TIGER TIDAL STREAM INDUSTRY ENERGISER

EUROPEAN UNION
European Regional Development Fund

Tidal Stream Volume Manufacturing Roadmap

V1.0

May 2022

Interreg France (Channel Manche) England
EUROPEAN UNION
European Regional Development Fund

Document History

Revision	Date	Description	Originated by	Reviewed by	Approved by
1.0	Apr 2022	Completed report	CF/CW	OREC: SC/GS/MA UoEx: PT/SW	SC

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Acronyms

Acronym	Description
CB	Circuit breaker
CfD	Contracts for Difference
c-Si	Crystalline silicone
DNO	Distribution network operator
EIA	Environmental Impact Assessment
EPR	Ethylene propylene rubber
ERDF	European Regional Development Fund
HSE	Health, safety and environment
IP	Intellectual property
IRENA	International Renewable Energy Agency
JB	Junction box
LCOE	Levelised cost of energy
NAB	Nickel aluminium bronze
O&G	Oil and gas
O&M	Operations and maintenance
OPEX	Operational expenditure
PT	Power transformer
PV	Photovoltaic
R&D	Research and development
ROV	Remotely operated vehicle
TSE	Tidal stream energy

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XLPE	Cross-linked polyethylene

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Executive summary

Tidal stream energy (TSE) is an exciting renewable energy technology. It is set to become a UK marine energy success story, and both the UK and France are home to industry leading companies who have market ready products waiting to be deployed.

Studies have indicated that tidal stream could supply 11% of the UK's electricity demand, the equivalent of 11.5 GW of installed capacity [1]. In France, the La Raz Blanchard has some of the strongest tidal streams in Europe, with depth averaged velocities exceeding 5 m/s in some areas [2]. It has the potential for 1-2GW of capacity deployed [3] [4]. Organisations like Ocean Energy Europe, the Marine Energy Council and Renewable UK believe that 1GW of tidal could be deployed in the UK by the early 2030s. In December 2021, Bureau Veritas noted that tidal stream "has the potential to become one of the lead sources of renewable energies in the world", also touting the wider benefits like job creation [5].

Currently there only exists a handful of projects worldwide, with about 10MW installed in the UK. Historically due to lack of appropriate standards devices have been over-engineered to ensure survivability at sea and demonstrate proof of concept. They have largely been early prototypes, not designed for mass manufacture. However, as the industry advances, it is clear that manufacturing concerns will become paramount to ensure that larger numbers of devices can be constructed economically and deployed quickly.

This roadmap, based on analysis of scale up across other sectors, describes the key manufacturing challenges and considerations that need to be overcome to ensure that the industry can deliver the volumes of devices that are anticipated. It also suggests enabling actions that can be taken to accelerate the industry's manufacturing readiness and to help keep the industry on a sharp cost reduction trajectory. Key conclusions can be summarised as follows:

- The most problematic areas of the supply chain from a lead time and cost perspective are tidal turbine blades, electrical powertrain components (e.g. gearbox, generator) and wet mate connectors.
- Lead times for these components can be over six months, and in some cases even over one year (e.g. wet mate connectors). This would limit the sector to supplying smaller numbers of devices in the present (approx. <100MW farms).
- A significant reason for long lead times is the low volumes of components being procured. As these components tend to be bespoke (e.g. wet mate connectors), suppliers do not like to keep these in their inventory and tend to only manufacture when an order comes in. Buying in larger volumes would help to mitigate this problem, which should happen as larger projects gain consent and secure revenue support.

- There is more room to involve suppliers in the design process. Tidal turbine developers tend to do most of the design in-house, which means that expertise and learning from the wider supply chain is not fully utilised. There is room for collaboration in some areas where standardisation could be more straightforward, for example with wet mate connectors, foundations and subsea hubs.
- Generally, the sentiment is that suppliers will invest and upgrade facilities as the industry expands, flexing to meet the demand. This process will largely happen naturally, with companies recognising the commercial opportunity. Rather than financial assistance, most companies we talked to were keener for collaboration opportunities and a larger pipeline of projects being developed.
- Government support for tidal stream has been varied. A lack of revenue support since the closure of the Renewable Obligation Certificate scheme in March 2017 and subsequent loss of ring-fenced support in the Contracts for Difference in 2018 had reduced supplier sentiment, with some suppliers leaving the industry and others scaling back their TSE investments as the opportunities are limited. However, recent UK support for TSE through a ringfenced budget in the AR4 contract for difference (CfD) auction and news that Allocation Rounds will become annual events, has reignited interest in the sector.
- The site specific nature of TSE is a barrier, which has implications for volume manufacturing (as, for example it would be impractical to have the blade length and rating of each turbine tailored to the specific local conditions). As more knowledge is gained, we envision that a modular approach with distinct product classes designed for "plug and play" high volume manufacturing could be better from the perspective of both manufacturing costs and levelized cost of energy (LCOE).
- There are key areas where the industry can collaborate. Manufacturing research themes include blade design and materials, standardisation of wet mate connectors and subsea cables, design and manufacturing of foundations and subsea hubs. Across the UK and France there are examples of supply chain clusters which could also contribute to sharing of knowledge, for example companies working in Pembroke Dock.
- Testing is vitally important, and will help to inform the manufacturing process (for example informing technology developers about optimal material selection and component dimensions in areas such as blades). Design and manufacture of these test rigs can be expensive, and so developers should take advantage of testing facilities available at research institutions/academia where possible (for example ORE Catapult's 1MW and 3MW drive train test rigs, the University of

Edinburgh FASTBlade and FloWave facilities, testing facilities at the National Composites Centre).

- Other barriers identified included the need for improvements in blade manufacture, the need for improvements in foundation design, availability of vessels as the industry scales up and the need to move away from bespoke manufacturing of selected components.

The roadmap was formulated through literature review, examining the current manufacturing “state of the art”, and industry engagement, whereby we surveyed about 50 suppliers for the industry and interviewed 12 companies (including three tidal technology developers) to get their direct thoughts.

Key industry milestones and timescales are summarised in Figure 1. We believe consistent revenue support will naturally lead to a strong pipeline of projects. This will cause more suppliers to want to diversify into the tidal industry, improving competition and leading to lower costs and hence, a more competitive technology. By addressing the barriers identified in this study we believe that the industry in the UK and France could reach a cumulative capacity of 1.5-2.6GW by 2035, with hundreds of devices being installed per annum.

We identified eight key barriers to volume manufacture, and suggested actions that will reduce these over time as the industry matures. The evolution of these barriers and actions are shown in Figure 2.

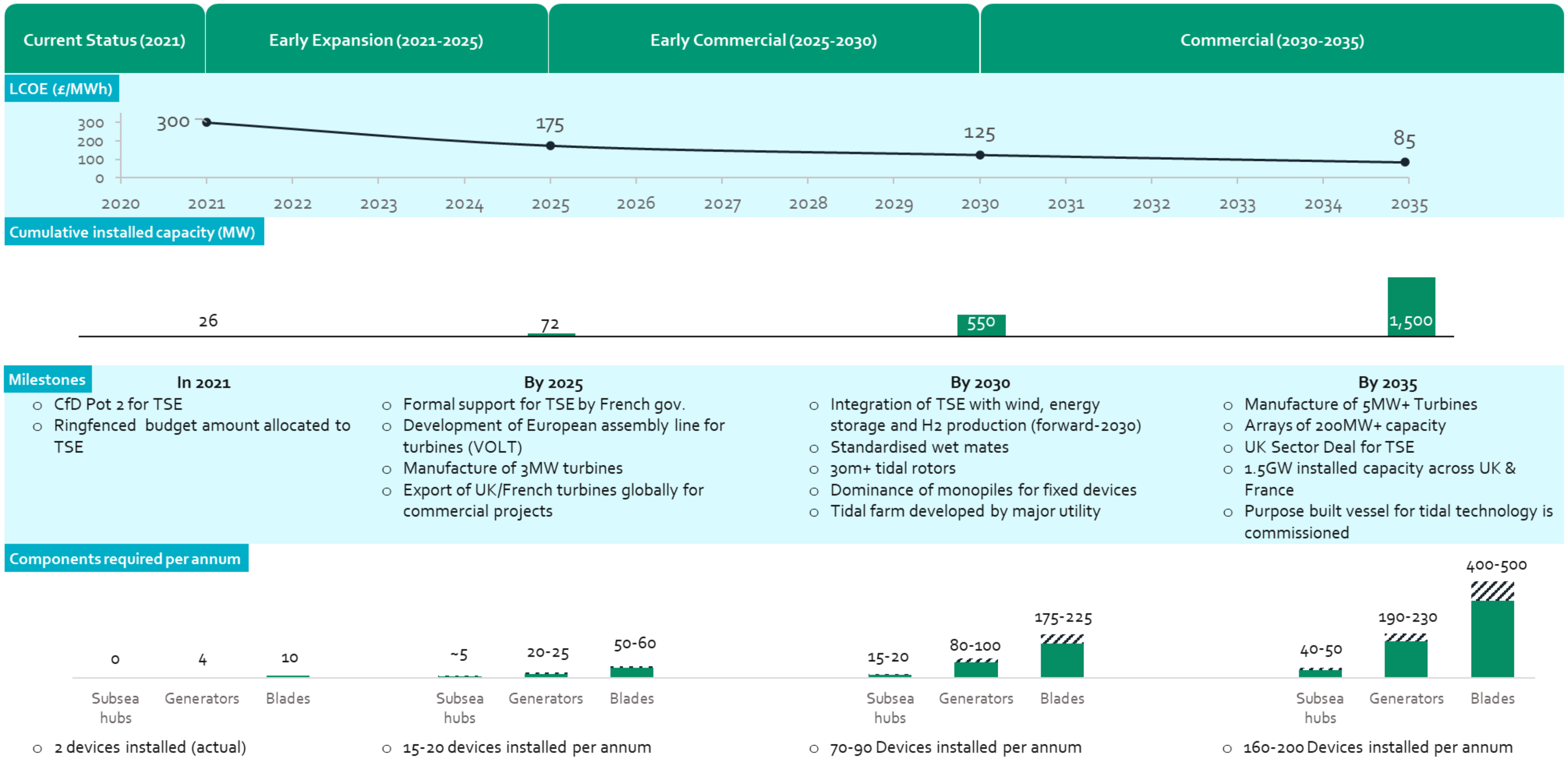


Figure 1 – TSE manufacturing and milestones out to 2035 - Baseline

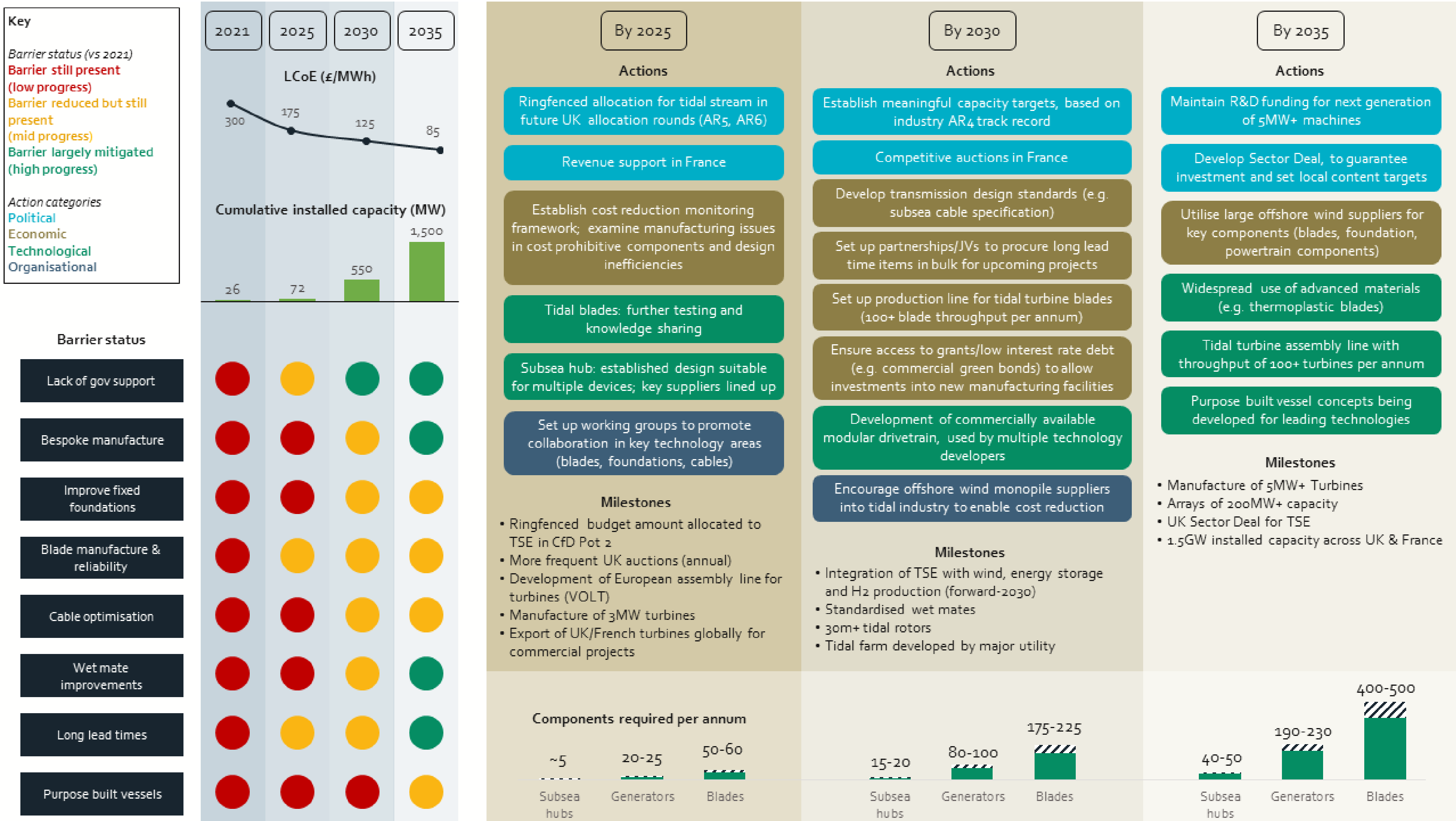


Figure 2 – Progression of the eight barriers to volume manufacturing (left), alongside the actions that could ensure that the barriers are reduced (right).

