UK Manufacturing Technology for Next Generation Turbines - JOULE CHALLENGE

Phase 1 – Summary report

Author: ORE Catapult / National Composites Centre **Date:** March 2022

Project funded by Department for Business, Energy & Industrial Strategy

DOCUMENT HISTORY

Revision	Date	Prepared by	Checked by	Approved by	Revision history
1	03/03/22	Kacper Stefaniak	Thomas Wildsmith, James Lightfoot	Thomas Wildsmith, James Lightfoot	1

CONTENTS

EXECUTIVE SUMMARY

In 2019 the UK became the first major economy to commit to a target of Net Zero carbon emissions by 2050. In doing so, the UK committed to the development of renewable energy generation and the reduction of its reliance on fossil fuels. The Offshore Wind Sector Deal, released in the same year, outlined the UK's ambitions to deploy 30 GW of offshore wind by 2030, which was subsequently increased to 40 GW by 2030 (of which 1GW is floating wind), cementing offshore wind power as one of the largest, affordable options for zero-carbon electricity production. A further reduction in the cost of energy will maximise our use of this renewable resource. The development and production of the next generation of large wind turbines will play a key role in continuing to reduce the cost of energy.

The Offshore Renewable Energy (ORE) Catapult and the National Composites Centre (NCC), part of the High Value Manufacturing Catapult, identified the opportunity to unlock a step change in device capacity by utilising composite materials, which offer significant performance opportunities. Composites will be essential in enabling the vision of a floating offshore wind device capable of generating 20MW+ capacity, with a cost of energy equivalent or lower than existing manufacturing processes and estimates. To further investigate this opportunity, ORE Catapult and NCC were tasked by the Department for Business, Energy and Industrial Strategy (BEIS) to undertake feasibility studies, a supply chain assessment and provide a roadmap for how the UK can capitalise on its high-value design and manufacturing capability to deliver next-generation wind turbine components in the UK context.

Phase 1 of the *Joule Challenge - UK Manufacturing Technology for Next Generation Turbines* project took place between October 2019 and March 2020 and produced the following outputs:

- Baseline turbine design parameters were established
- Potential 20MW+ wind turbine components designed and assessed, comparing conventional manufacturing processes and materials with next-generation processes and composites.
- The levelised cost of energy (LCOE) was modelled to assess economic impact
- A series of technology development plans were produced, highlighting technology gaps and potential UK stakeholders
- An initial technology development plan was established, focussed on addressing technology gaps and realising large-scale composite components throughout the turbine structure.

THE OPPORTUNITY

The Joule Challenge was developed as a route to assess the feasibility for increasing the volume of composite components for future floating offshore wind turbine devices. The application of composite materials using a design for manufacture methodology was identified as a route to de-risk future technological innovations and further support the growth of the UK manufacturing capacity for offshore wind.

UK Offshore Wind Market

The UK has the largest installed capacity of offshore wind in Europe and is second in the world (10.4 GW operational, June 2021). The offshore operational fleet is forecasted to grow significantly with a target of 40GW by 2030. To maximise the benefit to the UK economy, the Offshore Wind Sector Deal committed UK Government and industry partners to a series of targets including increasing UK content to 60 % by 2030. Increasing the UK manufacturing capabilities for offshore wind turbines is recognised as a route to achieving this ambitious content target. Currently, the UK has a low market share of major wind turbine component manufacturing, with blade manufacturing being the main exception. To increase this market share, by expanding capabilities in other major components, we need to build on existing UK technological advantages, one of which is the high-value design and manufacturing of composite components.

Increasing generation capacity of wind turbines

The opportunity for composite materials is further enhanced by the rapid growth in offshore wind turbines, with the current state-of-the-art being 16MW and future devices looking to exceed 20 MW generation capacity. Using current manufacturing processes and materials will create significant challenges around the size and weight of these components, for example, state-of-the-art turbine nacelles already weigh 500+ tonnes (SGRE 14-222 DD). This impacts load-bearing component design, transportation, and installation. There is also likely to be the need for significant investment in the manufacturing plants to produce components on this scale. This provides a potential window of opportunity to investigate alternative materials and manufacturing processes such as composites.

Floating offshore wind

A rapidly growing subset of offshore wind is the development and application of floating foundations, allowing developers to access deeper waters where consistent high wind speeds are available. Floating wind is likely to become an integral part of the wind energy generation mix and is expected to contribute a minimum of 1GW by 2030.

JOULE CHALLENGE – PHASE 1

A three-phase approach to the challenge was proposed, with Phase 1 incorporating the initial concept and feasibility assessment, Phase 2 covering the detailed analysis and design and Phase 3 including the final design for manufacture, development of prototypes and testing. The proposed scopes and outputs of each phase are shown in Figure 1.

