

Advancing tidal turbine blade manufacturing: Exploring current and alternative manufacturing methods

Ione LM Smith^{1,2} , Edward D McCarthy^{2,3}, Conchúr M Ó Brádaigh^{3,*} , Philipp R Thies⁴ , Selda Oterkus⁵ and Winifred Obande³

Proc IMechE Part L:

J Materials: Design and Applications

1–14

© IMechE 2025



Article reuse guidelines:

sagepub.com/journals-permissions

DOI: 10.1177/14644207251384754

journals.sagepub.com/home/pil



Abstract

Rotor blades are critical components of tidal energy converters, typically manufactured from thermoset fibre-reinforced composite (FRC) materials using vacuum infusion processing. High load demands result in thick-section laminates (10–100 mm), particularly at the blade root, posing manufacturing challenges. While tidal and wind turbine blades appear similar in design, the fundamentally different operational conditions result in distinct structural differences and, therefore, manufacturing requirements, offering opportunities for the tidal sector to innovate. Advances in materials and manufacturing technologies provide potential to rethink current practices for improved design and process efficiency. Additionally, the relative immaturity of tidal technology allows for early integration of circularity principles, minimising waste and optimising resources. This paper serves as a comprehensive resource for the tidal turbine blade sector, reviewing current manufacturing practices and exploring alternative techniques. Combining knowledge from academic literature and industrial reports, it outlines blade design, material selection, and current manufacturing processes. The paper evaluates emerging techniques and potential modifications to established methods. Due to the range of turbine designs in the sector, optimal materials and manufacturing combinations will differ. This study offers manufacturers valuable insights to support informed and strategic choices to improve and advance tidal turbine blade production.

Keywords

Composite manufacturing, thick-section composites, vacuum infusion, tidal turbine blades, turbine blades, renewable energy

Received: 19 June 2025; accepted: 6 August 2025

Introduction

Tidal energy holds significant potential as a reliable renewable energy source. The practical resource in the UK and British Channel Islands is estimated at 34 TWh/year, equal to around 11.5 GW of installed capacity.^{1,2} While technology across the sector varies, rotor blades are essential to most tidal stream energy converters. In addition to being continuously submerged in saltwater, tidal turbine blades endure high cyclic loads, requiring the use of thick-section laminates (10–100 mm), especially in the root.^{3,4}

Tidal turbine blades are widely manufactured from fibre-reinforced epoxy thermoset composite materials using vacuum infusion processing.^{3–7} Sustainability concerns around thermoset materials have driven the development of alternative resins such as liquid thermoplastic and recyclable thermoset resins.^{7–9} Although many of these resins have been designed as direct replacements in current manufacturing methods, the use of alternative resins provides the opportunity to utilise different manufacturing methods. Considering material selection and manufacturing processes together as opposed to two separate entities is essential in enabling more efficient engineering and cost-efficient production.

The literature on blade manufacture primarily focuses on wind turbine blades or improvements to conventional

manufacturing processes. However, the distinct operational conditions of tidal turbines subject blades to significantly higher loads, meaning that wind turbine blade designs cannot be directly transferred, thus limiting the applicability of current

¹EPSRC and NERC Industrial CDT in Offshore Renewable Energy (IDCORE), The University of Edinburgh, Edinburgh, EH9 3FB, United Kingdom

²FastBlade, Dunfermline, KY11 2XH, United Kingdom

³School of Engineering, Institute for Materials and Processes, The University of Edinburgh, Edinburgh, EH9 3FB, United Kingdom

⁴Faculty of Environment, Science and Economy, Engineering, University of Exeter, Penryn Campus, Penryn, TR10 9FE, United Kingdom

⁵PeriDynamics Research Centre, Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, G4 0LZ, United Kingdom

*The current affiliation of co-author Conchúr M Ó Brádaigh: Department of Materials Science & Engineering, Faculty of Engineering, University of Sheffield, Sir Robert Hadfield Building, Mappin Street, Sheffield S1 3JD, United Kingdom

Corresponding author:

Winifred Obande, School of Engineering, Institute for Materials and Processes, The University of Edinburgh, The King's Buildings, Edinburgh, EH9 3FB, United Kingdom.

Email: w.obande@ed.ac.uk

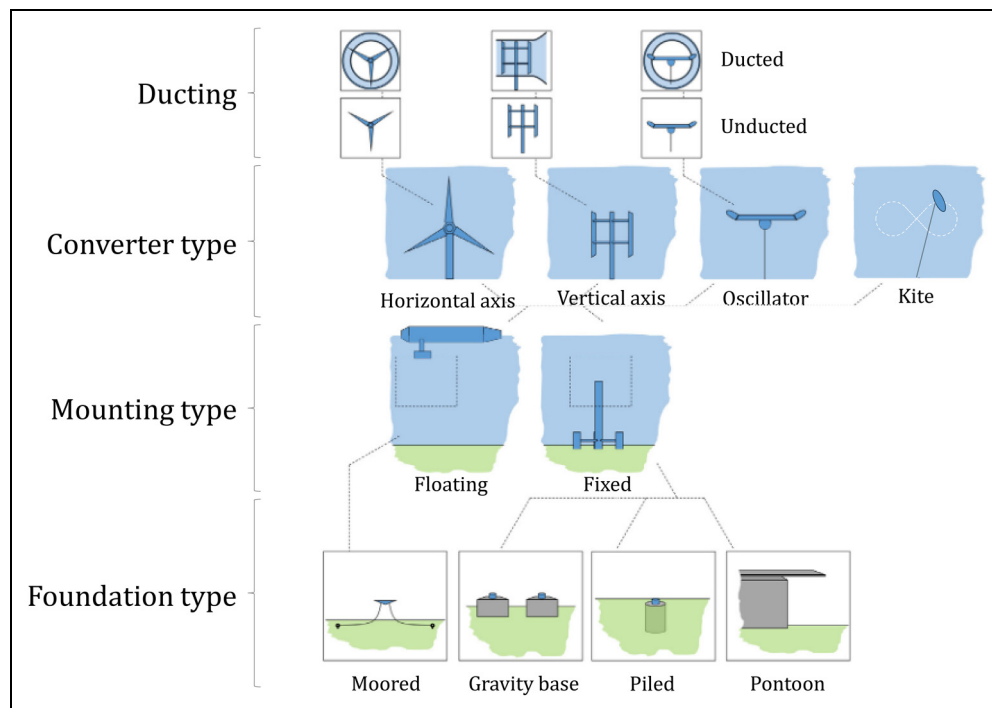


Figure 1. A summary of tidal energy converter devices. Adapted from Walker and Thies.¹¹

approaches. For blades of equivalent length, these higher loads necessitate different design principles and material selection strategies for tidal turbine blades compared to wind turbine blades. In parallel, the need to reduce the relatively high Levelised Cost of Energy (LCOE) of tidal energy calls for more efficient designs, reduced material usage and costs, and improved processing efficiency. As large-scale, well-established blade manufacturers remain focused on the wind energy sector, there is an opportunity and need for small-to-medium-sized enterprises (SMEs) to contribute to the development of tidal blade technology. As these firms enter an unfamiliar and emerging market, access to consolidated and reliable technical information becomes essential.

Therefore, the aim of this paper is to provide a comprehensive resource for manufacturers in the tidal turbine sector, both established and new entrants, reviewing current blade manufacturing practices and exploring the applicability of alternative techniques and materials. Drawing on academic literature and industry reports, while acknowledging that much proprietary information remains within the private commercial domain, this paper outlines current blade design considerations and material selection strategies. It reviews existing manufacturing and assembly processes, then examines emerging technologies and potential adaptations to established composite manufacturing methods. The study evaluates the potential for these alternatives to advance the commercial manufacture of tidal turbine blades, offering practical insights aimed at improving manufacturing efficiency and reducing costs.

Tidal energy converters

Energy can be harnessed from tides using tidal range or tidal stream converters. Tidal range systems typically take the form of tidal barrages, dam-like structures with turbines at

their base that capture the energy from the changing water level of the tides. Tidal stream technology exploits energy from the horizontal movement of tidal currents, driven by the ebb and flow of the sea, and is considered in this paper.^{10–12} The sector has seen a diverse range of technologies developed, tested, and deployed around the world, demonstrated by Figure 1. Most tidal stream devices are horizontal axis turbines, which may be mounted on floating structures with the turbines operating near the top of the water column, or on fixed platforms located on the seabed.^{13,14} While some developers have deployed fewer, larger devices, and others have implemented a greater number of smaller turbines, tidal turbine blades remain crucial components in most designs, as demonstrated in Figure 2.