1 Introduction

The Tidal Stream Energy (TSE) sector is an emerging, exciting form of renewable energy technology that uses tidal currents to generate electricity. It has a number of key advantages compared to other energy technologies, including:

- Close synergies with offshore wind technology. The majority of device concepts utilize horizontal axis rotors, with similar powertrain components and configuration. This means that offshore wind supply chains can be utilized, with access to similar cost reduction pathways.
- Tidal sites tend to be close to shore. For example, utilising the tidal flows channelled around headlands and between islands. This reduces the amount of export cable and transmission cost in the system.
- Tidal flows are driven by the relative movements of the Earth, Moon and Sun. This means that the tidal resource is highly predictable and can be forecast hundreds of years into the future, thus reducing balancing requirements and hence reducing cost in the wider energy system.
- The nature of the tidal resource means that it is completely uncoupled from other renewable resources, including wind and solar. This timing difference has potential advantages for the energy system, helping provide more consistent supply and reducing curtailment in the system.

Despite these advantages, the industry has struggled to grow in terms of deployed capacity. To date, the majority of projects have been pre-commercial demonstrator projects. In the UK there are only two TSE arrays (farms comprising of more than one device): SIMEC Atlantis's Meygen project in the Pentland Firth and Nova Innovation's Shetland Array.

A contributing factor for this has arguably been inconsistent government policy, and a lack of technology readiness in the sector, making it unable to compete since the transition to CfDs. As the technology is more expensive than other forms of renewable energy, this has restricted the flow of private capital into projects, with some form of initial revenue support being required for consistent, lower risk returns. The strong tidal currents and unique characteristics of each site means that installation and operations and maintenance (O&M) can be challenging, and the high energy density of water compared to air also means that the thrust loading on the turbines is higher (despite rotors being smaller).

While there have been significant previous studies focused on aspects like cost reduction, site assessment, improving energy yield, system design and environmental issues, to date there has been very little research into manufacturing considerations. While there has been some convergence into distinct devices classes (for example fixed bottom, floating, kite, horizontal axis and vertical axis), there is still a much wider variety of concepts compared to more established technologies like offshore wind or solar.

Through interviews with suppliers as part of the TIGER project, we have learnt that these different operating principles, bespoke components, and target markets bring up different challenges that require different manufacturing solutions to push the industry forward.

It is widely regarded that the technology has reached a point of operational reliability and survivability, e.g. MeyGen (SIMEC Atlantis turbines), Orbital Marine Power, Sustainable Marine Energy in Canada and Tocardo turbines. These examples of installed tidal technology have reached a state of continuous operation and are approaching a normalised O&M schedule. The next phase is to further demonstrate performance and reliability in a commercial project.

ORE Catapult assessed the state of the TSE sector and published findings in their 2018 TSE and Wave Energy Cost Reduction and Industrial Benefit report. It found that the TSE has potential to reach a levelised cost of energy (LCOE) of £150/MWh by 100MW installed (up from around 10MW which is currently installed), reducing to £90/MWh by 1GW installed, then to £80/MWh by 2GW installed – which would be cheaper than new build nuclear. This cost trend is shown in Figure 3. Further reductions are possible with additional focus on innovation and continued reductions in the cost of capital, as has been seen in offshore wind. Significant cost reductions are expected in the near-term as the industry takes the step from pre-commercial arrays to commercial projects. Scaling up to volume manufacture is a critical step in reducing the LCOE of TSE technology.

We want to see the TSE sector transition from single pre-commercial prototypes and small batches of devices to hundreds of devices installed per annum. To achieve this, consideration of manufacturing barriers and the transition to volume manufacturing for tidal stream is the next challenge. An efficient manufacturing process will unlock significant cost reduction potential for the industry, leading to lower project costs and an easier proliferation of worldwide deployment.

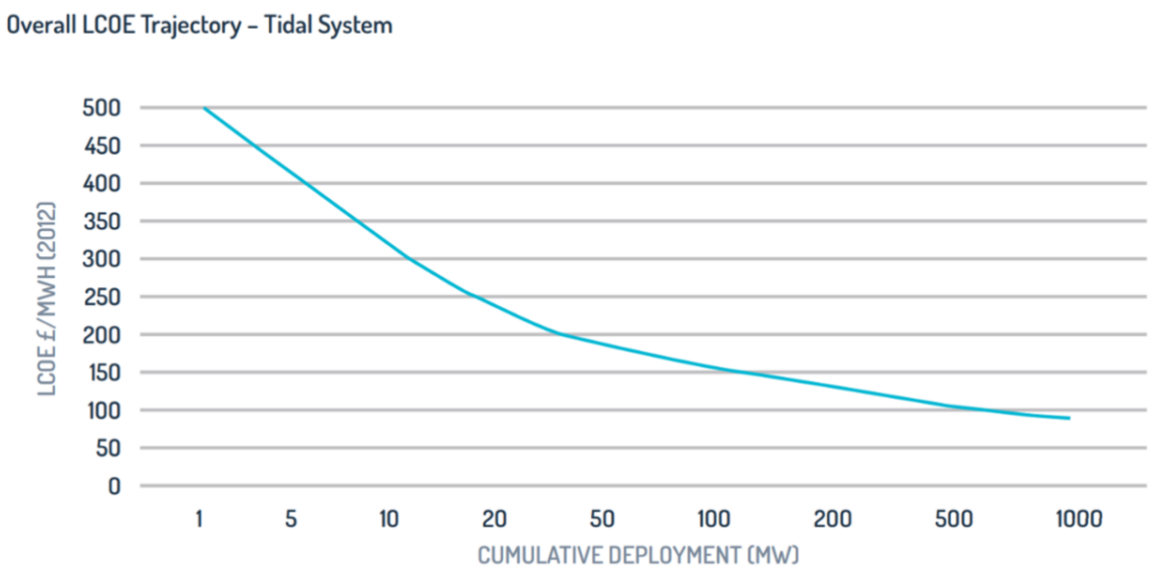


Figure 3 – Estimated TSE LCOE trajectory to 1GW

This report assesses the current manufacturing state of the art in the TSE sector and also presents a roadmap to outline present barriers and potential solutions that will help to prepare the industry for future growth and success out to 2035.

1.1. Aims and objectives

The aim of this study was to create a roadmap to outline how the tidal industry can smoothly transition from manufacturing small batches of devices in the present to hundreds of devices and 100MW+ arrays in the future.

This was to be achieved through the following objectives:

- Analyse the current manufacturing "state of the art" and other industries to see if there are lessons that the TSE industry can learn.
- Develop a market forecast to understand how many components would be required for a fully commercial tidal industry in the UK and France.
- Create a supplier questionnaire and interview key suppliers to get their sentiment on the industry and understand the current manufacturing capabilities.
- Interview TSE turbine developers to understand where the key manufacturing issues and cost constraints are.
- Describe the main sector barriers with implications to manufacturing and provide some suggestions to help upscale the sector for future growth.

This roadmap includes descriptions of the main barriers for commercialisation and upscaling, as well as identifying opportunities and policies that will help the industry to grow and provide meaningful contribution towards 2050 net zero targets. Focus is on the UK and France, but the challenges and recommendations are largely relevant for other markets too.

1.2. The TIGER Project

In 2019, the Interreg France (Channel) England Programme approved the biggest ever Interreg project. The TSE Industry Energiser Project, known as TIGER, is an ambitious €45.4m (~£38.76m) project, of which €29.9m (66%) comes from the European Regional Development Fund via the Interreg France (Channel) England Programme. It has been designed to be game-changing for the European TSE sector by bringing together leading tidal stream developers to collaborate and share best practice to accelerate deployment and provide evidence of cost reduction.

The TIGER project was launched in October 2019 and will be complete in June 2023. It falls within the funding category for low carbon technologies, whose managing authority is Norfolk County Council. They co-fund collaborative projects between organisations in the south of the UK and the north of France.

The project is delivering new designs for improved performance and lower cost turbines, as well as associated infrastructure and ancillary equipment. It is establishing cross-border partnerships to develop new technologies, test and demonstrate them at a number of locations across the Channel region, and use the learning from this development to make a stronger, more cost-effective case to UK and French Governments that tidal stream energy should be a part of the future energy mix.

The TIGER project will demonstrate that TSE is a maturing industry, capable of achieving an accelerated cost reduction pathway, and will position the Channel region at the heart of the sector by:

- Addressing technology challenges.
- Building the supply chain.
- Switching on new sites.
- Installing new turbines.
- The project aims to drive the growth of TSE by consenting 10+MW of new tidal capacity at sites in and around the Channel region, thus driving innovation and the development of new products and services. This will ultimately lead to:
- A reduction of greenhouse gas emissions (approximately 11,000 tonnes per annum).
- Investment in coastal communities, leading to an economic increase in GVA of €13m (~£11.1m) per annum.
- A tidal energy cost reduction towards the European target of €150/MWh (~£128/MWh).

The total theoretical TSE capacity in the Channel region is nearly 4 GW, enough to power up to three million homes. Proving that TSE generation can be cost-effective on a large scale could open the door for it to become the renewable energy of choice in coastal locations with strong tidal currents globally, helping the growth of clean, green energy production and tackling the climate emergency.

TIGER will make a stronger, more cost-effective case for TSE to become part of the energy mix in the UK and France by harnessing economies of scale via volume manufacturing and multi-device deployments. Coastal communities used as ports of deployment will benefit from knock-on investment and job creation.

1.3. Report structure

This report continues with the following sections:

- Section 2: Literature review, summarising the learning that can be gained from other industries and roadmaps.

- Section 3: Description of the current manufacturing state of the art, including the main components, methods and materials used in the TSE sector.
- Section 4: Insights from industry engagement that was used to shape the roadmap.
- Section 5: The final roadmap, including policy recommendations and potential barriers.

2 Literature review

In this section a review of existing literature has been undertaken to gauge how manufacturing can be upscaled for TSE. To do this, research into barriers that have stifled the growth of TSE will be examined before exploring barriers that offshore wind faced when it was at a comparable stage of market maturity. To gain insight into potential issues that TSE may face once it has come of age, the challenges that offshore wind faces today moving towards 2030 are put forward. Following this, examples of approaches taken by the solar photovoltaic (PV), automotive and aerospace industries are discussed, with these industries having been transformed in the long-term through enhancing and upscaling their manufacturing processes while growing their supply chain capabilities. At the end of this literature review, a summary discussion is presented before conclusions are drawn on this section of the report.

2.1. TSE Energy – Key Issues and Challenges

The purpose of this report is to identify avenues in which TSE can achieve improved economies of volume, with this increase in manufacturing capability being vital in supporting a decrease in the LCOE. To support this, key barriers to need to be removed. In the context of the UK and France, the greatest barriers with implications for the TSE industry as a whole have been identified as:

- The lack of a clear, structured policy position from government that supports a pipeline of TSE projects that increase in capacity and volume over time. If government support can help in creating said pipelines, for example by providing revenue support in the form of a Contracts for Difference (CfD), project developers can access a sustainable revenue stream, get devices in the water and reduce costs via “learning by doing” [6], [7].
- The need for advancements in blade reliability. To date, the most common reason for TSE projects being unsuccessful is due to mechanical blade failure [8]. There are multiple factors which contribute towards blade failure, such as fatigue loading and corrosion from biofouling within the marine environment. This makes improvements in blade reliability and manufacture one of the biggest areas in which cost reductions can be made [6].
- The need for optimisations in mooring and foundations to lower costs. Innovations are needed to improve the material efficiency of fixed tidal foundations. Without some government intervention, advancements in moorings and foundations will develop at a slower pace and at a smaller scale [6], [7], [9].
- The need to develop suitable vessels for the installation and retrieval of devices and foundations. Suitable vessels do exist, but the TSE industry must compete with offshore wind and oil & gas (O&G) for their services. This is particularly the case for larger devices fixed to the seabed on gravity base or monopile

foundations, which require heavy lift or jack-up vessels. Financial support from government that increases accessibility to appropriate vessels while using locally trained workforces to install turbines is one way of improving installation processes [7], [9].

- By some estimates, O&M can account for around 43% of the LCOE for fixed TSE [6]. Demonstrations in improved O&M processes will enable a lower lifetime cost of TSE which in turn will increase its competitiveness against more established low carbon technologies [7].
- A lack of understanding of optimal spatial arrangements for large arrays and how one turbine interacts with another with regards to wake effects, blockages and potential cumulative impact effects [10] [11].
- A complex, costly planning and approval process creates a dynamic where the price of environmental assessments which until reviewed carry no guarantee of success, cause TSE to have a very poor risk/reward compared to that of more mature low carbon technologies, particularly when it comes to environmental impact assessments [6], [7].