Phase 1: Concept and Feasibility	Phase 2: Detailed analysis and design	Phase 3: Design for Manufacture, Prototype and Testing
Scope • Outline requirements for sub-systems and components for 20MW device • High level technical assessment of HVDM opportunity for material and manufacturing changes • Produce detailed business case of specific components • Business case and proposal for Phase 2.	**Scope** • Updated 20MW reference device • Further design and analysis of specific components identified in Phase 1 • Industry and supply chain engagement to support development and delivery • Business case and proposal for Phase 3 • Preliminary plan for validation/testing of components at scale	**Scope** • Manufacturing development for sub-scale components for relevant component work-streams • Manufacturing development for full scale technology demonstrator • Testing and validation of sub-scale components and full-scale demonstrator • Support knowledge transfer and upskilling of UK supply chain to enable adoption of technology
Outputs • Initial reference device parameters (20MW) • Feasibility review of components completed • Component and programme level business cases for further development completed.	**Outputs** • Preliminary design packs for components • Solutions developed for technology gaps. • Component and programme level business case for prototype manufacture produced. • Critical stakeholders engaged	**Outputs** • Prototype components manufactured in the UK (scaled / full scale) • Components validated / tested. • Technology embedded in UK industry & able to commercialise

Figure 1: Joule Challenge - 3 Phases of scope and outputs

At the end of each phase, the key criteria for assessment include:

- The impact on the LCOE – the industry continues to drive down costs and so increases in cost are less likely to have wider uptake.
- The feasibility of component design and manufacturing – proposed designs needed to have realistic routes to manufacture.
- Sustainability and environmental impacts – whilst cost is a significant driver, the wind industry continues to be part of the green economy and therefore sustainability is a core consideration.

Component Development

For Phase 1, the project team focussed on the development of an initial set of reference specifications for a 20MW turbine using a series of different turbine configurations, including upwind, downwind and two-bladed options. Using these specifications, a range of component options was developed for the blade, tower, main shaft, and hub. At each stage, both composite and, where relevant, a baseline steel design was completed for comparison. Concept designs were carried out aiming to reduce mass, reduce LCOE and improve the annual energy production (AEP) for the overall turbine. This report will not go in-depth on the concept components designed and developed in the programme, however, for reference, an example of the designs considered for the tower is shown in Figure 2. For each concept, a high-level component business case was developed assessing the potential mass savings, the opportunity for knock-on improvements in the turbine and estimated costs for manufacture using appropriate materials and processes.

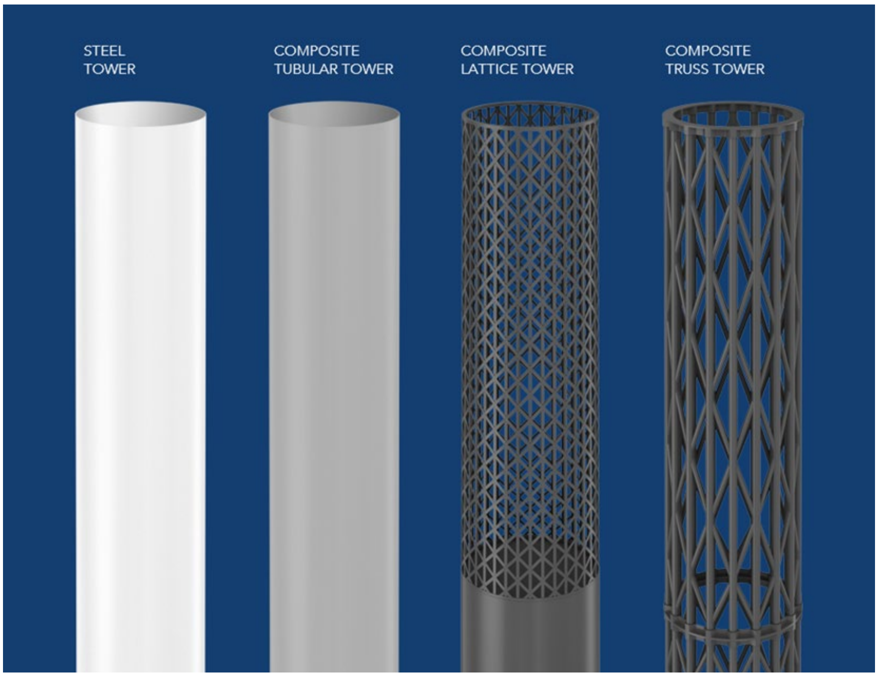


Figure 2: Example of HVDM possibilities with composites for tower structures in Phase 1

LCOE Assessment

One of the aims of Phase 1 was to design and assess potential 20MW+ wind turbine components, comparing conventional manufacturing processes and materials with alternative processes and composites. During this feasibility study, our engineering assessments of those factors have shown that LCOE reductions compared to a baseline steel design can be realised. Crucially, we have identified a 'virtuous spiral' whereby the lightweight design of one component enables the lightweight design of other components.

Cost estimates have been developed for components of a 20MW turbine for a range of scenarios in which different turbine components are replaced by composite equivalents. One of the key benefits of composites is their high strength and stiffness to weight ratio, which can lead to dramatic reductions in component masses. This means that it is important to account for follow on savings that arise as a result of mass reductions.

Assessment has been made of the LCOE of these design options using a cost model that includes a multitude of effects, including carbon fibre price, substructure type, balance of plant configuration, OPEX, capacity factor, discount rate and asset life. For each design, costings were made for the application of composite materials to variants of the main shaft, the tower, the hub, and to all three components together.