Blade design

Although tidal and wind turbine blades may appear similar in overall form, their design requirements diverge significantly due to the distinct operational environments in which they function. The greater density of water compared to air allows tidal turbines to generate more power than wind turbines with similar blade dimensions.^{17,18} Tidal turbine blades are typically 2 m to 10 m in length, whereas the longest manufactured wind turbine blade is currently 131 m.^{19–24} Within the tidal energy sector blade design varies depending on factors such as rated power and therefore size, position in the water column and site specific conditions. Both wind and tidal turbine blades begin with a circular root and transition into an aerofoil profile that tapers along the length, as illustrated in Figure 3.^{3,17,25,26} Due to the shorter overall length of tidal turbine blades, this transition in cross-sectional profile occurs over a smaller distance. This results in rapid changes in stresses, requiring the redistribution of load away from the root into structural elements such as shear webs and spar

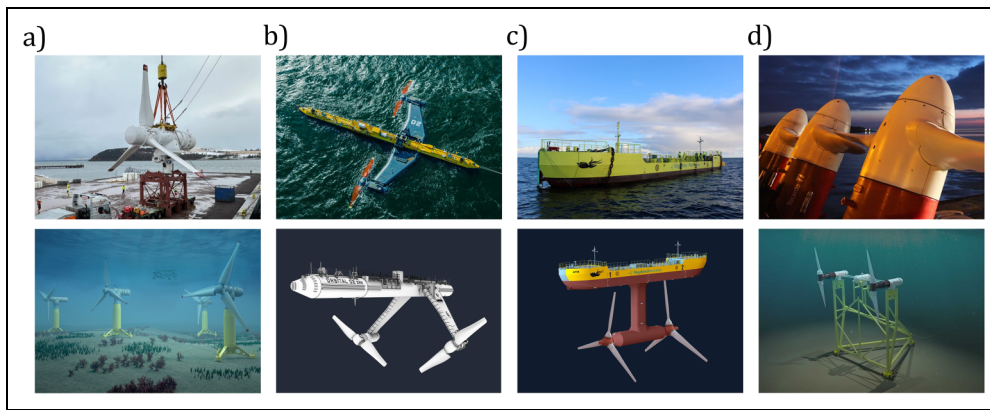


Figure 2. Tidal turbine devices deployed or scheduled for deployment in the UK by various developers. a) MeyGen - Proteus Marine Renewables, b) Orbital Marine Power, c) Magallanes Renovables, d) HydroWing - QED Naval - Tocardo. **Image credits:** a) Provided by MeyGen and Proteus Marine Renewables; used with permission. b) Provided by Orbital Marine Power; used with permission. c) Provided by Magallanes Renovables; used with permission. d) From van Unen,¹⁵ HydroWing¹⁶; used with permission from Tocardo and Inyanga Marine Energy Group.

caps.^{3,17,25,26} Operating in turbulent marine environments with high flow speeds, tidal turbine blades experience spatially and temporally varying loadings driven by the combined effects of shear, turbulence, and wave-induced velocities.^{17,18,27–30} These high loads necessitate balancing the pressure difference between the blade's exterior and interior, which is sometimes achieved by filling the cavity with foam. Additionally, the continuous exposure of the blade skin to saltwater poses risks of material degradation and water absorption, which can compromise the blade's mechanical properties over time.^{3,17,25,26,30,31} Priorities in design therefore differ between tidal and wind turbine blades. Whilst minimising weight is highly important for wind turbine blades, for instance, strength and fatigue resistance are arguably more critical in tidal turbine blades.

To address these challenges and minimise the risks of intervention in difficult operating conditions, tidal turbine blades are designed with thick laminate sections to enhance structural resilience, Figure 3. Definitions of what constitutes a thick-section laminate vary in the literature, with reported thicknesses ranging from 10 mm to 100 mm. These values typically depend on the position along the blade, with the root exhibiting the greatest skin thickness due to the combined effects of blade weight, hydrodynamic loading, and resulting bending moments.^{3,4} Factors such as site specific operating conditions and design parameters, including overall size, geometry, and reinforcement strategy, have direct influence. Material selection also has a significant impact, e.g., a glass fibre-reinforced composite part will need to be thicker to achieve the same strength properties as its carbon fibre-reinforced counterpart.^{4,18,32–34}

Material selection

Fibre-reinforced composites (FRCs) are generally used in tidal turbine blades due to their high specific strength and stiffness and corrosion resistance, where a resin matrix is reinforced with fibres. While carbon fibres (CFs) offer higher strength than glass fibres (GFs), their higher costs renders the resulting composite parts more expensive. The selection of CFs or GFs is, therefore, driven by performance

requirements, design and economics and a combination of the materials is sometimes used. Fibres are combined with a thermoset-matrix polymer resin, generally epoxy, to form a FRC. Glass fibre-reinforced polymers (GFRPs) are commonly used for the skin of the blade as they are a more cost-effective option for a large surface area, while carbon fibre-reinforced polymers (CFRPs) are used for high-strength or high-stiffness components such as the root or spar.^{17,25,27}

Thermosets have traditionally been the preferred matrices for composite applications because of their excellent manufacturability, good mechanical properties, environmental resistance, and low cost. The cross-links in thermosets provide the durability and structural resilience required for tidal turbine blade components. However, these same bonds typically prevent melting and reshaping, which are essential characteristics for many conventional recycling processes that are applicable to thermoplastics. Although several solutions are under development, there are currently no large-scale recycling technologies for managing decommissioned turbine blades, so blades are incinerated or disposed

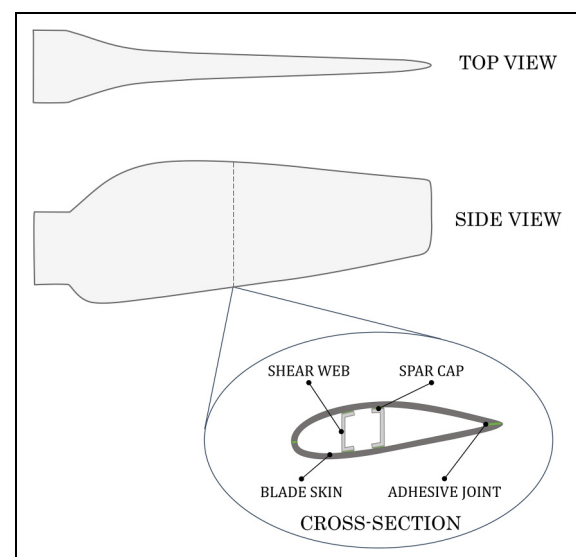


Figure 3. General design of a tidal turbine blade.

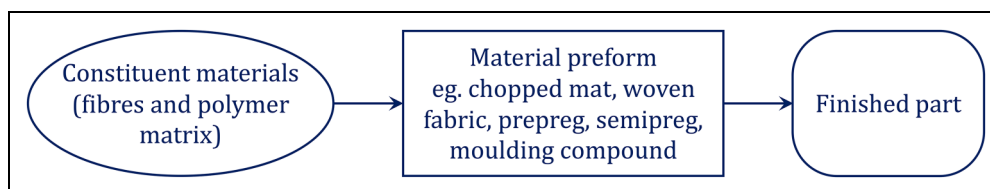


Figure 4. Process from constituent materials to finished part.

of in landfill if they are not repurposed. At present, the waste generated by the tidal energy industry is relatively low due to the limited number of deployed devices, most of which are yet to reach their end-of-service-life (EOSL). Nevertheless, it is estimated that 1 GW of tidal energy capacity will result in around 6,000 tonnes of blade waste. Predictions indicate that the UK will have 0.9 GW of installed tidal capacity by 2035, highlighting the significant potential for waste generation.^{14,35}

Although turbine-blade recycling solutions are under development, many remain at a low technology readiness level (TRL), are expensive, or impose other detrimental environmental impacts.^{7,9} As this rapidly expanding field lies beyond the scope of the present paper, this section instead provides an overview of inherently recyclable resin materials suitable for tidal turbine-blade manufacture. The ability of thermoplastics to be melted and reformed offers the opportunity to recycle parts at their EOSL. While thermoplastics offer superior toughness, impact resistance and favourable out-of-plane properties, they are generally solid at room temperature. The requirement for high temperatures and pressures to overcome their high melt viscosities during processing limits their applicability.^{36–39} Recent advances in recyclable liquid thermoplastic resins (LTPRs), such as Elium[®], demonstrate strong potential to directly replace epoxy in current vacuum infusion manufacturing processes.^{5–8,26,40,41} These acrylic-based resins can be processed at ambient temperatures due to their low viscosity and undergo in-situ polymerisation without the need for external heat input. Resulting parts typically exhibit high strength, toughness, impact resistance and ductile failure behaviour.^{36,40,42–45} LM Wind Power, a subsidiary of GE Renewable Energy Business, produced a wind turbine blade from Elium[®] as part of the ZEBRA (Zero wastE Blade ReseArch) project. They are now planning to conduct structural lifetime testing and assessment of recycling methods.^{46–48} Meanwhile, National Renewable Energy Laboratory (NREL) produced tidal turbine blades using Elium[®], measuring 2.5 m in length, which were deployed in Verdant Power's test site in New York's East River for six months.^{26,49,50} The testing showed incompatibilities of the LTPR with epoxy foam currently used in epoxy blades. Although initial tests indicated that epoxy paints were suitable for use, areas on the blade that were missing paint were noted at the end of submersion testing. The blades also exhibited adhesive failure along the leading edge, initiated between the FRC skin and the epoxy foam in the cavity. The research highlights the importance of further development to ensure the compatibility of these resins with foams, adhesives, and overlay resins, which might be used in production.²⁶

Significant progress is being made in the development of recyclable thermosets comprising degradable or dynamic covalent bonds that are recycled using thermal techniques or

chemical factors such as solvents.^{7,9} Commercial recyclable epoxy-based materials include Recyclamine[®] (Aditya Birla^{51–53}), EzCiclo (Swancor^{54–56}), Vitrimax (Mallinda⁵⁷), and the Reprocessable, Repairable, and Recyclable (3R) resin system (CIDETEC^{58–60}).⁹ These systems are designed to work with existing manufacturing processes and are offered in either prepreg or liquid resin formats, depending on the specific product. In 2020, Siemens Gamesa produced RecyclableBlade wind turbine blades using Recyclamine. These blades were installed by REW in the Kaskai Offshore Wind farm in 2022 and later in the Sofia Offshore Wind Farm, Dogger Bank.^{9,61–64} MingYang Smart Energy used EzCiclo to develop wind turbine blades.^{9,65} Swancor, the producers of EzCiclo, signed a letter of intent with Siemens, and from 2026, all resin supplied to Siemens will be recyclable, contributing to RecyclableBlade and increasing Siemens' capacity.^{66,67} Additional environmental concerns regarding the energy-intensive processing of epoxy resins include the use of toxic compounds, high carbon dioxide emissions, and the reliance on finite petrochemical resources.^{68,69} These issues have prompted research into bio-based resins as alternatives.^{68–71} Although some projects are evaluating the suitability of bio-resins for blade manufacturing, they seem to have a lower TRL than those discussed previously.^{72–74} Although recent advances in recyclable thermosets focus on wind turbine blade production, they show great promise for the future of tidal turbine blade manufacturing.