2.2. Learning from the UK's offshore wind journey

One of the great success stories of the last decade has been the rapid expansion of UK offshore wind and how quickly cost reductions have been made. This can be demonstrated by the continuous lowering in strike prices met at CfD auctions, with the lowest strike prices going from £114.39/MWh in Allocation Round 1 (2015) to £39.65/MWh in Allocation Round 3 (2019) (Both adjusted to 2012 prices) [12], [13]. In

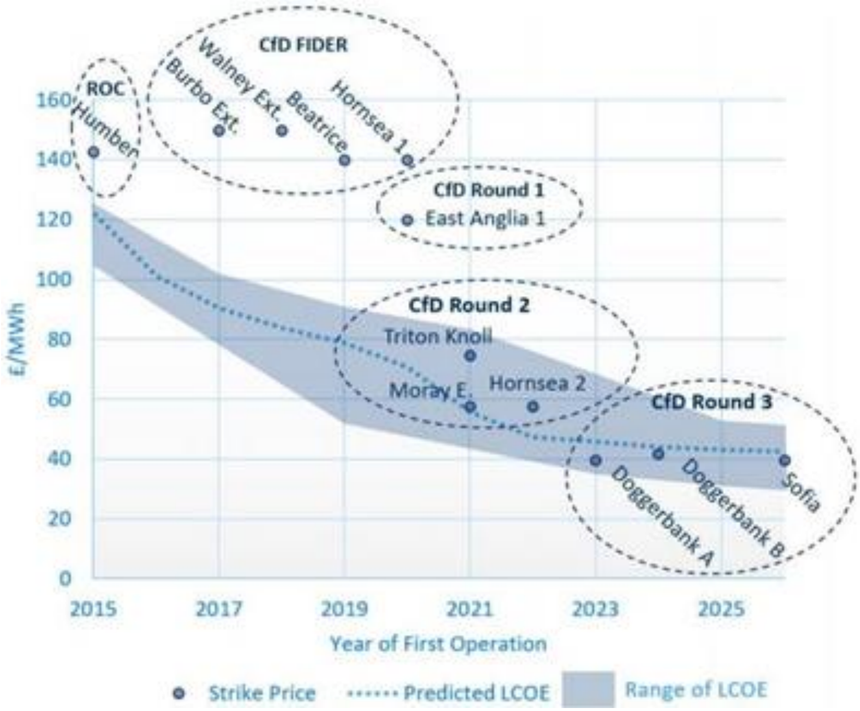


Figure 4 – CfD auction strike prices and estimated LCOE by auction round [14].

Figure 4 the fall in CfD auction strike prices and the estimated LCOE for each auction round is illustrated [14].

With CfD Allocation Round 4 in 2021/2022, strike prices are expected to drop further. This is apparent from the provisional administrative strike prices published in September 2021 [15]. The upscaling in installed offshore wind capacity from 1.3GW in 2011 [16], to 10.4GW in 2020 [17], can be attributed to commitments made by government and industry at the beginning of the 2010’s, with the main priorities including [16]:

- Funding innovations that reduce the cost of projects.
- Minimising risk to investors and introducing pricing mechanisms that support de-risking (i.e. CfD).
- Creating a clear planning and consenting process.
- The development of a mature supply chain.
- From the points listed above, the approaches made to remove market barriers for offshore wind a decade ago bear some similarity to the market barriers that TSE faces today. This could give policymakers a framework to draw knowledge from if they wish for the TSE industry to follow a similar trajectory to that of offshore wind.
- Regarding global offshore wind, recommendations put forward in 2009 to grow the industry (before offshore wind became the mass-manufactured technology that we see today) included [18]:
- Developing stronger, lighter materials to enable larger rotors and nacelles, and to reduce dependence on steel for towers.
- design of a new generation of offshore turbines with a minimum O&M requirement.
- Accelerate automated, large-scale manufacturing closer to installation sites for economies of scale and cost reduction, with an increased number of recyclable components.
- For offshore deployment, make sufficient purpose-designed vessels easily accessible.

2.3. UK offshore wind moving forward

As offshore wind turbines are scaled-up while prices move down, a clear and ambitious strategy is paramount to the continued success of the industry. Central to this is the Sector Deal which aims to have 40GW of offshore wind installed by 2030 [17]. With such bold targets comes the discovery of new barriers for the industry to overcome, with several recommendations to remove said barriers listed below [19]:

- Continue to remove barriers to the consenting process. Actions include collaboration with relevant government bodies to develop a *"strategic level approach to Marine Spatial Planning and the Habitats Directive derogation process across UK Government".*
- Annual CfD allocation rounds to avoid developers rushing to achieve consent and ensuring a steadier set of order books across the supply chain. Until recently, allocation rounds were approximately every two years [20], but in 2022 the UK government announced annual auctions.
- A strategic approach to increase UK content in the domestic supply chain as well as UK companies becoming key competitors in the global supply chain.
- A strategy for floating offshore wind to eventually compete with bottom-fixed in the long-term. Government funding in the near-term would support this.
- Allowing geographical diversity of offshore wind to fairly distribute the benefits of the industry as well as improve security of supply nationwide.

2.4. Lessons learnt from other industries

This section describes the lessons that can be learnt from other industries which have greatly advanced their manufacturing and developed their supply chains.

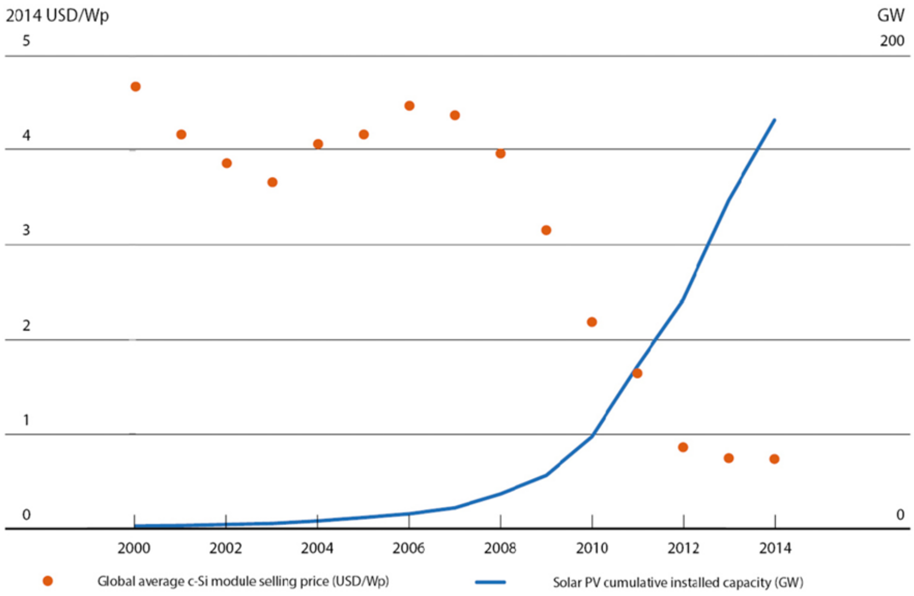


Figure 5 – PV module prices and cumulative global PV deployment 2000-2014 [21].

2.5. Solar PV

For the global PV industry, the last 20 years have seen vast reductions in the unit cost of panels, alongside exponential growth in panel production, especially for crystalline-silicone (c-Si) modules. Reductions in the unit cost of c-Si modules and increases in installed global capacity for PV are shown in Figure 5 [21].

To continue this trend of increased manufacture and reduced cost, recommendations put forward by the International Renewable Energy Agency (IRENA) to spur the long-term growth of PV included [22]:

- Encouraging the formation of localised supply chains and local manufacturing (i.e. high proportions of domestic content).
- Putting emphasis on education and training to ensure skill gaps are not present when trying to create local supply chains for modules and inverters.
- Assisting in upscaled manufacturing of higher efficiency solar cells which will take up less space to produce an array of a given capacity, as well as using cheaper materials which will further drive down manufacturing costs.
- For the UK, main recommendations to encourage long-term growth of PV manufacturing have included [23]:
- Giving local authorities more autonomy in decision making for their local power networks and implementing pricing mechanisms which will help facilitate this
- Bringing in regulations which future-proof new buildings for PV

- Taking action that forces Distribution Network Operators (DNO's) to prepare for the emergence of solar PV/storage combinations as a significant part of their networks.

2.6. Automotive

Of all the industries being discussed in this section, the automotive industry by far is the oldest. It has seen itself mature over 100 years, with its development taking place over a period that has seen the rise of production lines and the introduction of automation to increase production efficiency. In Figure 6 the global production of automobiles is shown for the period 1900-2016 [24].

One of the better-known philosophies that has been influential in increasing manufacture volume and reducing time throughout the automotive production process is the Toyota Production System. This philosophy focuses on minimising the "seven wastes" seen within the supply chain and production line which includes overproduction, wait times between operations and inappropriate processing [25], with areas of this philosophy being perfectly transferable to mass manufacturing in a wide range of industries.

When assessing the future automobile industry, manufacturing processes will become almost fully automated, with robotics being crucial in reducing human interaction as AI allows them to become more productive, efficient, and ecologically friendly [26]. With the automotive sector seeing substantial growth in electric vehicles in recent years, upscaling in the manufacture of batteries has become of equal importance, and with this has seen the emergence of "gigafactories" which has allowed for more centralised production, increasing units produced per annum while driving down costs by having a

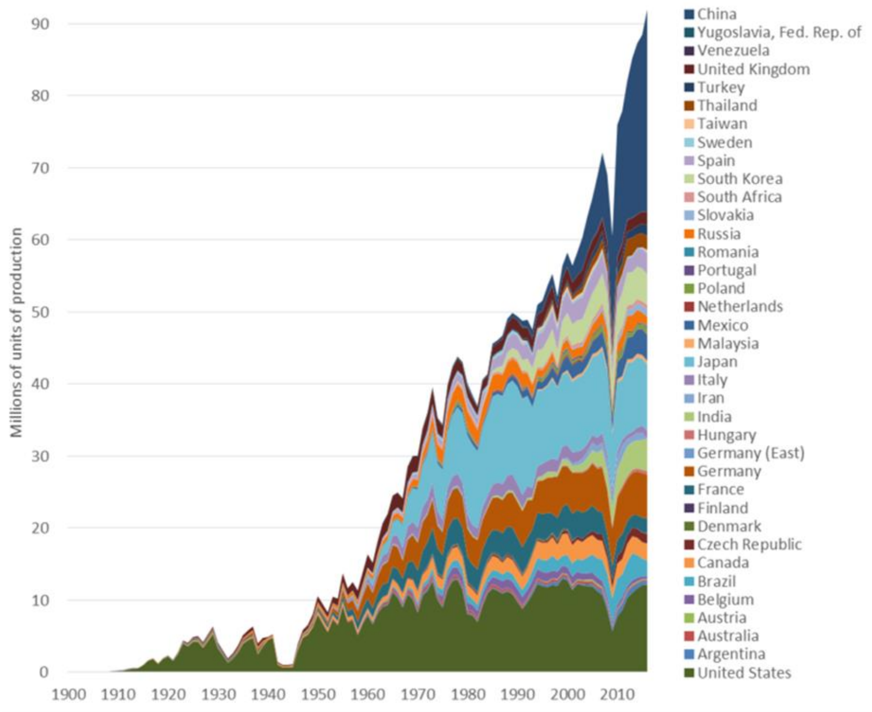


Figure 6 – Global automobile production per annum, 1900-2016 [24].

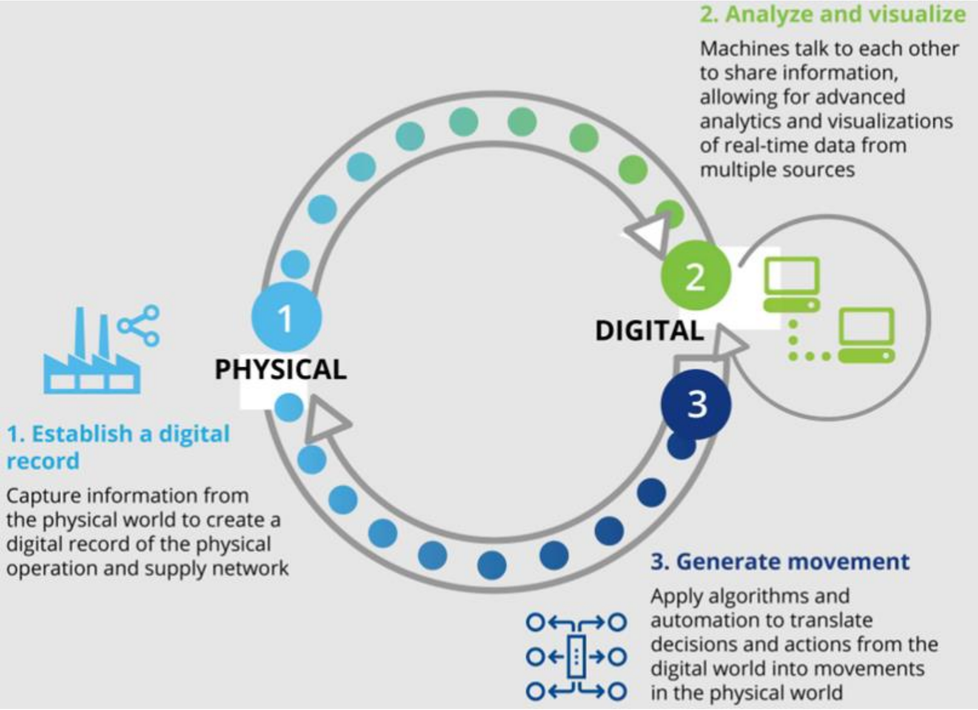


Figure 7 – Physical-to-digital-to-physical loop [30].

greater proportion of components being made in-house [27]. Between 2018 and 2028, Europe is expected to see its global share of Lithium-ion batteries increase from 4% to 17%, with demand being sufficient to the point where the UK could operate two gigafactories by 2025 (subject to suitable locations being selected and securing all necessary permits) [28].

2.7. Aerospace

Similar to the automotive industry, automation and digitalisation has been cited as some of the most effective methods to upscale manufacturing and increase the productivity and competitiveness of the sector. As human involvement reduces in the manufacturing process, what human workforce remains will require *"the understanding of, and ability to operate across, numerous disciplines".* This shift to digitalisation will not only be used to increase the efficiency seen in the manufacturing process, but across the entire aerospace supply chain with the emergence of Industry 4.0 [29]. Industry 4.0 is the fourth industrial revolution which enables digitised manufacturing which, unlike previous automated technology, has far superior analytical and communication abilities, and uses these abilities to learn from previous operations to optimise future operations using physical-to-digital-to-physical loops as shown in Figure 7 [30].