A range of different turbine scenarios has been considered, including several different blade designs. Each blade design was costed using the best available estimates for material quantities. [1] Starting from a baseline validated by research at the University of Bristol, several designs have been considered: downwind; high tip speed; sail; modular; and bi-foil root, all of which are elaborated upon in Appendix 1.

For the baseline, downwind and high tip speed blades, the Aeroelastic Turbine Optimisation Methods (ATOM)[2] optimisation software was utilised to ensure the concepts passed the prescribed design load cases, giving a high degree of confidence in the blade bill of materials. Aeroelastic assessments could not be completed for the bi-foil root, modular blade, and the sail/semi-sail designs due to existing tools being unsuitable for these designs. However, concept-level designs were generated so that further assessments could be carried out in the future. In the case of the sail-based designs, the power coefficient (CP) values have been estimated from engineering judgements and industrial knowledge.

It was concluded that by using composite materials for major components a 20 MW+ turbine can be produced that gives a £0.89/MWh reduction in LCOE when compared to a scaled equivalent using conventional materials (steel and cast iron).

Several options were selected to quantify the individual impacts on the LCOE of replacing key components with a composite equivalent for the baseline turbine design. The overall impact of all three technologies together was also studied and summarised in Table 1.

Component	Change
The tower	Rolled steel replaced with a composite tubular/lattice/truss tower
The main shaft	Cast iron replaced with a composite equivalent
The hub	Cast iron replaced with a composite equivalent

Table 1 Summary of component changes analysed

In addition to this, several other concepts have been investigated as summarised in

Table 2.

[1] S. Scott, P. Greaves, P. M. Weaver *et al.,* 'Efficient Structural Optimisation of a 20 MW Turbine Blade', Journal of Physics; Conference Series 2020.

[2] T. Macquart, V. Maes, D. Langston *et al, .* 'A New Optimisation Framework for Investigating Wind Turbine Blade Designs', 12th Congress of Structural and Multidisciplinary Optimisation, ISSMO, 2017

Component	Studied with the baseline metallic components	Studied with all composite components	Studied with all composite components except shaft
A Bi-Foil blade root	X		
A modular blade	X		
A downwind turbine	X	X	x
A high tip speed (TS) turbine	X	X	x
Sail*	X		
Semi-Sail*	X		

* variant analysed with high level assumptions on their effect on LCOE/AEP

Table 2 Summary of turbine concepts analysed in Phase 1

The LCOE is derived from the total project costs for the lifetime of the project (development costs, capital costs and operational costs) and the total energy produced, giving a cost per MW hour. By changing the design and manufacturing routes for components in the project we expect to see the LCOE change in the following ways:

- Change in turbine capital cost due to the change in the cost of the component;
- Change in turbine capital cost due to the change in the component mass impacting the requirements for other structural parts of the turbine (in particular the tower and the foundation);
- For the blades, the AEP can change and in the case of the high tip speed the drivetrain component mass was also affected because of reduced rated torque.

Based on the input assumptions and methodology, the resulting LCOE for 18 variants we modelled is shown in Figure 3. These LCOE figures are for direct comparison of variants in the project and should not be used as a comparison to current energy projects. From these data the results of note include the following:

- The mean LCOE was £51.29/MWh;
- The lowest LCOE was £50.40/MWh for variant 7a Baseline (Full composite except shaft) (2% lower than mean); and,
- The highest LCOE was £52.17/MWh for variant 6 Baseline composite with truss tower (2% higher than mean).

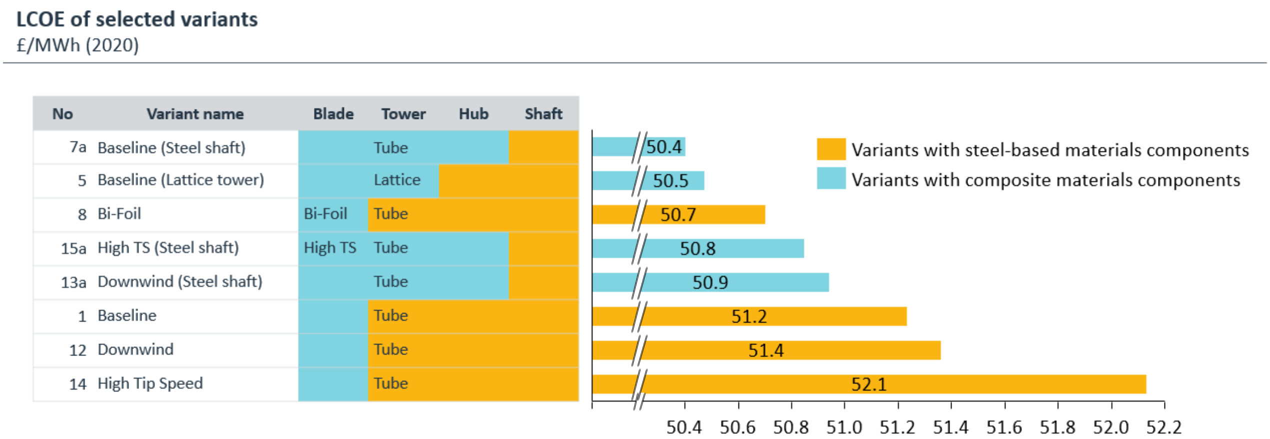


Figure 3 LCOE of analysed variants

The relatively high cost of the composite shaft meant that it had a detrimental impact on the cost of any variants in which it was included. This high cost was driven by a significant amount of high modulus carbon fibre in the layup, which is significantly more expensive than cast iron. However, even the turbine incorporating all the composite components (variant 7) had a lower LCOE than the baseline conventional turbine, despite the shaft and hub being approximately 3 and 1.5 times more expensive respectively. This highlights that the mass reductions enabled by composites can lead to lower LCOE even if the costs of the components themselves do not look competitive in isolation.