Material selection and manufacturing methods interdependency

Depending on the manufacturing method employed, precursor materials can take various forms as shown in Figure 4. Innovations in alternative resins, composite reinforcement forms and novel manufacturing methods, have significantly expanded the range of manufacturing options. Integrating material selection with manufacturing processes and capabilities during development facilitates alternative and potentially more efficient structural design.

In the literature, manufacturing methods are commonly categorised by fibre length, reinforcement form, resin form or resin type (thermoset or thermoplastic). While these factors are connected, this review will classify materials based on their form at the point of infiltration. For the purpose of this review, the following material forms are the main classes considered, though the list is not exhaustive.

- **Liquid resin:** The resin takes a liquid form at the point of infiltration, and fibres are a separate entity in a dry

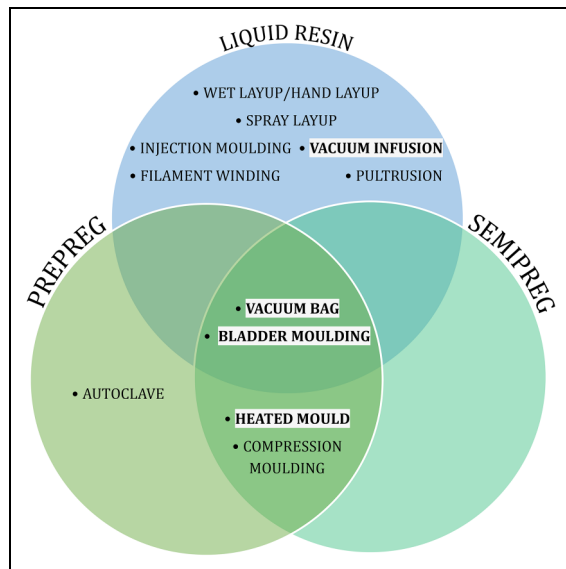


Figure 5. Composite manufacturing methods classified by material form at point of infiltration. Highlighted processes will be further reviewed in this study.

preform. The resin and fibres are combined during part manufacture, where resin flows into the fibrous preform.

- **Pre-impregnated material, ‘Prepreg’:** Reinforcement fibres or fabrics are impregnated with resin to create a partially consolidated material. This material may take the form of tape, tow, mats, or fabrics. Since the fibres are already impregnated, the resin requires minimal flow during manufacture to achieve full consolidation and form the final part.
- **Semi-impregnated material, ‘Semipreg’:** Fibres are interspersed with resin, which may be in the form of powder granules, strips, or commingled materials. Localised resin flow is necessary during manufacturing to achieve full consolidation and form the final part.

Figure 5 categorises composite manufacturing techniques and their use with different material system forms. Highlighted processes will be discussed in further detail in the following sections, and their suitability for the manufacture of tidal turbine blades will be assessed.

Current blade manufacturing and assembly

Tidal turbine blades are widely manufactured using vacuum infusion processing. Each blade is formed of two shells, which are individually produced using vacuum infusion before being joined together. To create each shell, a gel coat is first applied to a single-sided mould to protect the dry fibres. Fibres, in the form of mats or fabrics, are then placed into the mould. Root inserts and spar caps are positioned before laying additional dry fibres. Specific areas of the blade, such as the root, will typically be reinforced with more layers of fibre. Fibre orientations may be varied in certain regions of the blade to tailor mechanical properties. The fibres are then infused with resin, as described in the “*Vacuum infusion*” section, and later demoulded to leave a shell. Structural reinforcements, such as shear webs, are then attached, and the two shells joined together using

structural adhesive. Joining and the potential to manufacture blades as a single piece is discussed in more detail in the “*Removing the need for joining*” section. Additional materials or overlay resins may be applied to the leading edge for additional protection. Finally, the entire blade is post-processed, applying coatings such as filler, primer and paint. In some cases, the blade is then filled with foam.^{4,8,26,35,75,76}

Vacuum infusion

Vacuum infusion processing relies on the extraction of air to create a vacuum, which assists the continuous flow of low-pressure resin into dry fibres and consolidates the laminate. As outlined previously, dry fibres are placed into a mould and manufacturing aids are laid on top of the layup. These are generally single-use consumables. Resin inlet and vacuum outlet ports are carefully installed. An impervious layer of plastic film (vacuum bagging) is then draped over and sealed to the tool. The general layup sequence for vacuum infusion and the purpose of each consumable are summarised below.^{77–82}

- **Dry fibres:** Preform, e.g., chopped mat, woven fabric.
- **Peel-ply:** Porous layer that enables the vacuum to extract air and volatiles from the layup. Can be used to create a textured surface on the part.
- **Perforated release film (if applicable):** Enables the separation of consumables from the layup once the part has cured or polymerised. May be required for certain infusion media.
- **Infusion medium:** Sometimes referred to as infusion mesh/net, flow mesh/net or distribution medium. Typically used to assist the flow of resin across the surface of the fibre layup, before infusing through the thickness. A wide range of products is available, including extruded and knitted meshes.
- **Vacuum bagging film:** A broad selection of films are available for different applications with varying temperature limits.

To infuse the part, a pot of resin is connected to an inlet port using a feed line, normally positioned at the opposite end of the layup to the vacuum outlet to ensure resin flow through the fibrous preform by the vacuum, as demonstrated in Figure 6. When the laminate is fully infused, the inlet and outlet tubes are clamped, maintaining the vacuum in the bag. The material is left to solidify, and a post-processing heat treatment may be applied to enhance properties, as required for certain thermoset-matrix materials.^{77–82}

A summary of potential input materials for vacuum infusion is provided in Table 1. An evaluation of strengths and weaknesses associated with the process is provided in Table 2. Vacuum infusion is a well-established process and is commonly used in the manufacture of wind and tidal turbine blades, as well as small-scale production of small yachts. The process can be described using different names, and in the context of blade manufacture, is often referred to as Vacuum Assisted Resin Transfer Moulding (VARTM). There is a wide range of consumables and resin types available for different applications to ensure compatibility. Larger parts may require innovative gate strategies, where multiple

Table 1. Input materials and tooling requirements for vacuum infusion.^{26,77–79}

	Liquid resin
Resin	- Generally epoxy, unsaturated polyester, vinyl ester, phenolic (all thermosets) - Liquid thermoplastics, e.g. acrylic or polyamide reactive monomers
Fibres	- Any dry fibre preform e.g. woven fabrics, cloths, rovings - Any material
Mould tool	- Two halves, one fixed and one flexible

Table 2. Strengths and weaknesses of vacuum infusion.^{33,77–79,83}

Strengths	Weaknesses
- Ability to process large components of good quality; high fibre volume fraction, relatively low void content, good wetting of fibres. - Tailorability of mechanical and thermal performance is largely driven by resin selection.	- Expertise required for process design (e.g. location of resin inlet and vacuum ports) to ensure optimum flow and minimisation of defects. - Control of resin dependent on operator. - Difficult to keep unidirectional fibres straight during infusion. - Requires a relatively high volume of disposable components.

resin inlets are used to control the flow front of the resin. The location of these points is largely dependent on the part geometry. Vacuum infusion process optimisation is a significant area of research and development with various operating parameters strongly related to the part shape and design. As such, process-specific expertise is required.

Manufacturing challenges

Thick-section laminates occur throughout tidal turbine blades, particularly at the root, as discussed in the “*Blade design*” section. Conventional composite manufacturing challenges, such as incomplete fibre wetting, insufficient ply consolidation and trapped air are intensified in thick-laminate sections. These issues can lead to the formation of voids, uneven material curing or polymerisation, and dimensional inconsistencies. For liquid resins, there is a risk of variation in resin flow across the part, while prepreg materials may require multiple debulking stages to eliminate trapped air.^{4,32,77,79} Managing heat effectively during the production of thick-section laminates is critical and complex. Significant heat generated by exothermic reactions can result in defects, shape distortions, and uneven residual stresses, which arise from temperature gradients between plies.^{4,79,84,85} This heat generation is due to the cross-linking during curing in thermosets and free radical polymerisation in monomeric thermoplastics.^{44,85–87} Thicker laminates make it more difficult for generated heat to dissipate, prompting the development of low-exotherm resins, some of which

are targeted for wind and marine applications, where thick-section composites are frequently used.