When considering the interconnectivity that Industry 4.0 will bring between different technologies, several of these technologies have been listed below along with their application within the arena of aerospace manufacturing [30]:

- Additive manufacturing (3D printing) – Combining materials to speed up prototyping and improving the manufacture of individual components within aircraft.
- Blockchain – Improving data transparency between supply chain partners and enhancing validation in supplier performance.
- Digital reality – Using virtual reality to assist in optimising factory design while improving health and safety for factory workers.
- Internet-of-Things – Managing cost and demand of materials and components through big data analysis. Monitoring aircraft health via the use of data collected via sensors.

2.8. Conclusions

It is apparent that the lack of a structured policy position from government is the most problematic barrier that prevents TSE from becoming more competitive on the market while making future revenues more predictable. However, in the UK there is some room for optimism with TSE being included in Pot 2 of CfD's Allocation Round 4 while receiving £20m a year in ringfenced support [31]. The capacity that will be awarded to TSE this allocation round will be dependent on the amount of the Pot 2 budget it successfully obtains, alongside the strike prices that are met for TSE (£211/MWh being the administrative price ceiling) [32]. Outside of the lack of a clear project pipeline, the remaining barriers would appear to be ones that can be mitigated through the types of cross-national collaboration that TIGER seeks to achieve.

As the TSE industry is currently at a lower level of market maturity, learning lessons from a broad range of industries will help to develop a long-term strategy to enable the development of cost-competitive, mass-manufactured tidal turbines. By observing the progress of the offshore wind industry in the UK and globally, a foundation can be established in which the TSE industry can build on. This includes the development of appropriate funding mechanisms to support TSE, as well as financing innovations that drive down costs while maturing the supply chains of such innovations.

When looking at UK offshore wind and where it is today, a similar trajectory has been experienced by global solar PV, with both industries having experienced a rapid fall in the LCOE while seeing ever-increasing installed capacity. Ensuring a strong degree of localised content within each industries supply chain has been recommended to support the future growth of each set of technologies. However, despite there being recommendations to increase domestic content and train localised workforces in solar PV manufacture, the current PV cell market remains dominated by China. By heavily subsidising C-Si modules, China has supressed prices to the point where production and investment in new cell innovations has become financially unattractive elsewhere [33]. With this in mind, despite the TSE industry pushing hard to lower project costs in the near-term; the long-term focus for TSE should be placed on having a diverse set of solutions and not allowing one technology to slow innovation simply by being the cheapest option at a particular moment in time.

The automotive and aerospace industries have similarities in their approach to future-proofing their manufacturing, with further automation a key theme. Although it is difficult to draw comparisons between the manufacturing processes of these advanced industries and the nascent TSE industry, the concept of a more centralised production line which minimises waste via the use of Industry 4.0 technology is something for producers of both wind and tidal turbines to consider beyond the next decade.

So what are the key read across from other sectors?

- Technology and materials improvements driving up efficiency and reliability
- Easier installation
- Reduced O&M
- Now advancement of AI and automation

3 Current state of the art: components and manufacturing

TSE devices come in various scales and designs and are manufactured from a wide range of strong durable materials. In simple terms, a turbine structure consists of a rotor that has aerofoil shaped blades attached to a hub; a nacelle that houses a drivetrain containing a gearbox (or sometimes direct drive) which is connected to shafts, supporting bearings, a generator and other machinery; a tower, and ground-mounted electrical equipment.

Reducing the LCOE of the technology is key to making TSE cost competitive with other power sources. To achieve this, the real driving opportunity today is to increase device scale (rated capacity), introduce high volume production and improve material selection while ensuring all engineering design and manufacturing specifications are maintained to standards. In addition to weight and cost of these components, there are foundations or anchors and conventional ground-mounted electrical systems to take into consideration.

In engineering design, material selection is a one of the main criterions that determine the success of a final product. The material must satisfy both the function and design operating conditions of the component. The factors affecting the selection of current TSE turbine materials can be summarised as following:

- Component shape
- Dimensional tolerances required
- Mechanical properties (e.g., strength, stiffness, hardness, fatigue strength etc.)
- Chemical Properties (e.g., corrosion properties)
- Physical Properties (e.g., density)
- Life cycle cost (e.g., cost of material, cost of manufacture, cost of maintenance and cost of installation and removal).

Until now, the industry has focused on higher-cost, low-volume prototype blades (much as the wind turbine industry did during early stages of development). The blades of the device harvest the kinetic energy from the movement of water and transmit this through the main drivetrain to the generator. This is achieved as the water currents act on the surface of the rotor blades forcing them to rotate. The generated energy is transmitted via an export cable either directly to a user or fed into the utility grid. Tidal blades are shorter than equivalent wind turbine blades[1]. They are also significantly

[1] As a comparison: SIMEC Atlantis's 2MW AR2000 tidal turbine is designed with an approximate 20-24m rotor diameter (9m blade) which is much shorter than a 2MW wind turbine. For example the Vestas V90-2MW platform has a rotor diameter of 90m (44m blade length) [128].

stiffer and stronger, largely because of the difference in density between water and air and the complex loads tidal blades are subjected to [34].

The design and manufacturing of tidal blades has been led by a relatively small number of specialist suppliers. Some examples of tidal technology developers and their concepts built to date are listed in Table 1. While the wind industry has settled on three-bladed horizontal axis turbines as their main energy convertors, the TSE sector continues to innovate and develop differing technology concepts and devices.

There are differences in design of smaller and larger devices, allowing for the introduction of new material technologies and manufacturing methods. Smaller devices are generally designed for less extreme tidal conditions, with lower loads, and therefore material absolute strength (cross sections) can be reduced. . Some developers take the approach of developing smaller scale devices first (<100 kW), to demonstrate proof of concept and to allow device iterations to be manufactured and deployed more quickly. The majority of companies with turbines at these scales do plan to develop larger devices into the future, to take advantage of cost reduction through economies of scale. Material fatigue properties and mechanical properties are an important consideration in turbine design and materials selection. During the expected life cycle of the turbine, many components are expected to endure 4 x 10^8 fatigue stress cycles (for wind devices) which proves to be greater than aircrafts, automotive engines, bridges and most other man-made structures.

Company	Device	Rated power (MW)	Number of blades per rotor	Nominal blade length (m)	Project
SIMEC Atlantis	AR1500  Image source: [35]	1.5	3	9	Meygen (2018)
Orbital Marine Power	O2  Image source: [36]	2.0 (2x 1MW rotors)	2	10	EMEC deployment (2021)

Sabella	D10  Image source: [37]	1.0	6	5	Ushant Island (2015)
Nova Innovation	M100  Image source: [38]	0.1	2	4	Shetland Array (2016)

Table 1 – Examples of TSE technology developers and their devices manufactured to date.

3.1. Blades

3.1.1 Materials

Like offshore wind turbines, the blades of offshore TSE devices are typically manufactured using glass fibre-reinforced-plastic (GRP). An annotated cross section is shown in Figure 8 [39]. Other materials that have been explored for use as tidal blades include steel, aluminium, copper, various composites and carbon filament-reinforced-plastic (CFRP).

The advantages of GRP are that it is lightweight and not susceptible to corrosion. While leading edge erosion is a problem for wind turbines, reducing the lifespan of blades and requiring routine maintenance and blade replacement, this is not such a problem for tidal turbines. This is because locations tend to be rocky, with low amounts of sediment to cause the erosion. However, a problem for tidal turbine blades is that, because they are submerged, water can ingress into the blade. Studies have indicated that the fatigue life of water saturated blades can be reduced by 1-3 years, which can be counteracted by slightly increasing the laminate thickness [40]. Thinner blades are known to have better hydrodynamic performance [41], giving an example of the kinds of trade-off that must be considered at the product design stage.

Metal blades have been demonstrated on small prototypes, and some developers are considering them commercially. While these materials have high tensile strength, in theory improving lifespan and durability, the blades become too heavy for longer blade lengths. The additional weight is a problem both in design (for example more strength is needed in the blade root connection, bearings and foundation to counteract the front-heavy mass distribution) and for operations, as additional weight will require larger cranes and vessels at greater cost.

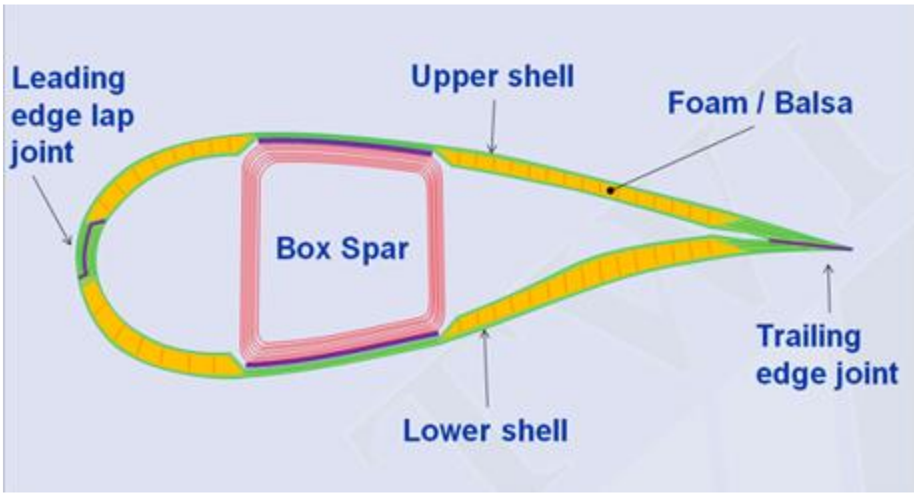


Figure 8 – Cross section of a typical wind turbine blade [39].

Tidal turbines are subjected to high and variable loading, which puts stress on the blades through high bending moments and shear loads [42]. For this reason, typically the blade root, where the blade is connected into the hub, will have metalwork for reinforcement.

An example of a more specialised composite used for tidal turbine manufacture is powder epoxy. Eire Composites, a supplier based in Ireland, use a material known as Composites Powder Epoxy Technology (CPET). Advantages include low exotherm (heat given off) during curing, a good fibre volume fraction (which has improved strength) and a long shelf life compared to traditional epoxy resins [42]. There are, however, environmental downsides including a relatively high water usage (especially if titanium dioxide is used to create the powder resin) [43].

3.1.2 Manufacturing Process

There are several well established manufacturing methods that are used for wind turbine blades and would also be suitable for composite tidal blades.

In its infancy, the manufacture of wind turbine blades was achieved by manual production methods, with blades often being produced using wet hand lay-up technology, in open moulds. This required applying resin using paint brushes or rollers, with the shells connected to the central spar using adhesive [44] This approach possesses many disadvantages including high labour costs, relatively low quality of products and environmental problems.

Later developments introduced vacuum infusion and prepreg ("pre-impregnated") technologies. The prepreg technology, derived from the aircraft industry, utilizes pre-impregnated composite fibres already containing an amount of the matrix material bonding them together.

At present, the most widely used manufacturing process for producing blades is resin infusion technology. This technology scales well to larger blades. During the process, fibres are placed in closed and sealed moulds, and resin is injected into the mould cavity while subject to pressure. As the resin fills the total volume between the fibres the component is cured with heat. The resin infusion technologies can be divided into two groups: Resin Transfer Moulding (RTM), resin injection under pressures higher than atmospheric pressure, and Vacuum Assisted Resin Transfer Moulding (VARTM), where resin is injected at pressures lower than atmospheric pressure. VARTM is the preferred method of manufacture. VARTM uses a vacuum to transfer resin into a fibre layup contained within a mould tool. Once the impregnation is acheieved the composite part is allowed to cure.

This manufacturing method is well suited for upscaling, since the number of resin inlets and vacuum suction points can be increased. However, in practice, upscaling can be challenging as the layer of dry fabrics must be kept in place so they do not slip relative to each other. Failing to do this will produce wrinkles at double-curved areas and areas with un-wetted fibres, and air bubbles can be entrapped in the bond lines.

Generally, the infusion process is cheaper, however, prepreg composites are more stable, with less varied mechanical properties than those produced by resin infusion. Prepreg technology is also relatively environmentally friendly [45] and makes it possible to achieve higher volume content of fibres.

Prepreg methods have been used on tidal turbine blades, for example Gurit's blade design for Andritz HYDRO Hammerfest's 1MW HS1000 turbine [46]. This was tested at EMEC in 2011. UK based supplied A C Marine & Composites used a resin infusion technique to manufacture blades for SIMEC Atlantis's Meygen project [47], and 10m blades for Orbital Marine Power's O2 device [48]. They also state experience with prepreg manufacturing capabilities

3.1.3 TSE Blade Limitations

Information detailing the range and extent of damage found and repaired in operating TSE devices is generally unavailable, due to lack of operating hours and commercial non-disclosure. The static loads and cyclic loading applied to the blade during initial verification and validation can result in failures of various modes. A major concern is that these modes are not easily detectable in-field since the damage does not originate from the external surfaces and may not be visible. For example, in thick composite parts, wrinkles may lead to the formation of compression failure and delamination. Cracks and delamination can also start from processing details such as ply-drops that locally cause a stress concentration. Cracks at trailing edge bond lines can be seen visually, but it is more difficult to assess how far they extend into the composite's structure.

In addition to the various structural loading effects, tidal turbine blades can also be subjected to cavitation, bio-fouling, erosion and corrosion while in operation. These factors will affect the durability and the performance of tidal turbine blades and must be considered in the development of TSE conversion systems.