Error! Reference source not found. Figure 4 compares downwind (13a) and high tip speed (15a) variants. Both incorporate a composite hub and a composite tubular tower and have estimated LCOE values only ~1% higher than the lowest result (7a). In the downwind variant (13a) incorporating the lightweighted composite components helps to offset the higher costs in the downwind mechanical brake and couplings making it more cost-effective than the baseline equivalent (12). Similarly, for the high tip speed (15a) variant, incorporating the light-weighted composite components helps to offset the higher costs in the high tip speed tower and blades, making it more cost-effective than the baseline equivalent (variant 14). In future work, it is worth considering combining the high tip speed and downwind designs to maximise the cost benefits.

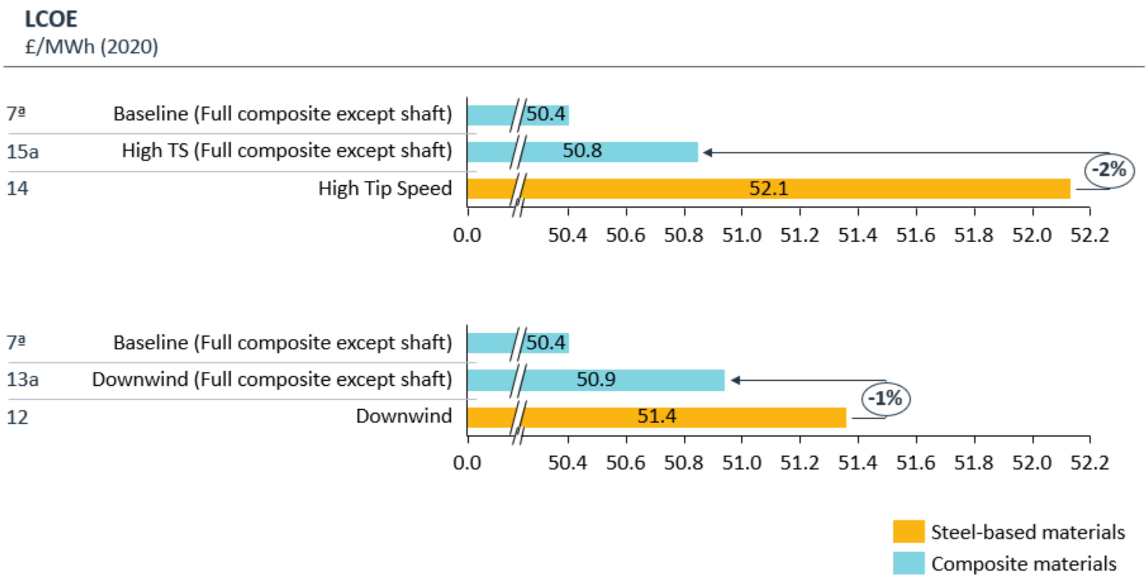


Figure 4 LCOE of downwind and high tip speed variants

The truss tower had a high cost compared to the lattice and tube tower options. This was driven by the requirement for carbon fibre composite and the number and cost of joints, but it had a very low mass. The high cost was partly driven by the uncertainty in the jointing methods, so these options are worth exploring further in future work.

The key finding was that composites are competitive with conventional materials based on the cost analysis performed in Phase 1. At this stage, the combination detailed in Table 3 is judged to be the most compelling basis for a 20MW turbine and we conclude that these groups of components should be taken forward to a more detailed design phase.

Component	Variant
Tower	Composite
Main shaft	Cast iron
Hub	Composite
Blade speed	High tip speed
Turbine configuration	Downwind

Table 3 The most compelling variant in terms of LCOE

We have also identified other components/variants which need further investigation to fully inform our evaluation. These include truss/hyperboloid tower variants, composite shaft, and sail blade. Therefore, we recommend that these are also taken forward to the next stage.

Modular blades show great promise for increasing design flexibility through tip exchange and reduced transportation costs. These have been demonstrated at scale, however, the sole use of mechanical instead of bonded joints does not appear to have any great benefits for offshore blades. The next phase will focus on bonded joint systems, or hybrid approaches to combine blade modules and segments and sole mechanical joints will not be taken forward.

Whilst the feasibility study sought to identify the factors most likely to impact LCOE, our engineering assessments of those factors have been limited by the time and resources available for Phase 1. A more robust, detailed engineering approach will be completed as part of the second phase of the project to accrue the further cost of energy advantages and realise the full potential of the opportunity for composites.

