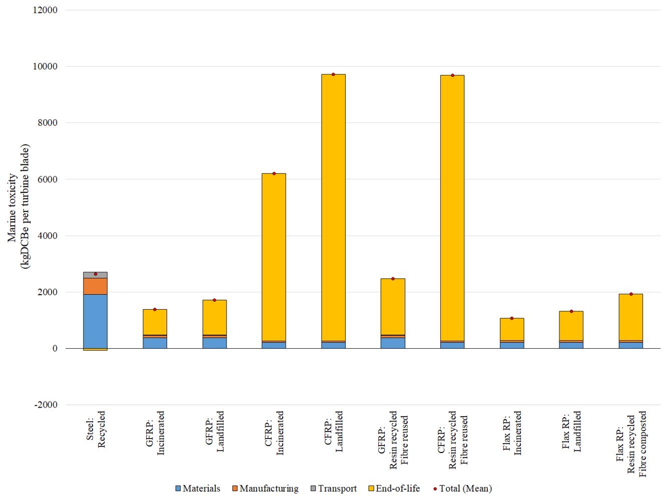

Fig. 8. Life cycle marine ecotoxicity impact for ten turbine blade material and treatment cases

Although incineration of CFRP has only marginally lower greenhouse gas emissions than landfilling of the material, human health implications are very different (see Fig. 6). Again CFRP is the most environmentally damaging material choice, particularly if sent to landfill. If incinerated at the end of life, CFRP life cycle human health impacts are similar to those of steel. The cause of the significant impact of carbon fibre in the landfill case is due to the potential for leakage of metals into water (primarily Zinc, but also Lead, Mercury and Aresnic), and the polyacrylonitrile fibres. Sulfidic leachate is particularly high (contributing around 43% of total toxicity). When manufactured using recyclable resin, carbon fibre composites still have significant human health impacts at end-of-life. This is largely due to the low quality of the recovered fibre material, which requires an equal mass of new carbon fibre to be manufactured in order to ultimately produce a high quality fibre, and thus brings the impact of carbon fibre manufacture into the end-of-life impact in this case. Aside from CFRP, steel has the greatest impact on human health, and it is notable that steel has by far the greataest carcinogenic health impacts of any case. In all other cases, carcenogenic impacts make up less than 4% of the total impact, whereas in the steel case where the figure is 13%.

Blades using the recyclable resin show low toxicity impacts since landfill is avoided, but the manufacture and disposal of the recovery solution does bring some toxicity risks, hence these blades have a slightly higher total toxicity impact than the non-recycled flax case.

The two marine ecology impact categories we considered (Fig. 7 and Fig. 8 show similar trends in results, and both show similar result trends to the human health impact results in 6. In both marine ecotoxicity and marine eutrophication, the CFRP blades again show the most negative environmental impact of the materials considered. In the marine eutrophication cataegory, CFRP end-of-life treatment by landfill causes over ten times greater end-of-life impact than incineration, again as a result of groundwater contamination risk, damaging runoff, and nitrogen release.

TABLE III
MATERIAL MASS AND RELATIVE COST ESTIMATE OF TURBINE BLADE (DATA FROM [8] [20] [21])

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

IV. Discussion

A. Cost

In addition to environmental impacts, we considered the material cost of the options included in this study. In the wind turbine industry, material and manufacturing cost is estimated to make up around 40% of total turbine costs [8]. 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 IV-A.

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 these 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.

Any change to an existing design, for example of materials or manufacturing method, is likely to increase cost and expose the developer and investors to additional financial risk in the short term due to equipment and training costs, and the loss of a competetive advantage and confidence in product reliability gained through experience of the previous technique or material. 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-understood material, but may allow access to improvements in environmental impact not achievable with current materials, which notwithstanding its importance as a separate issue, 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.

It is also very likely that a material change could affect other changes to device design, particularly if the new material has a significantly greater or lower mass. 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 the GFRP blade considered here was changed to a Steel blade, the total increase in the mass of three blades would be around 8 tonnes, representing approximately a 5% increase in nacelle mass. This would require additional stiffness in the support structure, potentially modifications to gearbox and pitch control systems, and may demand additional gravity base support, all of which would increase the environmental impact of the complete device. 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. It is notable that one additional tonne of steel raw material would increase the total device greenhouse gas emissions by around 1950 kgCO_2e, equivalent to almost 10% of the total emissions of a current GFRP turbine blade.

V. Conclusions

By assessing ten material and end-of-life treatment cases using LCA, we have identified the most environmentally damaging and least environmentally damaging cases. We have also considered cost, and found that the material with the lowest environmental impact also has the potential to be the cheapest. However, this study was based on a single case study blade, and only one manufacturing method was considered. We suggest the study should be expanded to include manufacturing methods and the full product life cycle. We draw the following conclusions from this work:

- 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, and bio-based and recyclable products offer lower environmental impacts, as well as the potential to reduce blade mass and cost.
- All composite materials, when disposed of by depositing in landfill, produce significant ecosystem and human health impacts due to the potential for release of metals in landfill runoff and nitrogen release. Incineration of composite materials contributes signifcantly to stratospheric ozone depletion, but the impact of end-of-life disposal by incineration on marine ecology is relatively low. With a marine ecology focus, incineration appears to offer the lowest impact method of disposal for non-recyclable materials.
- Carbon fibre allows lower mass turbine blades to be manufactured, 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.
- Steel offers reduced impacts in many categories compared to composite materials, but has significantly higher impact in categories related to terrestrial ecotoxicity and carcenogenic human health impacts, as well as high greenhouse gas emissions. The largest downside of steel blade manufacture is the mass, which is likely to drive additional impacts and emissions in the wider turbine due to required upgrades to support the comparatively heavier blades. Thus, steel appears unlikely to be a feasible solution for tidal turbine blades as the industry moves to larger devices.
- Recyclable 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. The recovery solution required has a large land use requirement, 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.

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

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