3.2. Nacelle/Hull

The nacelle component of a turbine contains an array of complex machinery including a yaw system (optional), gearbox (optional), generator, drive brakes, shafts, bearings, oil pumps and coolers, controllers and more. These parts are mounted onto the structural frame of the nacelle. The frame is made of two main parts. The front end of the nacelle is commonly made of cast steel and holds the yaw system, gearbox, and main shaft. The generator, transformer, and electrical cabinets are positioned to the rear frame constructed of formed and welded steel.

3.3. Gearbox

Some commercially available TSE devices are based on the use of a gearbox (e.g. Minesto, OMP, SIMEC & Andritz Hydro Hammerfest) while some are direct drive and hence do not need a gearbox (e.g. Hydroquest, Sabella, Nova Innovation). The gearbox of a tidal turbine transmits the power from the low-speed high torque rotor to the generator operating at high speed and low torque. Unfortunately, due to the unforgiving operating and environmental conditions that TSE turbines are subject to, there are several challenges to designing and manufacturing a robust TSE turbine gearbox. The high torque rotor when transferring its mechanical movement to the gearbox subjects the drivetrain to enormous amounts of force. The gearbox must be designed to withstand these high loads to prevent premature wear of internal components, achieve longer preventive maintenance cycles, and prevent costly breakdowns. As of 2021, one of the largest manufacturers of gearboxes is Winergy, a German company who have supplied over 175GW of wind turbine gearbox capacity worldwide. The physical configuration of gearboxes varies depending on the types of gears employed, examples of gear types are shown in Figure 9 [49].

For candidate tidal turbines, a four-stage configuration is used consisting of three planetary stages and one helical-parallel stage with a ratio of approximately 200:1. Usually, the components are manufactured using steel, aluminium or brass – this is the case for both planetary and spur gears.

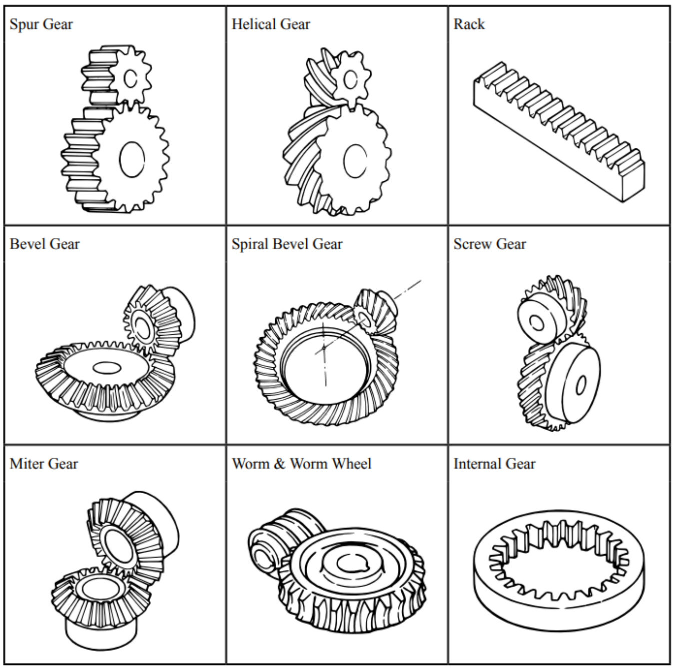


Figure 9 – Types of gears used in different gearbox configurations [49].

Due to the level of complexity and inaccessibility, tidal turbine gearboxes can result in a significant cost increase in the event of unplanned maintenance and long downtime. Failures in gearboxes are essentially related to the uncertainty associated with loading condition during the design phase. The common gear failure modes reported are pitting, spalling and bending fatigue.

An alternative to the gearbox is direct drive technology. This eliminates the need for a gearbox, with conversion achieved electrically rather than mechanically. Direct drive technology has increased efficiency as kinetic energy is almost always lost during energy transfer in a gearbox system. With fewer moving parts, direct drive design is less complicated to maintain, and higher energy yield is possible. The disadvantages of direct drive are that costs are higher and the generator is much heavier (2-5x), leading to a heavier nacelle even with the absence of a gearbox [50]. While direct drive turbines have been shown to have higher absolute failure rates in wind turbine applications (up to 30-100% greater), the failures are generally less catastrophic with less associated downtime (for example gearbox replacements will require heavy lift vessels) [51].

3.4. Generator

The generator of a tidal turbine converts the mechanical energy into electrical energy by using the properties of electromagnetic induction. A simple generator consists of magnets and a conductor, where the conductor is usually a coiled wire. As for a wind and tidal turbine generators, the shaft connects to an assembly of permanent magnets that surrounds the coil of wire. When the rotor turns the shaft, the shaft spins the assembly of magnets, generating voltage in the wire. The most common used generators in wind and tidal energy applications are induction, doubly fed induction, and permanent magnet synchronous generators. The leading suppliers are European companies such as ABB, Ingeteam, Siemens (via its purchase of Flender), and Elin, though a few OEMs outside of Europe have in-house manufacturing capabilities.

3.5. Foundation

Foundation structures are a key component of tidal turbines for keeping the devices on station. They also play the role of providing support for the turbine by transferring the loads to the seabed. As a result of intense and complex hydrodynamic forces exerted onto these structures, they require rigorous designs and are often large profiles on the seabed. There are several types of foundation structures that can be utilised, with this section looking at gravity base, monopiles and mooring systems in detail. The choice of foundation type is primarily based on technology strategy (i.e fixed bottom, floating or mid-water column) and then dependent upon local environmental conditions of the TSE site. High-volume manufacturing of these foundation types presents several challenges to the industry including logistics, sea-bed damage prevention, scalable manufacture processes and effective installation procedures.

3.5.1 Gravity base

Gravity base foundation types are one of the most commonly used in tidal turbine devices, utilising the fundamental laws of gravity to keep the device safely and securely on the seabed. It is critical that the weight of the structure is sufficient in securing the device as there is no permanent attachment to the seabed [52].

Current state of the art

Gravity base foundations consist of a supporting steel structure with added concrete or steel ballast blocks, which provides the mass required to weigh down the device to the seabed. Ballasts are effectively counterweights and hence require dense materials to provide adequate anchorage. The supporting structures are commonly assembled into a tripod configuration with the ballasts being integrated into each leg.
Gravity base foundations due to their size and mass are often transported to site on large and very expensive Heavy lift vessels or jack-up barges. In some instances heavy lift barges, pulled by tugs, have been used as a more cost-effective solution, although only viable over relatively short distances and at benign tidal sites. Some Gravity base foundations are designed to be buoyant and towed out to site and then lowered through its own ballast system. Suitable for one off installations, gravity base foundations aren't considered economical for large arrays where a drilled or piled monopile solution is considered more cost effective.

Materials: structural steel

The supporting structure must be manufactured from a high strength material as a result of the hydrodynamic loads transferred from the device and the subsea environment. Steel is primarily used for this due to its high strength properties, with an average ultimate tensile strength (UTS) of 400-1100 MPa, however this value is dependent on the carbon content within the steel [53]. The UTS is a mechanical property demonstrating the maximum stress a material can withstand while being subjected to tension.

Structural steel is not resistant to corrosion so before installation the structure requires a protective layer such as corrosion resistant paint and or cathodic protection systems. It is crucial that the component is fully resistant to corrosion so to avoid unnecessary maintenance and also to allow for maximum structural integrity for the life of the project. Structural steel has continually been used over other corrosion resistant materials, like Stainless Steel, due to its lower cost – even with the protection systems in place. It is also a relatively lightweight material, as material cross sections can be kept small due to a high ultimate tensile strength, allowing for easy transportation. In the context of volume manufacturing, this type of material lends itself well as a result of its attractive properties:

- Easy fabrication
- Recyclable
- Design flexibility

Carbon steel, stainless steel and nickel aluminium bronze (NAB) offer good corrosion resistance. While carbon steel comes in 3 main types, low or medium carbon steel is often used. For example, AISI 1018 and AISI 1045. Carbon steel AISI 1018 is mild/low, and it is widely used for engineering materials and in ocean applications. It also possesses good strength and ductility, considerably affordable and is easy to weld and cut.

Carbon steel AISI 1045 is a medium type. It is easy to weld and can receive heat treatment. Stainless steel is known for its corrosion resistance in many environments which carbon and low alloy tool steels would corrode. Examples of stainless steel include SS304, SS316, and SS316L. SS316L is the most preferred metal as it possesses properties closest to carbon steel S355, which is the main steel grade used in offshore subsea structures. This material provides high strength and ductility. However, SS316L is susceptible to pitting and crevice corrosion.

NAB has great strength and corrosion resistance that is commonly used in marine applications, especially ship propellers. Its corrosion resistance originates from a protective oxide film with a thickness of around several hundred nanometres.

Materials: concrete

With gravity base foundations relying on the weight of the structure to anchor it to the seabed, the primary material used in ballast blocks has been concrete. Concrete is a cheap material to purchase, without the global price fluctuations of steel [52] and has also been used in similar applications within offshore wind and O&G, proving its suitability. Concrete also possesses corrosion resistant properties enabling the ballasts to have a long operational lifetime however, as concrete requires steel reinforcement, there is a potential that this steel begins to corrode compromising the integrity of the ballast. Concrete foundations are bigger than their steel counterparts, as concrete is about three times less dense than steel. To get the necessary weight they have to be large, creating the issue of highly expensive manufacturing and transportation procedures. An increased size in ballasts translates to a larger supporting structure for the device [54], introducing more material costs. With ballasts of this size, concrete also has the potential to cause irreversible damage onto the seabed. While the impact is less than piled foundations, the footprint of these foundations is larger and so a greater seabed area will be affected. Concrete is also a carbon intensive material to produce which has implications when considering the life cycle analysis of technologies and their carbon footprint.

Materials: grey cast iron

More recently, grey cast iron alloy has been explored as an alternative material for the ballast counterweights. This material is a type of iron alloy containing carbon and silicon [55] where it can be made through a process of recycling steel, lending itself well to a low-cost, high-volume manufacture process and limited environmental impact. Grey cast iron alloys are also around five times denser than concrete which facilitates both the ballast and supporting structure to be greatly reduced in size. This means more foundations can be transported and installation costs will be significantly lower. Sabella have integrated this new ballast type into their turbine foundation design which allowed them to reduce the mass and volume of the support structure by two thirds [54]. A visualisation of their foundation is shown in Figure 10. Grey cast iron is well known for its simple machinability which allows for adaptability to various design requirements and further drives down the manufacturing costs involved. This form of cast iron also displays uncommon resistance to corrosion and impressive strength properties, proven through its extensive use in water distribution and plumbing applications [55]. The rate of corrosion for this material in some cases has been measured at around 0.2 millimetres per year, which is negligible within a subsea environment but could have an impact over the full project lifecycle (20+ years) [56].

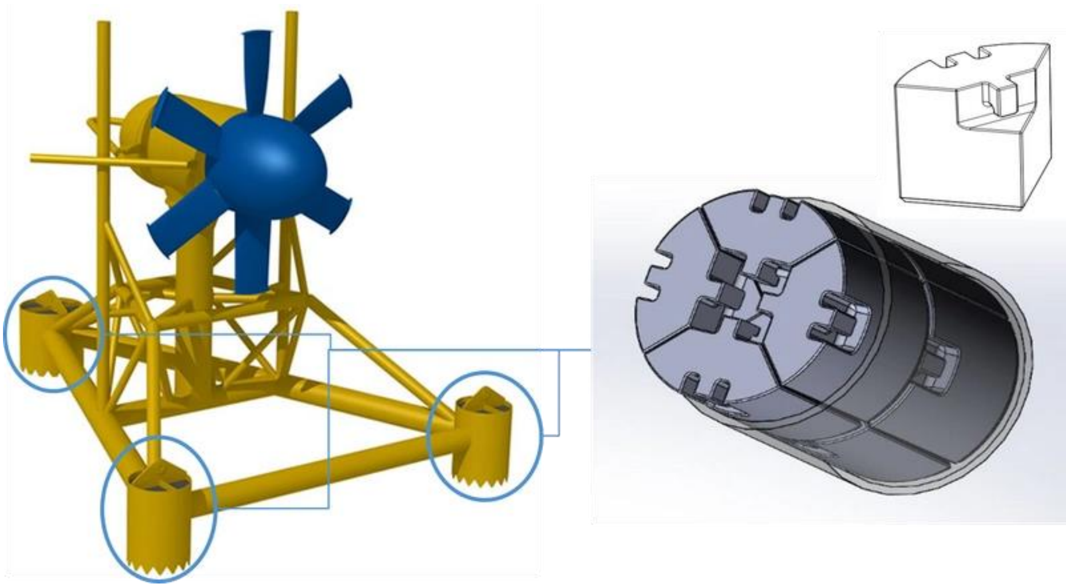


Figure 10 – Cast iron ballast used by Sabella on D10 turbine [54].

Manufacture

With some foundation structures reaching widths of 20m, for example Sabella's D10 turbine [57], this means large port areas must be dedicated to the manufacture of these structures. The manufacturing process also requires significant lifting capability, for example ANDRITZ HYDRO Hammerfest's turbine support structure weighs 150 tonnes [58].

With steel making up the majority of material used, this leads to an efficient manufacture process due to its flexibility with different shaping techniques such as casting, rolling and cutting. With prefabricated components already available this also allows for fast and economic manufacture procedures. As required in marine applications, steel must go through an anti-corrosion process as well as manufacture process. The surface of the steel must be prepared before any protection is applied and this is so that a sufficient surface quality is present in accepting the protective layer. A common technique is Manual Blast Cleaning in which utilises grit abrasives to achieve the desired surface finish. Paint coatings are then applied, often in a multi-coat paint system. Airless spray is primarily used in the application of these paint layers however brushes and rollers may also be used [59]. Joining techniques vary depending on the components involved but steel lends itself well to different methods such as welding, bolting or riveting. For support structures it is commonly seen that the components are joined by welds.