Technology Gaps

The technology gaps highlighted in Phase 1 can be split into systems-level and component-level design/manufacture challenges, which will be investigated by ORE Catapult and NCC respectively as part of Phase 2.

The most significant technology gaps at the systems-level design include:

- A suitable controller which can mitigate extreme and fatigue loading for a floating downwind turbine.
- Development of an integrated nacelle and drivetrain concept.
- Development of an optimised tower-floater system.

The most significant composite design and manufacture gaps and challenges include:

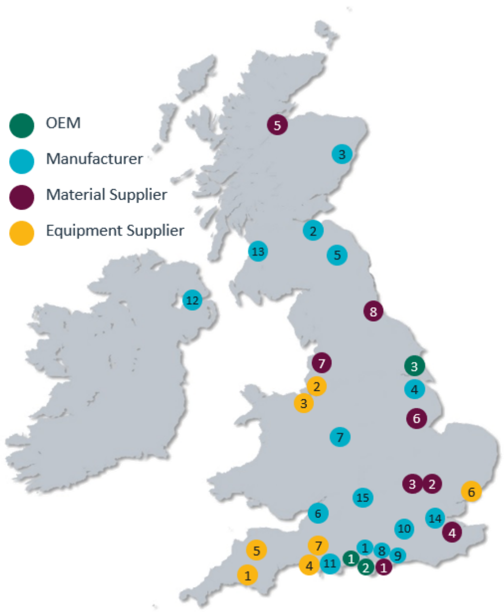
- Characterising the fatigue response of the materials proposed for turbine component construction, then the development of a suitable low-cycle fatigue life assessment tool to calculate the fatigue life of the structures.
- Bringing down the wholesale cost of carbon fibre per unit mass. This will open the design space for more lightweight design concepts and lower the cost of manufacture of the turbine and reduce the LCOE of the system.
- Significantly increasing the rate and size envelope of automated deposition manufacturing technologies to produce large composite structures.

Supply Chain and Environmental Impact Assessment

Another part of the Phase 1 study was focused on a preliminary assessment of the potential to grow a domestic supply chain to support the new, composite-based turbine designs. We have identified that the UK content of offshore wind farms – UK share of the total lifetime value of an offshore wind project – was weakest in major turbine components. The UK share of capital expenditure on the turbine itself was less than 15%, whereas there is a greater than 70% share of operations and maintenance expenditure. There is therefore room for growth in the UK supply of major turbine components.

We concluded that there was no current manufacturing capacity in the UK to build conventional components at the scale and rate required for a future 20MW+ platform. This highlights a current gap in the market where composite components and the corresponding supply chain can be developed. The existing UK composites supply chain covers a wide range of capabilities, particularly in the design and manufacture of large structures and precision manufacturing equipment. Manufacturers of large structures reside mainly within the aerospace, marine and construction sectors and these organisations would need to make significant investments to adapt their businesses to the wind industry. This, however, was not expected to be a blocker to entry for all companies. The large size of the components and the forecast production rate to meet the UK deployment targets suggests that materials suppliers could expect large growth in composite raw material demand, split across glass and carbon fibres and resin systems. This will require the biggest market players, such as INEOS Composites, Owens Corning and Gurit to invest in new capabilities and possibly establish a dedicated supply of fibres and resins. In addition, to meet structural requirements at a reasonable cost and positively disrupt the market, the processing of low-cost carbon fibre should be brought online in the UK.

Figure 5 shows the potential UK supply chain consisting of blade OEMs, composite materials and equipment suppliers, ranging from UK-based multinationals to SMEs. The assessment was non-exhaustive and further engagement will be carried out during Phase 2. It is worth noting that the analysis was conducted in 2020 and some companies could trade under a different name now.



OEM	
1	LM Wind
2	MHI Vestas
3	Siemens Gamesa

Manufacturer	
1	AC Marine
2	ACT Blade
3	Balmoral Group
4	Flocktons TVP
5	Forbes Technologies
6	GKN Aerospace
7	GKN Automotive
8	Magma Structures
9	Marine Concepts
10	McLaren
11	Norco Composites
12	SiloTank
13	Spirit Aerosystems
14	Technobell
15	Unipart Manufacturing

Material Supplier	
1	Gurit
2	Hexcel
3	Huntsman Advanced Materials
4	INEOS Composites
5	SGL Carbon
6	SHD Composites
7	Sigmatex
8	Solvay

Equipment Supplier	
1	Composites Integration
2	Cygnet TexKimp
3	Electro Impact
4	Loop Technology
5	Pipex
6	Pultrex
7	VFE – Autoclaves & Ovens

Figure 5 Map of the identified stakeholders within the UK

The lifecycle environmental impact of the composite turbine was compared to the baseline and significant environmental benefits were found. A reduction in embodied carbon of around 55% was calculated for the turbine components studied, which would also bring about reductions in other harmful environmental impacts. However, if the turbine end-of-life is considered then it is critical that the increased use of composites does not exacerbate this already difficult issue. Taken together, the composite tower, shaft and hub more than quadruple the volume of composite materials in the turbine structure. These materials must not be landfilled at the end of the turbine life, so a design for reuse and recycling must be followed. The sustainability and recyclability of the composite materials will be further investigated during Phase 2. Elements of blade design to be considered in Phase 2, including the selection of lower impact materials and circular design principles for blades, will be underpinned by the work underway in the SusWIND programme[3].