Innovations such as Gurit’s SPRINT[®] address some of these challenges. These materials incorporate a pre-cast, pre-catalysed resin film positioned between layers of dry fibres that have not yet been impregnated with resin. As such, they are classified as a semipreg in this review. Designed for use like conventional prepreps, they require a vacuum bag and the application of heat to achieve the form of the final part. When a vacuum is applied, air is evacuated from the fibre bundles and between layers through the dry fibre network. Increasing the temperature allows the resin to soften and flow into the dry fibres. The resulting void content is very low – typically quoted between 0% and 0.5%.^{77,87,88}

Without proper management of the manufacturing process, laminates may exhibit deformation, defects, and undesirable residual stresses, leading to reduced and variable mechanical properties through the thickness. To mitigate the risk of failure and compensate for uncertainties in material properties, conservatively high design factors are applied. While this approach enhances reliability, it also increases material usage and cost, and may exacerbate the aforementioned challenges.

Alternative manufacturing methods

Although vacuum infusion is widely used to manufacture wind and tidal turbine blades, new materials and the relative immaturity of the tidal sector provide the opportunity to re-evaluate current practices. The remainder of this study will discuss alternative manufacturing methods that could be used in the production of tidal turbine blades.

Vacuum bag and oven

The vacuum bag process shares similarities with vacuum infusion but is used with prepreg or semipreg material forms, as outlined in Table 3. Figure 6 may be referenced for the general layout, with the following adaptations: the resin flow inlet is excluded, prepreg or semipreg plies are used

Table 3. Input materials and tooling requirements for vacuum bag and oven.^{77–79,89}

	Prepreg or Semipreg
Resin	- Generally epoxy - Thermoplastics
Fibres	- Any that form a prepreg or semipreg
Mould tool	- Two halves, one fixed and one flexible

Table 4. Strengths and weaknesses of vacuum bag and oven.^{33,77–79,89}

Strengths	Weaknesses
- Robust process, tool dimensional tolerance and repeatability. - Ability to process large components of good quality. - Ability to maintain straight fibres in spar and root using prepreg.	- Material cost high versus non impregnated input materials (additional storage costs). - Tooling must withstand higher temperatures than resin infusion since tool must be placed inside the oven. - Requires a relatively high volume of disposable components.

Table 5. Input materials and tooling requirements for heated moulding.^{4,27,32,90}

	Prepreg or Semipreg
Resin	- Heat-curable resins that can be incorporated into prepreg or semipreg form prior to part manufacture - Thermoplastics and thermosets
Fibres	- Fibres that can be incorporated into prepreg or semipreg form prior to part manufacture - Glass, carbon
Mould tool	- Two fixed halves and flexible inner

Table 6. Strengths and weaknesses of heated moulding.^{4,27,32,90}

Strengths	Weaknesses
- Increased fibre volume fraction results in lighter and more durable parts. - Suitable for high-quality, high-volume production. - Potential to cure the blade in one piece. - Mechanical properties of parts manufactured from powder epoxy superior to equivalent vacuum infusion laminates. - If using thermoplastic powder semipreg – easy to store and no exothermic reaction.	- Patented process. - Labour intensive, especially if using multiple sacrificial bags. - Difficult to achieve target vacuum levels with ceramic tooling. - High temperatures needed to process powder epoxy (~180 °C) or thermoplastic powders (>200 °C).

instead of a dry fibre preform. Plies are assembled into the mould, with rollers used to eliminate air pockets between them. A layer of release film is typically applied before bagging the layup and drawing a vacuum. Prepreg and semipreg materials require the application of heat to soften the impregnated resin, enabling it to flow into the fibres. The entire setup can then be placed in an oven.^{77,78,89}

The strengths and weaknesses of using the vacuum bag process with an oven are evaluated in Table 4. The vacuum bag process is commonly used with prepreg materials to manufacture large components, such as large yachts and train components. Whilst the majority of wind turbine manufacturers utilise vacuum infusion and liquid resin, Vestas are reported to use prepregs.⁸ Using prepreg material with vacuum bagging and applied heat can offer advantages comparable to autoclave processing, in which high heat and pressure are applied in a sealed vessel to produce high-quality parts. Although autoclaving is relatively costly, vacuum bagging

– when used with prepreg materials and carried out in an oven – may enable significant cost and energy savings. Where cost and infrastructural constraints are key decision-making drivers, manufacturers may realise near-autoclave benefits by combining vacuum bagging and heating, achieving a standard of quality that is well-suited for the intended application, albeit slightly lower than the highest attainable quality. Improved laminate quality further enables component design optimisation – for example, through the use of thinner, higher-quality sections that achieve the same structural performance as thicker, lower-quality laminates, which would likely contain more defects. Although the prepreg materials that deliver this enhanced quality are relatively expensive, the higher material cost may be offset by a reduction in overall material consumption.

Heated moulding

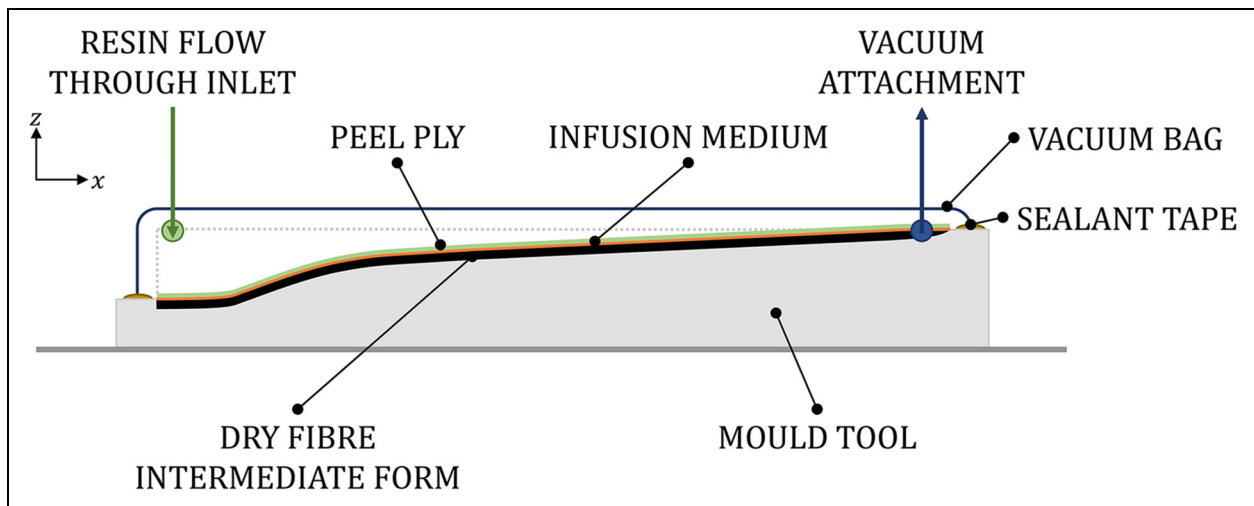
A heated ceramic-FRC mould was developed by ÉireComposites for use with semipreg materials, comprising fibres and heat-curable powdered resin or prepregs, as summarised in Table 5. Layers of the semipreg are placed into a ceramic-FRC mould, Figure 7(a), with the option to place layups for individual components in sacrificial vacuum bags, which provide additional consolidation. Applying a vacuum to the inside of the tool forces the bags outwards, taking the form of the tool, Figure 7(b). Heat is then applied

Table 7. Input materials and tooling requirements for bladder moulding.^{92–99}

	Liquid resin, Prepreg or Semipreg
Resin	- Thermoplastics
Fibres	- Dry fibres as fabric - Carbon, glass, aramid
Mould tool	- Two fixed halves and flexible inner

Table 8. Strengths and weaknesses of bladder moulding.^{92–99}

Strengths	Weaknesses
- Good control over fibre volume fraction. - Good consolidation of layup due to pressure resulting in higher strength parts. - Tunable process for shape, weight, strength, stiffness, toughness. - Potential to automate – ability to lay down preform quickly. - Potential for reduced labour and waste versus traditional prepreg methods.	- Limits on size of structure and thickness due to clamping pressure required. - Potentially more suited for parts of constant/similar cross-section. - Expense and limited durability/reusability of bladder.

**Figure 6.** Cross-section of vacuum infusion setup for a tidal turbine blade shell. An air gap is shown between the layup and vacuum bag for illustrative purposes; in practice, the bag conforms to the layup as air is evacuated, creating a vacuum.

to the top and bottom surfaces of layups using a combination of tool heating and hot air injection into the tool cavity. These conditions are maintained until the part has fully cured or polymerised, after which, it is left to cool before demoulding.^{4,27,32,90,91}

The heated mould process outlined in this section was designed specifically to manufacture wind and tidal turbine blades and is suitable for both thermoset and thermoplastic materials. This indicates significant potential, and the tool has been used to produce wind turbine blades.⁹¹ Although the combination of ceramic and FRC materials was intended to create a strong tool that can withstand multiple uses at high temperatures, the porous nature of ceramics considerably limits the tool's vacuum integrity, highlighted in Table 6. If this porosity were reliably resolved, the process could enable blades to be produced with shorter cycle times, reduced labour, as well as manufacturing the blade as a single piece, eliminating the need for adhesive and joining.⁹¹ This is discussed further in the “*Manufacturing a blade as a single piece*” section.