For the manufacture of concrete ballasts this follows the simple method of pouring concrete into the desired formwork with steel rebar inside to give the ballast strength. The difficulty comes from the size and lifting requirements of concrete ballasts.

3.5.2 Monopile

Monopiles are another foundation type used in securing tidal turbines to the seabed. An annotated depiction is shown in Figure 11 [60]. They have been extensively used within the offshore wind industry. The installation procedure is more involved than for gravity bases, however monopiles have smaller profiles on the seabed and will likely have cost benefits for larger arrays.

There have only been a few examples of monopile installations for TSE to date, likely due to the high costs of a one-off drilled pile installation. Two of the best known were Open Hydro's EMEC installation & Marine Current Turbines' in Strangford Lough). However, with a transition to array scale deployments and possible cost savings with volume, the prevalence of monopile foundations are expected to increase. Monopile foundations consist of a pile foundation and a transition piece. The pile is a hollow cylinder that is inserted vertically into the seabed to transfer lateral and axial loads from the device [61]. The transition piece is connected to the pile foundation so that the turbine device can be securely fixed to this foundation. This transition piece may also have a J-tube attached to it. This component is used to guide the required cables into the structure from the device. J-tubes can either be integrated internally or externally onto the foundation. These two components are commonly joined by a flange connection. Monopile foundations also commonly have scour protection, typically

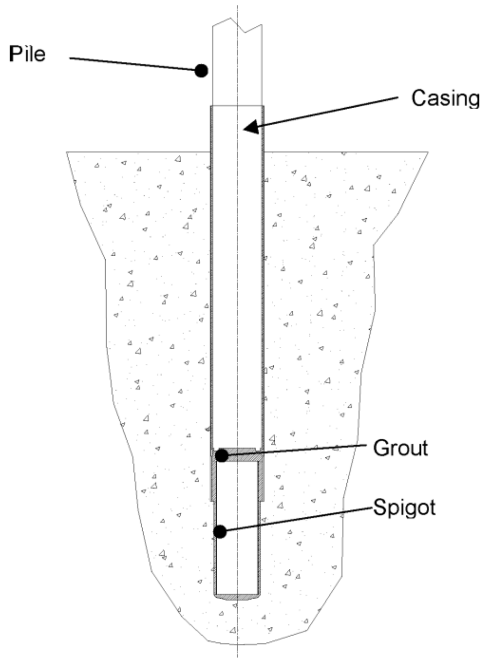


Figure 11 –Typical monopile features [60].

installed as shown in Figure 12 [62]. Scour is a natural process that involves materials on the seabed being displaced away from a structure and is caused by the flow of water [63]. Scour protection hence allows for longevity of this foundation type and allows for good structural integrity to be kept.

Installation

Firstly, the pile foundation is transported out to sea by barge and lifted into place by a crane, allowing the piles own weight to sink several metres into the seabed. An alignment tool is used during this stage to ensure that the pile is vertical. A hammer piece is then used to further drive the pile to the desired depth. Alternatively, if the seabed is too hard for piledriving, a drill may be used. This involves either an individual drill piece or a drilling tool inserted into the pile. To ensure an adequate fit is made, alignment tools are again used and grout is laid between the hole and pile foundation.

One benefit of drilling a hole first, over the driven method is that the flange for connection of the transition piece can be pre-installed before being submerged,

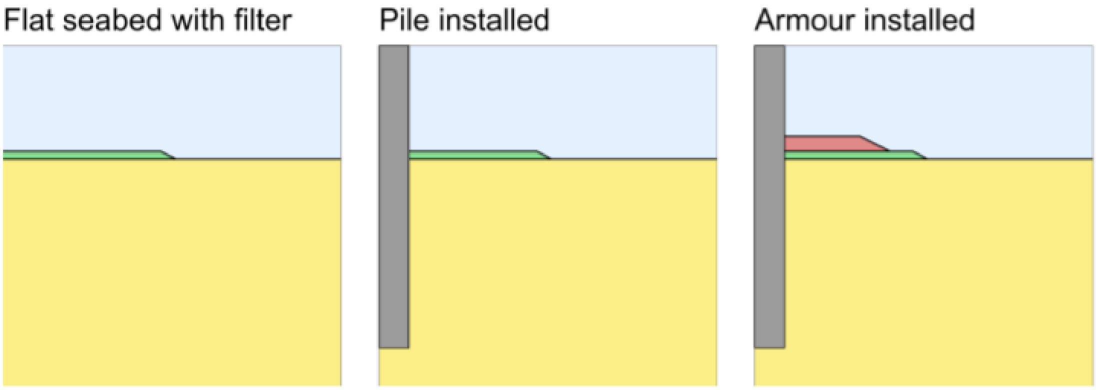


Figure 12 – Static scour protection [62].

streamlining the installation process [61]. There are currently two methods of installation for scour protection: static and dynamic scour protection. Static scour protection firstly deploys a filter layer in which the pile is then installed after. An armour layer is then placed above this filter layer. For dynamic scour protection, the first step is to drive the pile into the seabed and then the scour protection layer is installed.

The transition piece is then bolted onto a flange so that it is securely connected to the pile foundation. This is the fastest technique in integrating the two components together. Another common method is by filling in the ring space between transition piece and pile with grout. Spacers and hydraulic jacks are used to ensure the correct alignment during installation [61]. The tidal device can then be lowered onto the transition piece, however this often occurs once all the pile foundations have been installed in the array.

Materials

Both the pile foundation and transition piece are manufactured using structural steel. This relates back to Section 3.2.1.2 with many of the same justifications for use. This includes the need for corrosion protection systems. Cost effective monopile foundations also require an equity between the structures own weight and the stiffness of material used. This relationship between stiffness and self-weight relates to the frequency of the turbine device and structure. If the natural frequency (frequency of oscillation without external force) is matched with that of the applied excitation frequencies (tidal forces) then dynamic loading on the system will be greatly amplified resulting in intense fatigue on the structure [64]. This is one of the main reasons that steel is being used in this context with extensive used already within other offshore wind monopile foundation applications.

Scour protection

The initial filter layer used in static scour protection makes use of a fine material which has the ability to prevent small deposits like sand from escaping the surrounding area of the structure. The armour layer makes use of rocks with their size requiring to remain stable under the largest hydrodynamic forces they will experience. Dynamic scour protection does not make use of the filter layer, only the larger rock armour layer. Both the grading and size of rocks used is dependent on the conditions the scour protection is subject to and the profile of the protection i.e. thickness and diameter is dependent on the level changes of the natural seabed [65].

An alternative to using rocks that is being explored is the use of rubber mats. These can be made by recycling old parts such as tires, promoting a positive environmental impact. These anchored rubber mats also have the ability to house sea life by allowing sand deposits to form on the surface [66].

As tidal sites tend to be rocky, with sediment washed away by the currents, scour protection is not usually required, however rock dumping and rock bags have be known to be used for securing export cables in position on the sea bed to prevent movement.

Manufacture

As a result of monopiles extensive use in the offshore wind sector, their manufacture process has become cost-effective and streamlined. The manufacture of the piles follows a simple process of firstly hot rolling steel plates and this is to reach the desired dimensions such as thickness. The steel plates then undergo cold rolling and this is to transform the plates into cylindrical cans of a desired diameter. The cylindrical cans are welded at the seams so that they remain securely in the required shape. Then to reach the desired length of monopile, cans are circumferentially welded so that the whole structure is securely combined [67]. The transition piece undergoes similar manufacturing techniques by rolling steel to the desired dimensions however, transition pieces of course requires different requirements to those of pile foundations. As these components are manufactured using steel, they will undergo the same protective additive layer process as mentioned in the previous section so that the structure is protected from the oceans corrosive properties.

3.5.3 Mooring Systems

Some tidal turbines are deployed on floating foundations. Examples include the Orbital Marine Power O2, the Magallanes Renovables Atir and Sustainable Marine Energy's PLAT-I platform.

Orbital Marine's O2 2MW turbine is a floating horizontal axis turbine. It has been installed in Orkney utilising the catenary configuration. The O2 turbine utilises four gravity anchors each with concrete mattresses for scour protection [68]. Stud-link chains run along the seabed while synthetic rope is installed in the in the upper portion.

Floating structures use mooring lines to keep the device on station, with the majority of turbines exposed at sea level. The advantages are a higher tidal velocity further from the seabed and improved accessibility for ease of installation and maintenance. Disadvantages are susceptibility to wave action, large mass required for moorings, lower array density and the fact that devices become an obstacle for marine traffic.

Within offshore renewables there are two commonly used mooring approaches: the catenary mooring and taut mooring. The catenary mooring relies on the weight of the line where a portion of the mooring line runs along the seabed whereas taut mooring relies on the stiffness of the mooring line. Catenary moorings therefore create a larger footprint on the seabed but involves less anchorage cost than taut mooring systems. Taut mooring is the preferred option in deeper water (typically hundreds of metres), to minimise the mass and materials required in the moorings lines. These have a lower footprint on the seabed, however are subject to higher vertical loads and as a result require more expensive anchors [69]. Within these two categories, spread or single point mooring can be implemented and this is determined through analysis of the loads applied to the system, along with the mooring lines dimensions i.e. diameter and length [70].

Mooring systems comprise of different components such as mooring lines, connectors and anchors.

Mooring lines

Mooring lines are used as the connector between device and seabed and can consist of single materials or combinations of chains, wire ropes and synthetic ropes, with chains the most commonly used for conventional oil and gas/offshore vessels. Both stud-link and stud-less chains are used for mooring lines with stud-link chains primarily used in non-permanent mooring. As a result of the chains weight and overall cost, the use of this method becomes less practical. This is why wire ropes tend also be used to due their lower cost per unit length, while not compromising on strength.

Wire ropes are generally made up of 6 to 8 strands helically wound in a spiral configuration. There have been instances where wire rope and chains have been combined together, most commonly in catenary systems. As water depths become greater, synthetic ropes become the most advantageous option. Primarily used in taut systems, they have the advantage of being lighter and offering increased compliance due to their lower stiffness, compared to chain/wire rope [70].

Connectors

Connectors are used to combine different mooring lines, of the same or different material, and also to connect the lines to the device and anchor. As a result of the stress being concentrated to a small area of these connectors, there is great consideration into the fatigue life of this component. There are several types of connectors, all meriting different applications for example; kenter shackles to combine different sized chain together or the swivel connector to combine chain and wire rope lines and eliminate any torsion in the mooring line [70].

Anchors

There are a wide variety of anchor designs employed, with the ultimate decision made from analysis of loading requirements, soil types and depth of seabed. Examples are shown in Figure 13 [71]. Dead weight anchors are low cost and use gravity as a means to keep the device on station. Dead weight anchors can be used in both catenary and taut mooring systems due to their ability to overcome both vertical and horizontal loading. They are also adaptable to many soil types.

Another type of anchor is the drag embedment anchor, in which the bottom portion is buried beneath the seabed. This provides the resistance to the hydrodynamic forces that the system requires. These anchors are limited to catenary mooring systems as a result of their inability to resist horizontal loads and best perform in locations where the seabed is covered with substrates containing high contents of sand [70] typically areas with low tidal flows.

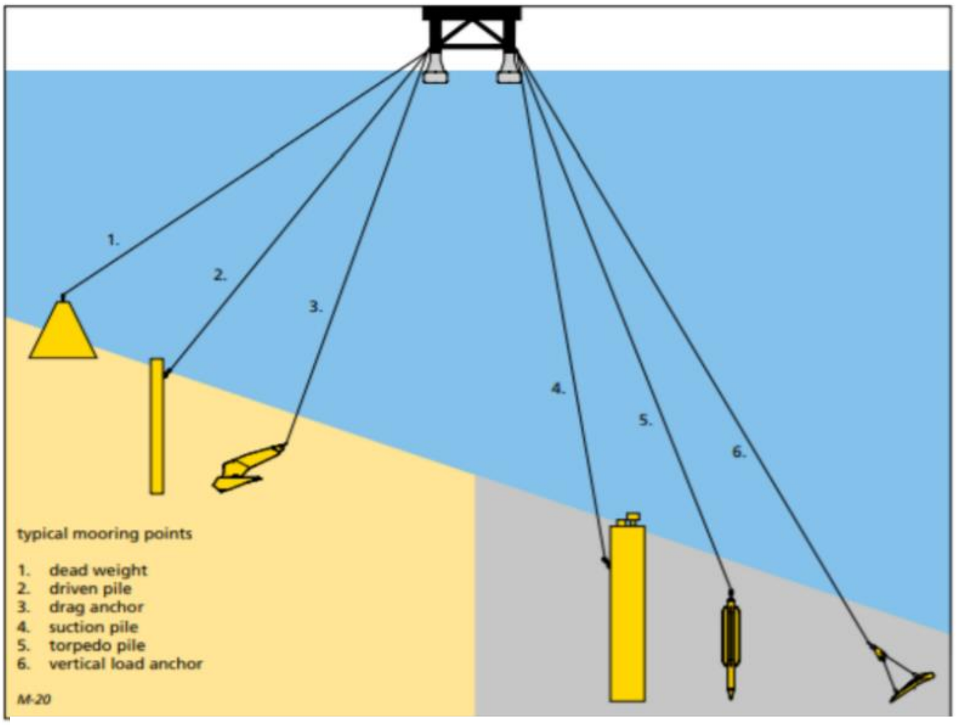


Figure 13 – Typical mooring anchor types. Shown are dead weight (1), driven pile (2), drag embedment anchor (3), suction pile (4), torpedo pile (5) and a vertical load anchor (6) [71].