[3] https://www.nccuk.com/sustainable-composites/activities/suswind/

PHASE 2 OVERVIEW

The Joule Challenge Phase 2 commenced in November 2021 and will be delivered by ORE Catapult and NCC, concluding in Q2 of 2023.

The overall aim for Phase 2 is to develop component-level designs for the next generation 20MW+ floating offshore wind turbines that realise the high-value manufacturing opportunities in the UK.

This will deliver the overall impacts of de-risking innovation and encouraging the design and manufacture of wind turbine components within the UK. Both impacts will enhance the UK's position as a world leader in the deployment of offshore wind turbines and will secure a greater share of UK content in manufactured components. This aligns with the overall ambition of the Offshore Wind Sector Deal where the UK has committed to increasing UK content to 60% and increasing exports to £2.6bn by 2030.

The objectives of Phase 2 are:

- Develop a 20 MW+ design architecture to allow detailed component design.
- Evaluate next-generation technologies to remove uncertainty around key components.
- Identify current manufacturing barriers and develop solutions.
- Engage with UK-based companies to:
    - Develop IP with UK companies and therefore UK PLC.
    - Ensure supply chain is engaged ahead of full-scale component manufacture.
    - Lay the foundations for increasing UK jobs and export opportunities.

Phase 2 of the Joule Challenge will focus on the design and manufacturing technologies needed for key components within a 20MW floating wind turbine and platform, with the ambition to demonstrate these in a potential Phase 3 of the programme. To ensure that a robust technology demonstrator could be constructed, the design of a wind turbine system and controller development will be carried out, as these are key inputs in the component design process. Overall, the process for the development of 20MW floating wind turbine components is shown in Figure 6.

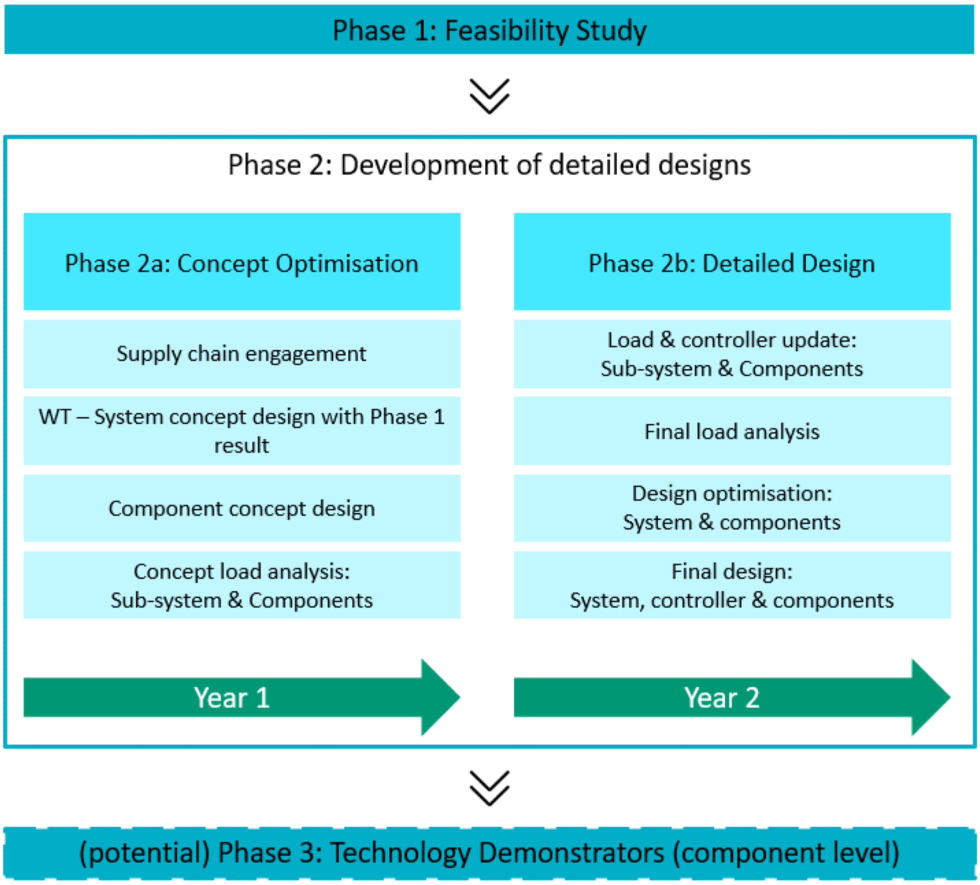


Figure 6 The process for development of 20MW floating wind turbine components

CONCLUSIONS

The Joule Challenge Phase 1 results highlight that transitioning to composite materials for a 20MW+ turbine system is feasible and brings the benefits of being more lightweight and sustainable and reducing the LCOE when compared to a conventional metallic baseline. The initial component designs show that significant mass savings can be made, allowing turbines to get bigger without significant mass increases. The initial LCOE estimates show that transition can be carried out cost-effectively. There is a potential UK supply chain in place that can be positioned to take advantage of the innovations developed within this programme, with the opportunity for cross-sector development and established businesses to pivot to support the offshore wind markets. Several technology challenges and routes to overcome these have been developed and will be refined further in future phases of the programme.