Bladder moulding

The initial setup of the bladder moulding process depends on the shape of the final part. If the prepreg or semipreg preform can be made in a near-net shape, such as a tubular section, the bladder is first inserted into the hollow preform. This assembly is then placed into the lower half of the mould, and the upper half is closed over it. Alternatively, if the preform cannot be shaped in this way due to its geometry, it is laid into both

the open lower and upper mould halves. The deflated bladder is positioned on top of the preform in the lower half, and the two mould halves are then clamped together. This method may be more suitable for components non-uniform in shape, such as tidal turbine blades, demonstrated in Figure 8. In both cases, air is introduced into the bladder, which expands and presses the preform against the mould surfaces, forcing it to conform to the shape of the tool. Heat is then applied through the mould, and, combined with the bladder pressure, this promotes resin flow while debulking and consolidating the layup.

The bladder moulding process can also be adapted for use with liquid resin and dry fibre preforms, replacing the prepreg or semipreg materials used in the previous method. As before, the initial layup depends on the final part shape. When using liquid resin, it is injected into the mould after the bladder has been inflated.^{92–99} Possible input materials for bladder moulding are detailed in Table 7. The bladder can be made from silicone rubber, polyamides (nylon), latex rubber, or polyetheretherketone (PEEK) with material choice determined by part geometry, processing temperatures, cost, and intended service life (reusability).^{93–95}

Some setups incorporate air and water cooling channels in the tool, which are activated after the target temperature is reached, reducing it to the demoulding threshold. Once cooled, the bladder air supply is shut off, allowing the bladder to deflate. It is then withdrawn from the end of the part, which is subsequently post-cured if required.^{92–99}

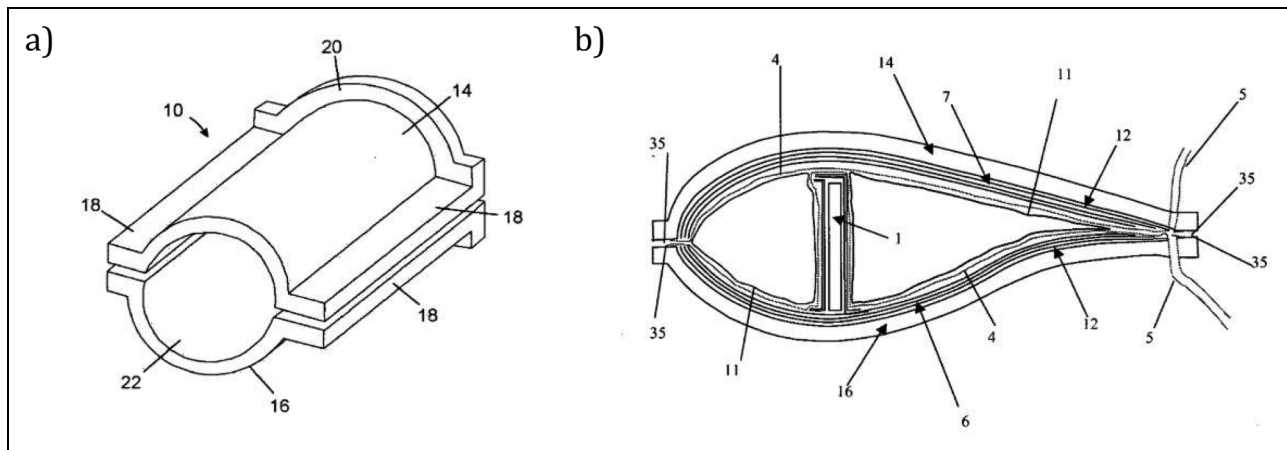


Figure 7. a) Heated FRC-ceramic mould tooling developed by ÉireComposites. b) Cross-section of the closed tool showing the blade shell and spar. Sacrificial bags have been applied before closing the tool.⁹⁰ Images used with permission.

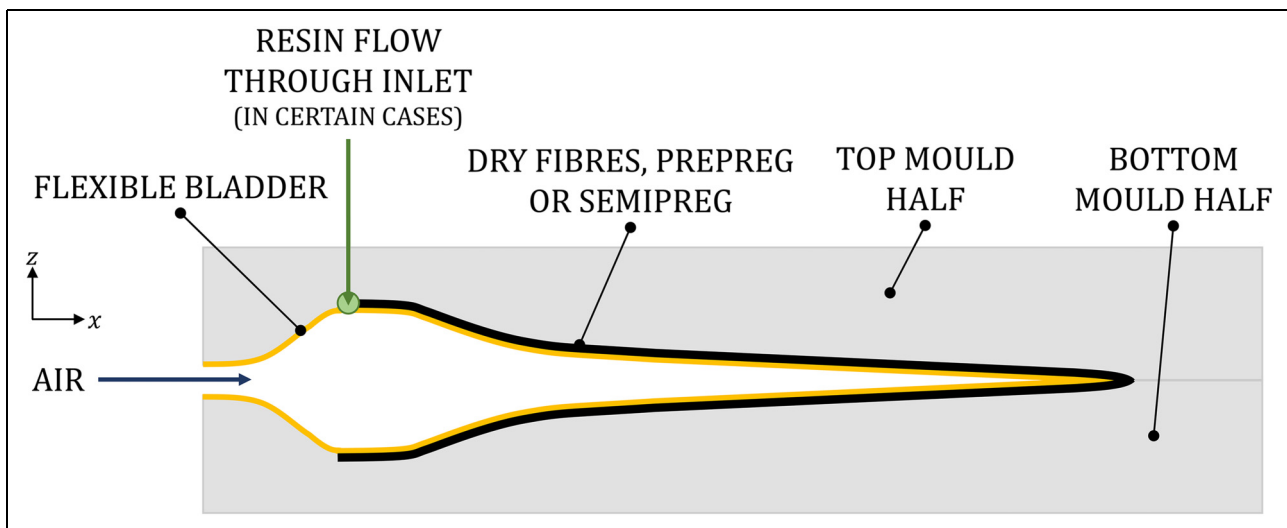


Figure 8. Cross-section view of bladder moulding process for a tidal turbine blade.

Bladder moulding is evaluated with respect to its strengths and weaknesses in Table 8. The process is currently used to manufacture hollow parts for various sectors including automotive, maritime and rail. This technology could be suited to producing tidal turbine blades in one piece, particularly for smaller structures. Heat can be applied by heating the entire tool, much like the heated moulding method discussed in the previous section, “*Heated moulding*”, or, more efficiently, by locally heating the surface closer to the part.^{90,95} Siemens’ IntegralBlade[®] utilises bladder moulding with liquid resin for manufacturing of large, one-piece wind turbine blades. The entire manufacturing setup is a closed mould process, and only one mould is required for the entire manufacturing process to create a wind turbine blade of 115 m in length.^{100–103} The use of a silicone bladder on the internal face of the part results in higher pressure on the layup, yielding better consolidation and a higher-strength part. This offers the potential to reduce the laminate thickness in a tidal turbine blade.^{90,104}

Removing the need for joining

Wind and tidal turbine blades are typically manufactured from two vacuum-infused composite shells. Structural

reinforcements and shear webs are bonded to spar caps using adhesive, which are then attached to the shells. Finally, the two shells are joined along the leading and trailing edges using additional adhesive. The adhesive is, therefore, load-bearing, and the strength of the bond line is integral to the structural integrity of the blade.^{8,105–107}

In wind turbine blades, bond lines can be up to 30 mm thick along a 70 m blade, adding significant weight and material cost to the structure.^{8,27,105,106} The large adhesive thickness can lead to high temperatures and thermal gradients during curing due to exothermic reactions, resulting in variable properties across the bond line. Thick joints also require extended curing times, increasing overall process time. As such, both thermal and time management are critical to ensuring consistent bond quality and maintaining manufacturing efficiency. Epoxy adhesives are widely used due to their high strength, dimensional stability, and suitability across a broad temperature range. To avoid complex repair operations during the service life of a blade, ensuring compatibility between the adhesive joints and FRC skins is essential.^{8,9,105–107}

Using thermoplastic resins in the manufacture of blade skins provides the opportunity to use welded joints,

eliminating the need for adhesives or mechanical fasteners and thereby reducing potential weaknesses at joint interfaces. Welded joints could offer greater strength and significantly reduce process time than adhesive joining. However, most welding methods require close contact between parts, which can be challenging for large, complex structures such as blade skins. Additionally, joining thick sections presents further difficulties.^{9,44,108,109} Resin welding has been investigated as a joining method in which dry fibres are placed along the joint of polymerised skins and infused with liquid thermoplastic resin using vacuum infusion, without requiring heat or post-processing.¹⁰⁸ At the joint interface, the fresh resin partially dissolves the polymerised matrix, enabling re-polymerisation and the formation of a homogenous material. The study observed that resin welding achieved comparative lap shear strengths to traditional adhesives at a bond line thickness of 1 mm. Although adhesive strength was substantially higher at a bond line thickness of 0.5 mm, it was found to be highly affected by thickness, decreasing sharply as thickness increased.¹⁰⁸ The authors suggest that resin welding may therefore be suited to thicker bond lines found in turbine blades, supporting further development of the method for use in large-scale structures.