Piles are also used within mooring systems, similar to monopile foundations. As they are driven into the soil by a hammer tool, both horizontal and vertical loading is resisted allowing for both catenary and taut mooring configurations to be supported. Where soil types such as clay soils do not make driven piles possible other methods such as suction piles are implemented. These have openings at the bottom end of the pile allowing for a pump to create a vacuum and drive the pile into the seabed [70]. The anchors may also depend on scour protection depending on the marine environment**.**

Materials

Structural steel

Structural steel is used in a wide variety of the components for mooring systems for example; mooring chains, piled anchors, dead weight anchors and connectors. The advantages of this material have been described in Section 3.5.1. With components such as chains and connectors having areas of concentrated stress, steel is well suited to this environment due to its high fatigue life. Some providers of subsea mooring connectors are able to subject their connectors to intense testing cycles, with First Subsea’s connectors subjected to fatigue cycles exceeding 3 million [72].

Wire rope

Wire ropes are made up of multiple carbon steel wires wrapped around each other forming a helix. This helix strand can also then be coated in synthetics such as polyethylene to enable corrosion protection [70]. Although they commonly possess small diameters, due to the use of carbon steel they are able to resist large tensile forces. One benefit of using wire rope over chains as the mooring lines is that, due to their helically wound arrangement, they offer more elastic properties than chains. In the context of volume manufacturing, wire ropes are the more economic option than chains as the overall cost per unit length of wire ropes is cheaper. This type of wire rope however does not possess good resistance to abrasion and hence why it is commonly used alongside chains – with chains being on the seabed where most abrasion occurs.

Synthetic rope

The most common material used in synthetic ropes for mooring is polyester however there are other common examples such as nylon, aramid and high modulus polyethylene (HMPE) [70].

		Nylon 6	Polyester	Vectran® HT	Aramid	HMPE	Steel
Property	Density (g/cm^3)	1.14	1.38	1.4	1.45	0.97	7.85
	Melting point (°C)	218	258	400 (chars)	500 (decomposes)	150	1600
	Modulus (N/tex)	7	11	54	60	100	20
	Tenacity (mN/tex)	840	820	2286	2000	3500	330
	Break extension (%)	20	12	3.8	3.5	3.5	2 (yield point)
	Moisture (%)	5	<1	<0.1	1-7	0	0

Table 2 – Properties of synthetic rope materials compared to steel [73].

From Table 2 it can be seen that polymer ropes can be significantly more lightweight than steel chains, helping to bring down material and installation costs. They do also not suffer from corrosion issues, and It can also be seen that the tenacity of these synthetic materials exceed steel by significant margins. Tenacity is effectively the breaking force of a fibre. If the design requires synthetic ropes to be in contact with the seabed then protection from abrasion is crucial however, in taut systems where synthetic ropes are commonly used, the mooring line will not be in contact with the seabed [73]. An issue presented with the use of synthetic ropes is that in certain materials, there can be an irreversible extension on the rope as a result of loading. This means that regular maintenance will be required in ensuring the mooring lines remain in operational condition [74].

Manufacture

For components such as chains, piles, dead weight anchors and connectors, these follow similar manufacturing techniques as other steel components as described above for different foundation types.

Chain manufacturing is a well established, largely automated process. The main steps are outlined in Figure 14 [75]. A steel wire or rod is fed through a forming machine. Each link is cut from the wire and bent into interconnected links using a series of roller arms. Larger chains will require a hydraulic press to shape, with a slower manufacturing process. Typically the links will be welded, for example using flash butt welding methods, before being heat treated to harden the metal, for example by heating and rapidly cooling via a pool of water. The chain can then be finished using shot blasting methods and painted.

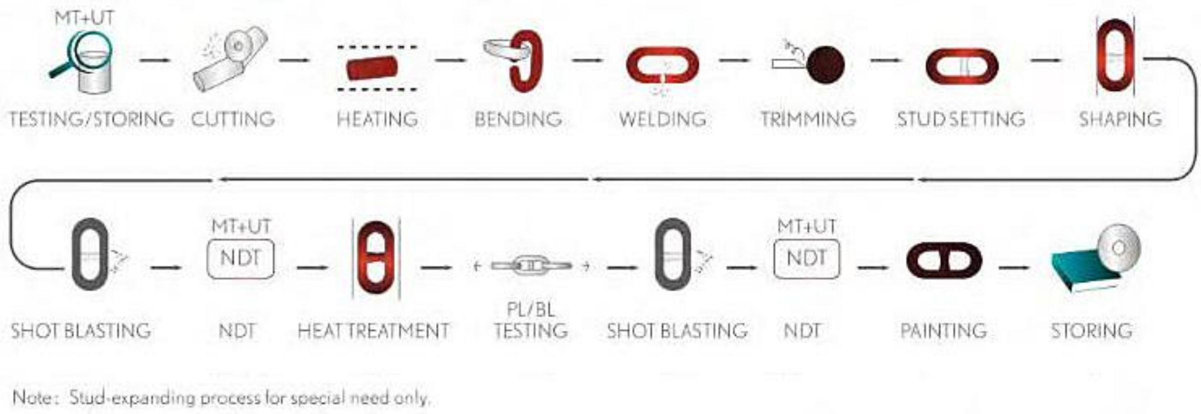


Figure 14 – A typical chain manufacturing process [75].

For steel wire, the first manufacturing process is patenting, a heat treatment, which involves the steel wire being passed through a furnace at high temperatures exceeding 900°C. The wire is then allowed to cool and then the wires go through a process known as drawing. Drawing stretches the steel wires. These wires are then wrapped into helical strands in which the strands are wrapped into a rope following the same helical pattern [76].

Synthetic rope manufacturing, as for the above components, is highly automated. It is a standardised process, with commercial production greatly ramped up during World War II as nylon ropes were used for parachute chords [73]. The process starts with strands of yarn, wound through a series of cylinders to twist them into larger strands of multi-filament yarn via a spool. This is typically achieved using a stranding machine. During this process the yarns might be coated in a protective coating (e.g. polyurethane). The yarn is combined onto a bobbin, via a take up spool, and a maypole braiding machine used to braid outer layer of yarn onto a core yarn centre. Figure 15 shows some examples of Dyneema synthetic rope being manufactured using these machines.

Figure 15 – Machinery used to manufacture Dyneema synthetic rope. Top: Multiple strands of rope are brought together using a stranding machine to manufacture the synthetic rope sections. Bottom: An example of a braiding maypole machine, used to braid the rope sections together into the final product. Source: Atlantic Braids Ltd, Youtube (https://www.youtube.com/watch?v=ndmXL-ygqdM&t=201s, accessed 05/05/22)

3.6. Offshore transmission system

Offshore transmission systems enable the electricity produced by TSE arrays to be transported safely and efficiently back to shore so it can then be imported to an onshore transmission system or distribution network. Due to the hostile conditions experienced at TSE installation sites, additional design factors must be considered to ensure all subsea components of the transmission system are appropriately engineered and sufficiently installed to endure the strongest of tidal flows. Out of the many components that make up the transmission system, the focus in this section will be on subsea cables, wet mate connectors, subsea junction boxes, and supporting onshore electrical infrastructure. The current state of the art will be presented for each mentioned component in terms of its material choice and manufacturing process before the limitations of each component are given where relevant. It must be acknowledged that, unlike several previously mentioned TSE components, many of the components that form TSE transmission systems do not face manufacturing barriers and are applicable for use in multiple applications such as offshore wind, O&G or general subsea interconnector transmission.

3.6.1 Array cables

Subsea cables consist of array cables and export cables. An array cables can be defined as a “subsea power cable connecting an offshore electricity generator with other offshore generators”, while an export cable can be defined as a “subsea power cable connecting an offshore electricity generation project to a point to which power is delivered” [77]. Although the materials used in certain parts of subsea cables can vary, they will often contain Copper or Aluminum conductors, polypropylene yarns for outer protection and armour bedding, and Cross-Linked Polyethylene (XLPE) or ethylene propylene rubber (EPR) for insulation [77], [78]. Figure 16 shows a typical three-phase AC subsea cable cross-section.

When focusing on subsea cables, distinction must be made between static and dynamic cables. Static export cables were initially used in offshore renewables as many of the environments they were operating in did not have to consider the harsh wave & high tidal flow conditions. However, when these cables are introduced to dynamic conditions, many eventually succumb to some form of fatigue damage [79]. This makes dynamic cables an essential part of the array/export cabling network on offshore wind and TSE projects. Dynamic cables will have floating components that enable them to move with wave and tidal flows. Because of this, they can endure the bending and twisting forces they are subjected to and are less likely to suffer mechanical damage in various sections [80]. In Figure 2, a subsea cable arrangement for floating wind is shown which comprises of both static and dynamic cabling [81].

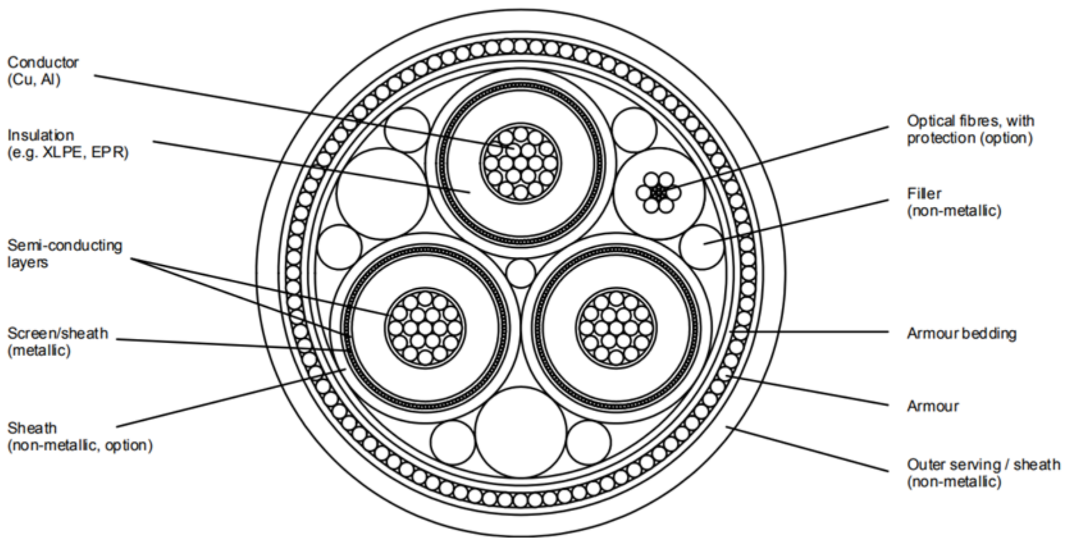


Figure 16 – Three-phase AC subsea power cable cross-section [58].

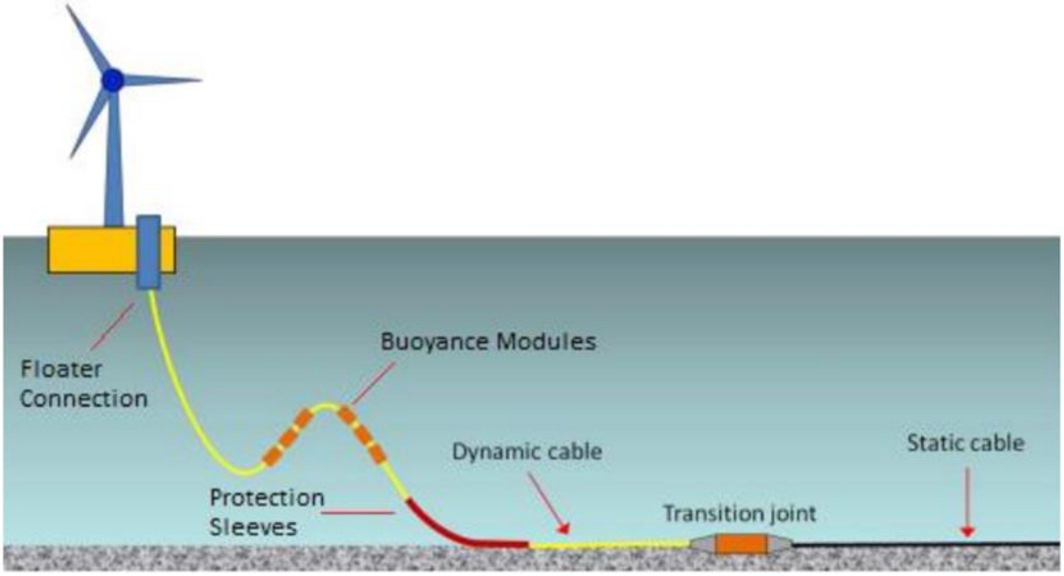


Figure 17 – Floating wind subsea cabling arrangement [81].

To manufacture subsea cables, wires of aluminium or copper are wound into a larger core before applying an inner layer of XLPE or ethylene propylene rubber (ERP) insulation. A three-phase subsea cable typically contains three insulated conductor cores, as well as fibre optic cables. Subsea umbilicals are of a more complex design with the need to include thermoplastic hoses alongside low voltage cables for communication purposes. When considering the umbilical, they tend to be more bespoke in nature to meet varying customer requirements. To complete the insulated internal layer, horizontal and vertical lay-up machines twist the internal components into a helix, an amour layer is then added for additional strength, with this layer commonly being made of coiled galvanised steel, before an XLPR or ERP outer sheath is added which exhibits the physical strength and moisture resistance capabilities for subsea applications [82].

One of the main limitations that array and export cables currently face is their reliability. Focusing on offshore wind, subsea cable failure accounts for 75-80% of the total cost of all offshore wind insurance claims [83]. Asides from cable reliability, TSE must also focus on optimising cabling arrangements as larger arrays are developed in the future. However, with offshore wind offering a foundation to build from, as well as subsea cabling coming in a range of sizes and voltages, the development of optimised cabling arrangements is not something that will be impeded due to a lack of manufacturing capacity.