Phase 2 of the Joule Challenge has now been launched and will allow the programme team to deliver a detailed analysis and design, further underpinning the case for future investment, and engage with key stakeholders.

Appendix – Summary of Phase 1 Blade Concepts

Bi-Foil Blade Root

The transition from the circular blade root to the aerofoil shape of a conventional wind turbine blade has very thick aerofoils which are not very aerodynamically efficient. One method that has been considered to rectify this issue is the use of a bi-foil root, in which the blade splits into two foil sections as it approaches the root area as shown in Figure 7. Whilst this leads to significant increases in AEP, questions remain over how the joints between the root and the bi-foil sections could be realised in practice. The high increase in power coefficient for this type of design means that it is worth taking forwards to the design sprint, but it will be challenging to analyse with existing tools.

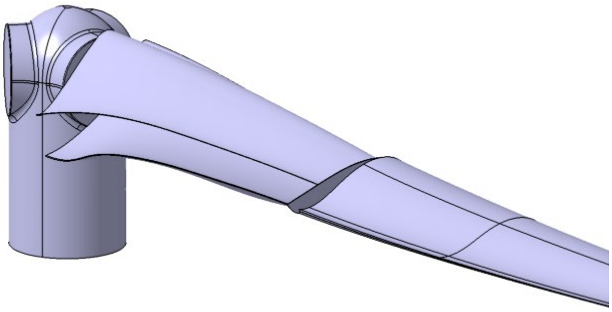


Figure 7 Bi-foil blade root

High Tip Speed Rotor

High tip speed blade designs are known to have significant benefits in terms of LCOE. Increasing the tip speed means that the rotor is spinning faster, which gives the same amount of power for a lower-rated torque. As the rated torque is strongly correlated to the mass and cost of the gearbox and generator, increasing the tip speed can reduce the cost of these components. Reducing the mass of these parts can have follow-on benefits for the tower and foundations.

Increasing the tip speed means that the effect of wind gusts is smaller relative to the speed of the blade so the turbine experiences more steady loading, which can help with the fatigue life of the tower and drivetrain components.

However, there are limiting factors on tip speed. The first limit is noise, which is not a significant issue offshore. The next is leading-edge erosion (in which raindrops erode the leading edge of the blades over time, leading to a reduction in aerodynamic efficiency and eventually structural failure), which is a major problem for the industry. However, it is known that helicopter-style leading edge protection can offer a lifetime solution to leading-edge erosion, albeit with higher up-front costs than current solutions. If the limit imposed by erosion is removed, then the next limit on tip speed is the requirement for the rotor to be aero-elastically stable and avoid the blade beginning to experience torsional vibrations. Finally, higher tip speed blades are slenderer, so more reinforcement is needed in the blades to satisfy strength and tower clearance constraints – eventually, the increase in the cost of the blades will outweigh any decrease in the cost of drivetrain components.

The software used to design the blades (ATOM) was initially used without a constraint on tip speed for the Phase 2 design. If the resulting design is found to have a tip speed that would be acceptable to industry, then it will be used as is and be redesigned with a tip speed constraint if this is not the case.

Downwind Rotor

Downwind rotors have the potential to reduce LCOE by reducing the constraint around tower clearance from the blade design that can lead to lower material usage. In Phase 1, a somewhat low-fidelity approach was used to approximate a downwind rotor, with the tower clearance constraint simply removed. There are several load cases involving emergency stops that could challenge this assumption, although there are control strategies that could mitigate this. There were other aspects of downwind turbine design that were not considered in Phase 1, including the effect of tower shadow on fatigue loading, which requires complex alterations to the controller. These reasons are likely why downwind rotors have not been widely adopted by industry.

Sail/Semi-Sail Blade

The sail concept in Phase 1, shown in Figure 8, aimed to reduce the bill of materials and manufacturing costs of the blade. For the inboard part of the rotor, the aerodynamic shells of the blade were replaced with an inflatable aerofoil section. The aim of this was to reduce the size requirement for the expensive blade shell moulds and reduce the amount of material needed for the blade by eliminating the large panels near the maximum chord region of the blade. The change in AEP was estimated without the use of any simulation as simulating the combination of a flexible membrane with aerodynamic loading is extremely challenging and computationally expensive.