Manufacturing a blade as a single piece. Manufacturing blades as a single piece eliminates risks associated with joints, bonds and weld lines, while reducing dependence on part tolerances.²² Methods such as heated moulding, “*Heated moulding*”, and bladder moulding, “*Bladder moulding*”, lend themselves well to this design. The Siemens IntegralBlade[®] utilises a manufacturing method similar to bladder moulding (outlined in the “*Bladder moulding*” section), with the application of heat, to produce GFRP wind turbine blades using liquid epoxy resin. The same technology has been applied to create their RecyclableBlade, using Recyclamine-based epoxy resin.^{61,62,100–103} As part of the European Tidal Stream Industry Energiser Project (TIGER), a team from the University of Edinburgh, FastBlade, and Tocado Turbines manufactured four monolithic tidal turbine blades for QED Naval. Each blade measures approximately 3 m in length, and the new structural design has been reported to reduce weight, material usage, and manufacturing costs.^{22,110}

Conclusions

Tidal turbine blades are conventionally manufactured from thermoset fibre-reinforced (FRC) materials using vacuum infusion processing. While much of the existing literature focuses on the manufacture of wind turbine blades, the apparent design similarities between wind and tidal blades are outweighed by the markedly different operational conditions and scale, leading to distinct manufacturing requirements and presenting opportunities for the tidal sector to adapt lessons from other industries with transferable technologies. Innovations in constituent materials and their forms, advances in manufacturing processes, and the entry of new manufacturers into the blade sector create scope to question and enhance current manufacturing and assembly methods. The relative commercial immaturity of tidal technology allows circularity to be considered from the initial stages, adopting a systems approach that aims to minimise environmental impact and waste whilst maximising the

utility of resources across the entire product lifecycle. When considering material selection and manufacturing process together, the combination of thermoset FRC materials and vacuum infusion may not be the most suitable, with potential for improvements in part quality, structural performance, and material efficiency.

This paper presents an overview of current materials, vacuum infusion manufacturing, and assembly processes to guide new and existing entrants to the sector. In particular, the review of material advances applicable to tidal turbine blades highlighted that while there is significant potential, further development is required to ensure FRC blade shells are of suitable quality and compatible with other components. Compatibility may be achieved by modifying the blade shells or by adapting adhesives, fillers, and paints to suit the shell material, ensuring long-term durability. A range of composite manufacturing processes was considered, with three alternative methods evaluated for their suitability in tidal turbine blade production. Among these, the use of prepreg or semipreg materials combined with vacuum bagging and oven curing emerged as the most viable alternative to vacuum infusion of liquid resin, with minimal further development required. This method may offer similar benefits to autoclave processing but at a lower cost, making it a promising approach for improving tidal turbine blade manufacturing. Given the diversity of turbine technologies in the sector, the optimal combination and selection of materials and manufacturing methods will vary. This study equips manufacturers to make informed, strategic decisions that will ultimately enhance tidal turbine blade production.

ORCID iDs

Ione LM Smith  <https://orcid.org/0009-0008-9820-0815>
 Conchúr M. Ó Brádaigh  <https://orcid.org/0000-0002-8048-4222>
 Philipp R Thies  <https://orcid.org/0000-0003-3431-8423>
 Winifred Obande  <https://orcid.org/0000-0001-7367-7272>

Ethical considerations

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Author contributions

Ione L. M. Smith: Conceptualisation, methodology, project administration, investigation, formal analysis, validation, visualisation, writing - original draft preparation, writing - review and editing.

Edward D. McCarthy: Conceptualisation, validation, supervision, writing - review and editing.

Conchúr M. Ó Brádaigh: Conceptualisation, validation, supervision, writing - review and editing.

Philipp R. Thies: Conceptualisation, validation, supervision, writing - review and editing.

Selda Oterkus: Conceptualisation, validation, supervision, writing - review and editing.

Winifred Obande: Conceptualisation, validation, supervision, writing - review and editing.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors are grateful to EPSRC and NERC for funding for the Industrial CDT for Offshore Renewable Energy (EP/S023933/1) [I.L.M.S.] and financial support from the School of Engineering, University of Edinburgh through an Elizabeth Georgeson Fellowship [W.O.].

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability

Not applicable.

References

1. Coles D, Angeloudis A, Greaves D, et al. A review of the UK and British channel islands practical tidal stream energy resource. *Proc R Soc A: Mathem Phys Eng Sci* 2021; 477: 20210469.
2. The University of Edinburgh School of Engineering Policy and Innovation Group. Future economic potential of tidal stream & wave energy in Scotland [online]. https://www.policyandinnovationedinburgh.org/uploads/3/1/4/1/31417803/future_economic_potential_of_tidal_stream_and_wave_energy_in_scotland.pdf, 2025.
3. Jaksic V, Ó Brádaigh CM and Wallace F. Upscaling of tidal turbine blades: Glass or carbon fibre reinforced polymers? In: *Proceedings of the 12th European wave and tidal energy conference (EWTEC)*, 2017, pp.1–5, 27 August–1 September 2017. Cork, Ireland.
4. Finnegan W, Allen R, Glennon C, et al. Manufacture of high-performance tidal turbine blades using advanced composite manufacturing technologies. *Appl Compos Mater* 2021; 28: 2061–2086.
5. Chen J, Wang J and Ni A. Recycling and reuse of composite materials for wind turbine blades: An overview. *J Reinfor Plast Compos* 2019; 38: 567–577.
6. Carnicero R, Cano L and Cruz I. Lessons learned from the sustainable recycling process of a wind blade made with a new thermoplastic resin. *J Phys: Confer Ser* 2024; 2767: 072008.
7. Leon MJ. Recycling of wind turbine blades: Recent developments. *Curr Opin Green Sustain Chem* 2023; 39: 100746.
8. Nixon-Pearson O, Greaves P, Mamalis D, et al. WP4 – D1.1. Wind turbine blades design and manufacturing, current state-of-the-art literature review. Technical report, ORE Catapult, 2022.
9. Mishnaevsky L. How to repair the next generation of wind turbine blades. *Energies* 2023; 16: 7694.
10. Roberts A, Thomas B, Sewell P, et al. Current tidal power technologies and their suitability for applications in coastal and marine areas. *J Ocean Eng Marine Energy* 2016; 2: 227–245.
11. Walker S and Thies PR. A review of component and system reliability in tidal turbine deployments. *Renew Sustain Energy Rev* 2021; 151: 111495.
12. Zeiner-Gundersen D. Turbine design and field development concepts for tidal, ocean, and river applications. *Energy Sci Eng* 2015; 3: 27–42.
13. Ocean Energy Systems (OES). Tidal current energy developments highlights 2023, 2023. <https://www.ocean-energy-systems.org/publications/oes-brochures/document/tidal-current-energy-developments-highlights-2023/>.
14. Noble DR, Grattan K and Jeffrey H. Assessing the costs of commercialising tidal energy in the UK. *Energies* 2024; 17: 2085.
15. van Unen A. QED Naval and HydroWing acquire Tocado Tidal Power [online], 2020. <https://tocado.com/qed-naval-and-hydrowing-acquiring-tocado-tidal-power/> (2020, accessed 03 June 25).
16. HydroWing. HydroWing Technology [online]. <https://hydrowing.tech/hydrowing-technology/> (2025, accessed 03 June 25).
17. Kennedy CR, Jaksic V, Leen SB, et al. Fatigue life of pitch- and stall-regulated composite tidal turbine blades. *Renew Energy* 2018; 121: 688–699.
18. Gonabadi H, Oila A, Yadav A, et al. Structural performance of composite tidal turbine blades. *Compos Struct* 2021; 278: 114679.
19. QED Naval Limited. Tocado Tidal Turbines [online]. <https://qednaval.co.uk/technology/> (accessed 08 May 2025).
20. Marine Scotland Assessment. Case Study: Nova innovation - shetland tidal array [online]. <https://marine.gov.scot/sma/assessment/case-study-nova-innovation-shetland-tidal-array#:text=The%20rotor%20diameter%20is%209,5%20m%20to%2025%20rpm.> (accessed 08 May 2025).
21. SAE Renewables. MeyGen [online]. <https://saerenewables.com/tidal-stream/meygen/> (accessed 08 June 25).
22. Edinburgh Innovations. New Scottish blade a ‘step change’ for tidal energy industry [online]. <https://edinburgh-innovations.ed.ac.uk/news/new-scottish-blade-a-step-change-for-tidal-energy-industry> (2023, accessed 24 January 2025).
23. Ocean Energy Europe. MAXBlade project to develop world’s largest tidal turbine blade [online]. <https://www.oceanenergy-europe.eu/industry-news/maxblade-project-to-develop-world-s-largest-tidal-turbine-blades/#:text=MAXBlade%20will%20increase%20the%20length,their%20kind%20in%20the%20world.> (2023, accessed 08 June 25).
24. Recharge News. ‘Longest on land’: monster 131-metre wind turbine blade rolls out of Chinese factory [online]. <https://www.rechargenews.com/wind/longest-on-land-monster-131-metre-wind-turbine-blade-rolls-out-of-chinese-factory/2-1-1589282> (2024, accessed 08 June 2025).
25. McEwen LN, Evans R and Meunier M. Cost-effective tidal turbine blades. In *4th International Conference on Ocean Energy*, 2012, pp.1–5. Dublin, Ireland.
26. Murray RE, Beach R, Murdy P, et al. Structural characterization of deployed thermoplastic and thermoset composite tidal turbine blades. Technical Report NREL/TP-5000-88713, National Renewable Energy Laboratory, 2024.
27. Finnegan W, Allen R, Glennon C, et al. Smart affordable composite blades for tidal energy. In: *11th European wave and tidal energy conference*, 2015, pp.1–8. Nantes, France.
28. Lam R, Dubon SL, Sellar B, et al. Temporal and spatial characterisation of tidal blade load variation for structural fatigue testing. *Renew Energy* 2023; 208: 665–678.
29. Kennedy CR, Leen SB and Ó Brádaigh CM. A preliminary design methodology for fatigue life prediction of polymer composites for tidal turbine blades. *Proc Inst Mech Eng Part L: J Mater: Design Appl* 2012; 226: 203–218.
30. Carrere N, Tual N, Bonnemains T, et al. Modelling of the damage development in carbon/epoxy laminates subjected to combined seawater ageing and mechanical loading. *Proc Inst Mech Eng Part L: J Mater: Design Appl* 2018; 232: 761–768.