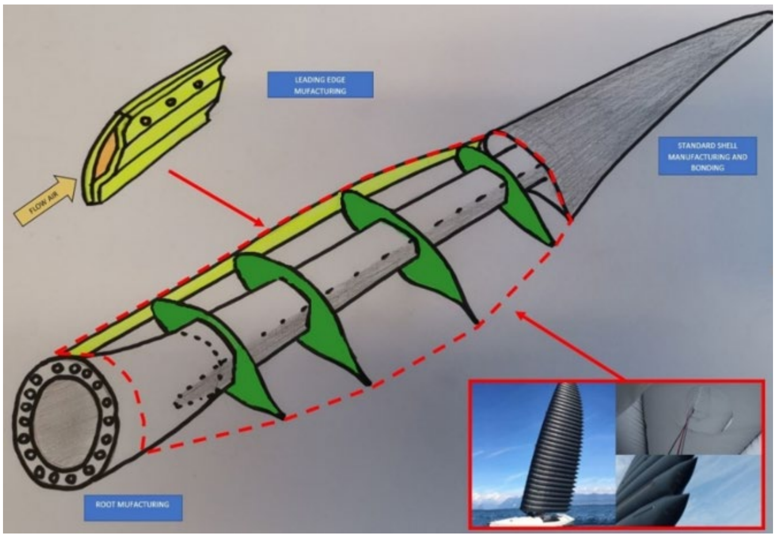


Figure 8 - Sail concept

Modular Blade

Conventional wind turbine blades are made as two half-shells that encompass the full length of the blade. The conventional shells transfer the aerodynamic loads to a structural spar box, which takes most of the loads applied to the blade. The shells are adhesively bonded to the spar and each other at the leading and trailing edges of the blade.

The mould tools for this type of blade design are extremely expensive, and there is considerable potential to reduce the cost of blades by splitting them in the spanwise (length) and chordwise (leading to trailing edge) direction as shown in Figure 9.

This could allow customisation of blades for specific sites by adding different tips which could enhance AEP or resistance to leading-edge erosion. In Phase 1 the mechanism that was chosen for joining the blades was a mechanical joint, which was not found to be favourable in terms of cost or blade mass, meaning that adhesive joints or thermoplastic welding appear to be more attractive options for Phase 2.

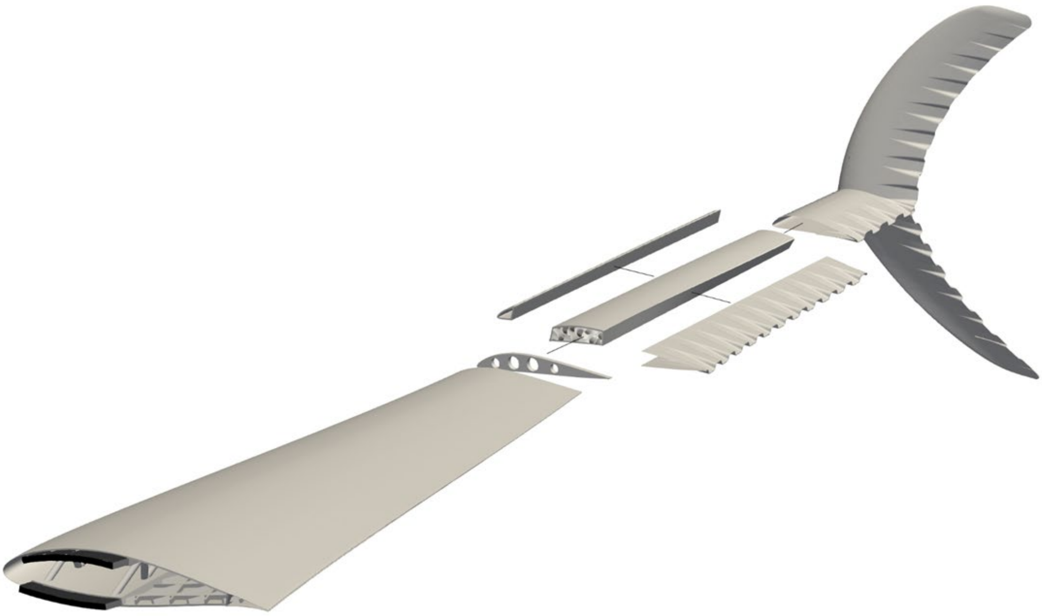


Figure 9 - Modular blade

ABOUT US

The National Composites Centre (NCC) is the UK's world-leading composite research and development facility; where innovators come when they need to make things lighter, stronger, smarter and more sustainable. With access to 'beyond' state-of-the-art technology and the best composites engineering capabilities in the world, the NCC collaborates with customers to solve the most complex engineering challenges of our time.

Part of the High Value Manufacturing Catapult, the NCC works across all manufacturing sectors and has forged strong links with aerospace, energy, defence, space, construction, infrastructure, auto, rail, marine and biomedical. It works with organisations across the board from micro enterprises through SME to disrupters, supply chain and OEMs, providing businesses with a de-risked environment to design, develop, test and scale their ideas and get them to market.

www.nccuk.com

ORE Catapult was established in 2013 by the UK Government and is part of a network of Catapults set up by Innovate UK in high growth industries. It is the UK's leading innovation centre for offshore renewable energy.

Independent and trusted, with a unique combination of world-leading test and demonstration facilities and engineering and research expertise, ORE Catapult convenes the sector and delivers applied research, accelerating technology development, reducing risk and cost and enhancing UK-wide economic growth.

Active throughout the UK, ORE Catapult has operations in Glasgow, Blyth, Levenmouth, Aberdeen, the Humber, the East of England, the South West and Wales and operates a collaborative research partnership in China.

ore.catapult.org.uk