31. Mishnaevsky L, Branner K, Petersen HN, et al. Materials for wind turbine blades: An overview. *Materials* 2017; 10: 1285.
32. Glennon C, Flanagan T, Doyle A, et al. Development of novel manufacturing techniques for composite tidal turbine blades. In: *SAMPE Europe Conference 18*, 2018, pp.1–8. Southampton, UK. Society for the Advancement of Material and Process Engineering.
33. Maguire JM, Sharp ND, Pipes RB, et al. Advanced process simulations for thick-section epoxy powder composite structures. *Composit Part A: Appl Sci Manufact* 2022; 161: 107073.
34. Bir GS, Lawson MJ and Li Y. Structural design of a horizontal-axis tidal current turbine composite blade. In: *ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering*, 2011, volume 5, pp.797–808. Ocean Space Utilization; Ocean Renewable Energy. Rotterdam, The Netherlands.
35. Walker SR and Thies PR. A life cycle assessment comparison of materials for a tidal stream turbine blade. *Appl Energy* 2022; 309: 118353.
36. Obande W, Mamalis D, Ray D, et al. Mechanical and thermomechanical characterisation of vacuum-infused thermoplastic- and thermoset-based composites. *Mater Des* 2019; 175: 107828.
37. Bhudolia SK, Joshi SC, Bert A, et al. Flexural characteristics of novel carbon methacrylate composites. *Composit Commun* 2019; 13: 129–133.
38. Teuwen JJ, Van Geenen AA and Bersee HE. Vacuum-infused anionic polyamide-6 composites: The effect of postprocessing. *J Thermoplast Compos Mater* 2012; 25: 965–986.
39. Chen BR, Deitzel JM and Gillespie JW. Micro-mechanical fiber waviness development in thermoplastic carbon fiber reinforced composite processing. In: *Proceedings of the American Society for Composites - 38th Technical Conference*, 2023, pp.1–11. Woburn, Massachusetts.
40. Murray RE, Beach R, Barnes D, et al. Structural validation of a thermoplastic composite wind turbine blade with comparison to a thermoset composite blade. *Renew Energy* 2021; 164: 1100–1107.
41. Kumar V, Elen M, Sushmita K, et al. Hygrothermal aging and recycling effects on mechanical and thermal properties of recyclable thermoplastic glass fiber composites. *Polym Compos* 2024; 0: 1–18.
42. Obande W, Ray D and Ó Brádaigh CM. Viscoelastic and drop-weight impact properties of an acrylic-matrix composite and a conventional thermoset composite – A comparative study. *Mater Lett* 2019; 238: 38–41.
43. Arkema. Elium[®] brochure 2024 [online]. https://www.arkema.com/global/en/products/product-finder/product-range/incubator/elium_resins/ (2024, accessed: 05 June 2025).
44. Obande W, Ó Brádaigh CM and Ray D. Continuous fibre-reinforced thermoplastic acrylic-matrix composites prepared by liquid resin infusion – A review. *Compos Part B: Eng* 2021; 215: 108771.
45. Bandaru AK, Hickey S, Singh D, et al. Influence of hygrothermal ageing on the novel infusible thermoplastic resin reinforced with quadriaxial non-crimp glass fabrics. *J Thermopl Compos Mater* 2023; 36: 3813–3836.
46. Offshore Engineer. 100% Recyclable: World's Largest Thermoplastic Wind Turbine Blade Made in Spain [online]. [https://www.oedigital.com/news/495107-100-recyclable-world-s](https://www.oedigital.com/news/495107-100-recyclable-world-s-largest-thermoplastic-wind-turbine-blade-made-in-spain)
47. GE. ZEBRA project achieves key milestone with production of the first prototype of its recyclable wind turbine blade [online]. <https://www.ge.com/news/press-releases/zebra-project-achieves-key-milestone-with-production-of-first-prototype-of-recyclable-wind-turbine-blade> (2022, accessed 12 June 2025).
48. offshorewindbiz. First Fully Recyclable Wind Turbine Blade Rolls Out [online]. <https://www.offshorewind.biz/2022/03/17/first-fully-recyclable-wind-turbine-blade-rolls-out/> (2022, accessed 12 June 2025).
49. energyposteu. New thermoplastic blades for coastal Tidal Energy turbines [online]. <https://energypost.eu/new-thermoplastic-blades-for-coastal-tidal-energy-turbines/> (2021, accessed 05 June 2025).
50. Office of Energy Efficiency & Renewable Energy. Tidal Power Turbine Demonstrates Thermoplastic Blades [online]. <https://www.energy.gov/eere/water/articles/tidal-power-turbine-demonstrates-thermoplastic-blades> (2022, accessed 12 June 2025).
51. Aditya Birla. Recyclamine [online]. <https://www.recyclamine.com/> (accessed 30 January 2025).
52. Aditya Birla. Recyclamine Technology [online]. <https://www.abg-am.com/portfolio/chemistry/recyclamine-technology/F008?tab=1> (accessed 05 June 2025).
53. Aditya Birla. Recyclamine [online]. <https://www.adityabirlachemicals.com/brand/recyclamine> (accessed 05 June 2025).
54. JEC. Swancor launched recyclable thermosetting epoxy resin “EzCiclo”, leading to zero-carbon era [online]. <https://www.jeccomposites.com/news/spotted-by-jec/swancor-launched-recyclable-thermosetting-epoxy-resin-ezciclo-leading-to-zero-carbon-era/> (2022, accessed 30 January 2025).
55. SWCF. Products: Ezciclo carbon prepreg [online]. <https://www.swcfc.com/en/products/detail/149> (accessed 05 June 2025).
56. Global Composites. Ezciclo RB519 [online]. <https://globalcomposites.eu/ezciclo-rb519/> (accessed 05 June 2025).
57. Mallinda. Recyclable & reprocessable thermosets [online]. <https://www.mallinda.com/> (accessed 30 January 2025).
58. CIDETEC. Materials with an endless lifespan [online]. <https://www.cidetec.es/gestor/recursos/uploads/imagenes/casos/3r-leading-technology/3R-technology-cidetec.pdf> (accessed 30 January 2025).
59. CIDETEC. CARBO4POWER [online]. <https://cidetec.es/en/proyectos/carbo4power/> (accessed 30 January 2025).
60. CIDETEC. CIDETEC will reduce the cost of parts in the aeronautical sector thanks to its 3R technology [online]. <https://cidetec.es/en/cidetec-will-reduce-the-cost-of-parts-in-the-aeronautical-sector-thanks-to-its-3r-technology/> (2021, accessed 30 January 2025).
61. CleanTechnica. Siemens Gamesa Begins Testing 115-Meter-Long Wind Turbine Blades [online]. <https://cleantechnica.com/2022/06/06/siemens-gamesa-begins-testing-115-meter-long-wind-turbine-blades/> (2022, accessed 05 June 2025).
62. offshoreWINDbiz. Siemens Gamesa Ships Out First Set of 115-Metre Wind Turbine Blades [online]. <https://www.offshorewind.biz/2022/12/20/siemens-gamesa-ships-out-first-set-of-115-metre-wind-turbine-blades/> (2022, accessed 13 June 2025).
63. Siemens Gamesa. RecyclableBlade Pioneering Technology [online]. <https://www.siemensgamesa.com/global/en/home/explore/journal/recyclable-blade.html> (accessed 30 January 2025).
64. Adnana Memija. Siemens Gamesa Rolls Out First Turbine Blade for RWE's 1.4 GW Sofia Offshore Wind Farm [online].

- <https://www.offshorewind.biz/2024/10/03/siemens-gamesa-rolls-out-first-turbine-blade-for-rwes-1-4-gw-sofia-offshore-wind-farm/> (2024, accessed 30 January 2025).
65. Recharge News. First recycled wind turbine blade out of Asia as Mingyang unwraps 75-metre green giant [online]. <https://www.rechargenews.com/wind/first-recycled-wind-turbine-blade-out-of-asia-as-mingyang-unwraps-75-metre-green-giant/2-1-1424689> (2023, accessed 05 June 2025).
 66. Adnana Memija. Swancor to Supply Recyclable Resins for Siemens Gamesa's Recyclable Blades [online]. <https://www.offshorewind.biz/2024/03/20/swancor-to-supply-recyclable-resins-for-siemens-gamesa-recyclable-blades/> (2024, accessed 30 January 2025).
 67. Nehls G. Swancor, Siemens Gamesa solidify recyclable wind blade partnership [online]. <https://www.compositesworld.com/news/swancor-siemens-gamesa-solidify-recyclable-wind-blade-partnership> (accessed 30 January 2025).
 68. Saitta L, Rizzo G, Tosto C, et al. Development and thermo-mechanical analysis of bio-based epoxy resin / cardanol blends as matrices for Green composites manufacturing. *J Polymers Environ* 2025; 33: 1561–1584.
 69. Iadarola A, Matteo PD, Ciardiello R, et al. Mechanical characterization of cardanol bio-based epoxy resin blends : Effect of different bio-contents. *Polymers* 2025; 17: 296.
 70. Chu F, Hu Y, Hu W, et al. Advancements in monomers and reinforcements of unsaturated polyester composites: Traditional, bio-based, and flame-retardant types. *Compos Part B: Eng* 2025; 294: 112171.
 71. Fekiaç JJ, Krbata M, Kohutiar M, et al. Comprehensive review: Optimization of epoxy composites, mechanical properties, & technological trends. *Polymers* 2025; 17: 271.
 72. Rinnovabili. Wind Turbine Blades made from bio-derived materials for more effective recycling [online]. <https://www.rinnovabili.net/tech-innovations-and-startups/recycling-tech-innovations-and-startups/wind-turbine-blades-made-from-bio-derived-materials-for-more-effective-recycling/#:~:text=Researchers%20at%20the%20U.S.%20NREL,the%20upcycling%20of%20old%20blades.> (2024, accessed 30 January 2025).
 73. Coxworth B. Fast-dissolving bio resin could drive recycling of wind turbine blades [online]. <https://newatlas.com/environment/pecan-bio-resin-recyclable-wind-turbine-blades/> (2024, accessed 30 January 2025).
 74. UK Research and Innovation. Eolian: Bio-based, repairable and recyclable vitrimer composites and advanced sensors for highly reliable and sustainable wind blades [online]. <https://gtr.ukri.org/projects?ref=10123065> (accessed 30 January 2025).
 75. LM Wind Power. How to build a wind turbine blade [online]. <https://www.youtube.com/watch?v=WxIhGxET7N8> (accessed 05 June 2025).
 76. Maguire JM, Mamalis D, Otomo S, et al. Passively morphing trailing edge design for composite tidal turbine blades. *Compos Struct* 2024; 337: 118090.
 77. Gurit. Guide to Composites [online]. <https://www.gurit.com/wp-content/uploads/2022/12/guide-to-composites-1.pdf> (accessed 05 June 2025).
 78. Rajak DK, Wagh PH and Linul E. Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review. *Polymers* 2021; 13: 3721.
 79. Hou Y, Taniguchi K, Mailly L, et al. Vacuum-Assisted resin infusion molding (VARIM) processing for thick-section composite laminates in wind turbine blades. In: *American Society for Composites 2012-Twenty-Seventh Technical Conference*, 2012, pp.1–18. Arlington, Texas.
 80. Summerscales J and Searle TJ. Low-pressure (vacuum infusion) techniques for moulding large composite structures. *Proc Inst Mech Eng Part L: J Mater: Design Appl* 2005; 219: 45–58.
 81. Easy Composites Ltd. Vacuum Consumables for Resin Infusion. <https://www.easycomposites.co.uk/infusion-vacuum-consumables> (accessed 21 January 2025).
 82. Easy Composites Ltd. Vacuum Bagging Consumables. <https://www.easycomposites.co.uk/vacuum-bagging-consumables> (accessed 21 January 2025).
 83. Del Pero F, Dattilo CA, Giraldi A, et al. LCA approach for environmental impact assessment within the maritime industry: Re-design case study of yacht's superstructure. *Proc Inst Mech Eng Part M: J Eng Marit Environ* 2024; 238: 153–170.
 84. Han N, Baran I, Zanjani JSM, et al. Experimental computational analysis of the polymerization overheating in thick glass/Elum[®] acrylic thermoplastic resin composites. *Compos Part B: Eng* 2020; 202: 108430.
 85. Xia WZ and Cook WD. Exotherm control in the thermal polymerization of nona-ethylene glycol dimethacrylate (NEGDM) using a dual radical initiator system. *Polymer* 2003; 44: 79–88.
 86. Obande W, O'Rourke K, Stankovic D, et al. Multi-stage, in-situ polymerisation for low-exotherm, liquid resin infusion of thick thermoplastic laminates at room temperature. *Compos Commun* 2024; 45: 101788.
 87. Maguire JM, Nayak K and Ó Brádaigh CM. Characterisation of epoxy powders for processing thick-section composite structures. *Mater Des* 2018; 139: 112–121.
 88. Gurit. Prepregs [online]. <https://www.gurit.com/prepregs/> (accessed 05 June 2025).
 89. Maguire JM, Simacek P, Advani SG, et al. Novel epoxy powder for manufacturing thick-section composite parts under vacuum-bag-only conditions. Part I: Through-thickness process modelling. *Compos Part A: Appl Sci Manufact* 2020; 136: 105969.
 90. Doyle A. European patent specification a heated mould for moulding polymeric composites, a method for making such mould and its use, 2012.
 91. Ó Brádaigh CM, Doyle A, Doyle D, et al. Electrically-heated ceramic composite tooling for out-of-autoclave manufacturing of large composite structures. In: *SAMPE* 2011, pp. 6–14. Long Beach, California, 23–26 May 2011.
 92. Composites Braiding. The future of composite manufacturing [online]. <https://compositebraiding.com/> (accessed 05 June 2025).
 93. Composites One. Creating Thermoplastic Composite Parts Using Bladder Moulding Process [online]. <https://www.compositesone.com/creating-thermoplastic-composite-parts-using-bladder-molding-process/> (accessed 05 June 2025).
 94. Innovative Composite Engineering. Bladder Molded [online]. <https://www.innovativecomposite.com/products/bladder-molding/#:~:text=What%20is%20Bladder%20Molding%3F,material%20in%20the%20closed%20mold> (accessed 05 June 2025).
 95. Composite Sourcing Solutions. Composites Bladder Inflation Moulding Support [online]. https://www.composite-sourcing.com/composite_bladder_molding_support.html (accessed 05 June 2025).

96. Composites World. Digital Demo: The Advantages of Thermoplastics Technology [online]. <https://www.compositesworld.com/articles/digital-demo-the-advantages-of-thermoplastics-technology?utm%20source=linkedin&utm%20medium=social&utm%20campaign=social22&utm%20content=Fromstron> (2022, accessed 05 June 2025).
97. Schillfahrt C, Fauster E and Schledjewski R. A methodology for determining preform compaction in bladder-assisted resin transfer molding with elastomeric bladders for tubular composite parts. *Int J Mater Form* 2019; 12: 1–15.
98. Schillfahrt C, Fauster E and Schledjewski R. Influence of process pressures on filling behavior of tubular fabrics in bladder-assisted resin transfer molding. *Advan Manufact: Polymer Compos Sci* 2017; 3: 148–158.
99. Bhudolia SK, Perrotey P and Gohel G. Optimizing bladder resin transfer molding process to manufacture complex, thin-ply thermoplastic tubular composite structures: An experimental case study. *Polymers* 2021; 13.
100. Siemens Gamesa. IntegralBlade® A key technology unique to the wind industry [online]. <https://pdf.archiexpo.com/pdf/siemens-gamesa/integralblades/88089-134499.html> (accessed 13 June 2025).
101. Siemens Gamesa. SG 14-236 DD Offshore wind turbine [online]. <https://www.siemensgamesa.com/global/en/home/products-and-services/offshore/wind-turbine-sg-14-222-dd.html> (accessed 30 January 2025).
102. Fowell A. Siemens Gamesa works on Recyclable Blades, Could This Boost the Company's Overall Performance? [online]. <https://www.techtimes.com/articles/276392/20220606/siemens-gamesa-works-on-recyclable-blades-could-this-boost-the-companys-overall-performance.htm> (2022, accessed 30 January 2025).
103. Duarkovic A. Siemens Gamesa Starts Producing 108-Metre Wind Turbine Blades in UK [online]. <https://www.offshorewind.biz/2023/02/15/siemens-gamesa-starts-producing-108-metre-wind-turbine-blades-in-uk/> (2023, accessed 30 January 2025).
104. Stiesdal H, Enevoldsen PB, Johansen K, et al. European Patent Application Method for manufacturing windmill blades, 2003.
105. Zarouchas D and Nijssen R. Mechanical behaviour of thick structural adhesives in wind turbine blades under multi-axial loading. *J Adhes Sci Technol* 2016; 30: 1413–1429.
106. Subrahmanian KP and Dubouloz F. Adhesives for bonding wind turbine blades. *Reinforced Plast* 2009; 53: 26–29.
107. Wacker G, Brügge D, Fach K, et al. Theory and practice: Requirements for adhesive bonding in marine structures. *Proc Inst Mech Eng Part M: J Eng Marit Environ* 2004; 218: 217–226.
108. Devine M, Bajpai A, Ó Brádaigh CM, et al. 'Resin welding': A novel route to joining acrylic composite components at room temperature. *Compos Part B: Eng* 2024; 272. DOI: 10.1016/j.compositesb.2024.111212.
109. Murray RE, Roadman J and Beach R. Fusion joining of thermoplastic composite wind turbine blades: Lap-shear bond characterization. *Renew Energy* 2019; 140: 501–512.
110. Matthew Perry. New 'state-of-the-art' tidal turbine blade manufactured by FastBlade in Scotland [online]. www.energyvoice.com/renewables-energy-transition/wave-tidal/uk-wave-tidal/539807/fastblade-university-of-edinburgh-tidal-turbine-blade-manufactured-in-scotland/ (2024, accessed 08 June 2025).