3.6.2 Wet mate connectors

Wet mate connectors are used in a range of sectors including O&G, offshore wind and TSE. Focusing on TSE, wet mates are used to connect individual turbines or turbine arrays to array or export cables. Compared to dry mate connectors wet mates offer several advantages, including removing the need to bring cables to the surface for connection or disconnection. This reduces the time and costs associated with installation and maintenance as well as the risk of damage during handling. Compare

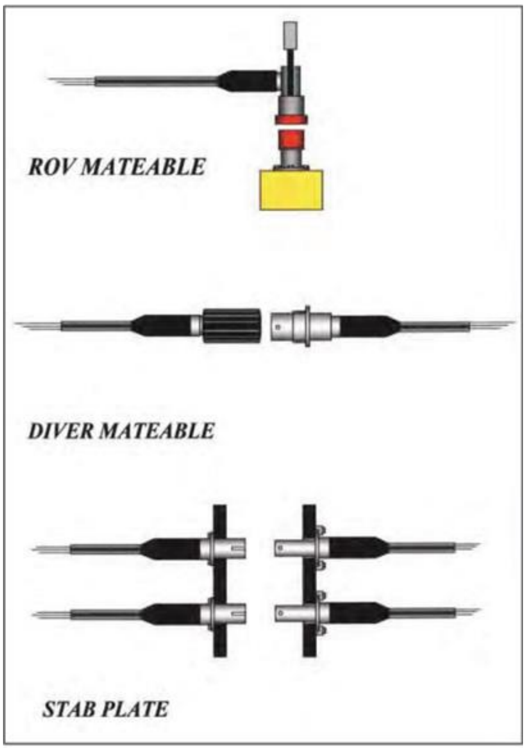


Figure 18 – Typical wet mate connector configurations [85].

this to working with dry mate connectors, which requires longer vessel hire periods, and larger windows of calm weather in which to operate [84].

The configurations of wet mate connectors vary. However, they typically come in three arrangements: remotely operated vehicle (ROV) mateable, diver mateable and stab plate. When considering health, safety and environment (HSE) considerations, ROV mateable designs will be far more preferable to diver mateable designs in many instances. When assembling multiple associated connectors, stab plates will often be the most desirable design [85]. In Figure 18 each configuration of wet mate connector is illustrated.

In terms of the materials typically used in a wet mate connector's body, titanium and inconel (an alloy primarily made of nickel and chromium) are used due to their physical strength and resistance to corrosion and heat [86]. Alternatively, 316L or super duplex stainless steel can also be used as materials for the connector body [85].

There are a wide range of wet mate designs which are developed specifically for operation with tidal converters. More recent examples which secured funding in the Quick Connection Systems programme run by Wave Energy Scotland include:

- Nova Innovation's NovaCan which has been used alongside their M100-D turbines using cost-effective, off-the-shelf components [87].
- Quoceant's Q-Connect which consists of modular subsystems that can be assembled in different configurations to provide quick and safe electrical connection of wave and TSE devices [88].

Figure 19 – Left: Nova Innovation's NovaCan connector [87]. Right: Quoceant Q-Connect connector [88].

These connectors are shown in Figure 19.

Regarding limitations seen in wet mate connections for TSE applications, many designs will be highly bespoke and as a result come at a high cost. However, some attempts at standardisation have been made. One example of this is MacArtney's 11kV (7.6MW) connector which was designed with the aim was to produce a "low-cost, high voltage generic wet-mate connector" [89].

When focusing on design limitations currently seen in wet mate connectors as a whole, increasing operating voltages above 36kV poses major challenges. While 11kV will be a suitable voltage for many TSE transmission systems to operate at due to their proximity to shore, offshore wind transmission operates at voltages of at least 33kV [90], with 66kV being the standard operating voltage [91]. For wet mate connectors of 66kV to become industry standard within offshore wind, far more research and investment is required to counter the effects of partial discharge and water treeing, both of which are exacerbated at higher voltages.

3.6.3 Subsea junction box

For offshore wind, in the vast majority of cases except where turbines are very close to shore, turbines are connected in strings to offshore substations. These collect and transmit power produced by each turbine to the mainland via a single cable route. This reduces costs as less cabling is required, and also allows voltages to be stepped up and hence transmission losses are reduced.

To date, TSE projects have seen turbines connected individually to the mainland. This approach had merits for early projects, as it meant that electrical system design was simpler and was easier to isolate and carry out maintenance on individual turbines when faults occurred (more of an issue for earlier projects with less developed technology and where reliability is lower). As the technology matures this becomes far less economically viable, especially for larger farms, as the supply and installation costs of cables become prohibitive. Offshore substations used in offshore wind are extremely costly and will not be required for the majority of TSE sites which are within 5km of the shoreline.

The middle ground for TSE is to use subsea junction boxes (JB), otherwise known as subsea hubs, to connect multiple devices (4-10) into a central node. The combined power can then be brought to shore via a single export cable per JB.

A JB's simplest function is to serve as an enclosure to protect multiple electrical connections. Within the marine environment, the means of protection on subsea JBs will be more complex than that of most other JBs. Although there are a wide range of JBs that are submersible by design, JBs used in TSE applications currently stand at a very early stage of development. At present, applications for submersible JBs include O&G, marine equipment, submersible vehicles and hydroelectric generation [92].

When considering the required characteristics of subsea JBs, durability is key to ensure the JB can withstand the water pressure of deep-sea environments. Outside of offering an enclosure to protect multiple electrical transmission connections operating at 50Hz or 60Hz, subsea JBs can also be used for monitoring applications which operate at a wide range of frequencies. An example of such a JB is the one used in Dynamic Load Monitoring LTD's system which accompanies inputs for data loggers used to monitor the force and movement exerted on the subsea cables of offshore wind turbines over extended periods of time, with the JB being comprised of stainless steel [93], [94].

One of the more common methods of ensuring JBs can withstand the water pressure of subsea environments is through the use of pressure compensators. These consist of an oil-filled water-tight housing in conjunction with a flexible membrane or bladder, with the internal electrical components insulated within the oil-filled housing [95]. A pressure compensator can made from a range of materials including metal film, rubber pipe and titanium pipe, with each of these materials having different advantages. For example, titanium pipe is lightweight and has a compact structure but is far harder to process than metal film or rubber pipe, while rubber pipe being easier to process, is often more prone to deterioration over time. One of the biggest concerns when using pressure compensators is the threat of external water leakage into the oil housing which can short circuit the enclosed devices. Water leakage is frequently caused by the external water pressure exceeding that of the oil pressure in the internal housing. Because of this, it is essential that reliable designs are implemented that ensure that internal oil pressure matches or exceeds that of the external subsea environment [96].

JBs designed for used in TSE systems are in the early stages of development. SIMEC Atlantis have implemented their own subsea hub design which can connect up to 4 TSE turbines to a single export cable. In addition to a JB, the subsea hub also features wet mate connectors for individual turbine connection, a dry mate connector designed for the installation of an export cable, and an extra wet mate connector designed for connection of an instrumentation sled. An illustration of the subsea hub is displayed in Figure 20 [97].

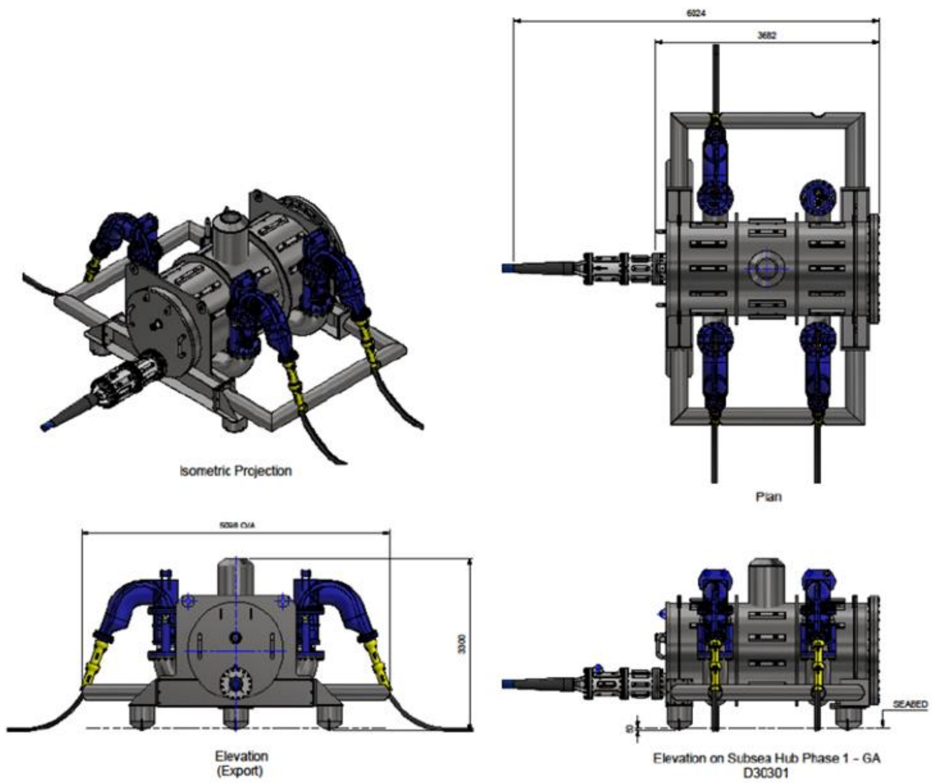


Figure 20 – SIMEC Atlantis subsea hub [97].

SIMEC Atlantis have indicated that the subsea hub will be improved for future TSE turbine installations. They plan to develop a next generation version that will contain a transformer within it so that loss minimisation can be achieved. However, with the addition of an internal transformer comes substantial additional weight to the new design.

3.6.4 Onshore electricals

Once electricity has been transported from turbine to shore, supporting electrical infrastructure, usually in the form of substations, will be used to ensure that the power generated is appropriate for import to onshore transmission and distribution networks. Substation power transformers (PT) are the main device that enable this and are used to step voltage up or down to levels that are compatible with the surrounding grid infrastructure. For safety purposes, substations will also include protective devices such as circuit breakers (CB) which will also be described in detail.

As mentioned previously, PTs step voltage from one level to another. This is typically achieved with the use of primary and secondary windings made of copper, configured around a core which confines magnetic fields that allow a pathway for magnetic flux to transfer power from the primary to the secondary winding. There are a range of materials that can be used in transformer cores, but for high voltage PTs one of the more common materials is cold rolled silicon steel sheets. The reason for assembling multiple layers of thin metallic sheets is to minimise eddy current losses during PT operation.

Figure 21 – Typical power transformer and conservator [98].

PTs in their design phase will be modelled off the concept of the “Ideal Transformer” which has negligible winding resistance, zero flux leakage, infinite permeability, and suffers negligible losses from eddy currents and hysteresis. However, no PT will exhibit such qualities so material selection is focused on loss minimisation. Therefore, material selection will consist of high conductivity windings and a core which is assembled of materials which possess a combination of high permeability, low flux leakage and eddy currents, and a hysteresis curve of minimum area.

To help regulate the temperature of a PT, oil is commonly used as a coolant. Oil cools the PT via natural convection or by using pumps. Additionally, PTs are equipped with a conservator to serve as an expansion tank to allow for the expansion of the oil when PT temperature increases. An example of this is shown in Figure 21 [98].

For PTs to be safe in transient or fault events, protective relays and monitoring devices will be used. Again, there are a range of options, but one common protective relay used

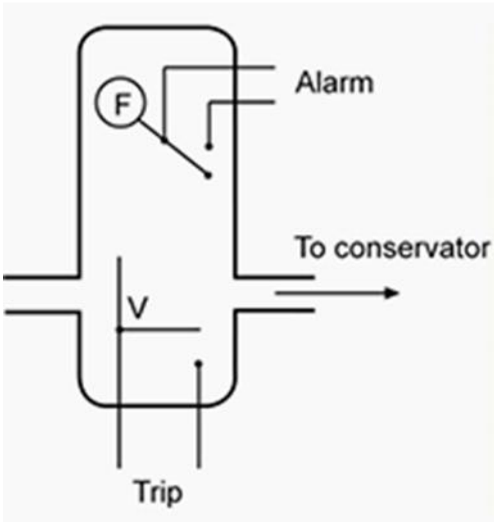


Figure 22 – Buchholz relay construction [99].

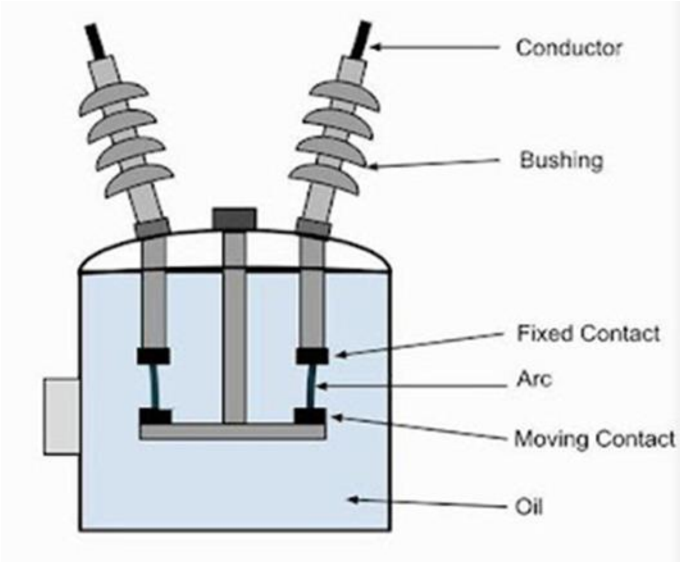


Figure 23 – Oil circuit breaker [100].

is the Buchholz relay. Buchholz relays are placed in the piping between the PT main tank and the oil conservator and will typically comprise of a pivoted float (F) and vane (V) as shown in Figure 22 [99]. The float and vane are both fitted alongside switches. In the case of minor faults, oil in the PT will evaporate into gas as the temperature rises, this along with a falling oil level in the relay casing will cause the float to fall and an alarm switch to be activated. For severe faults such as short circuits, oil will flow rapidly from the PT to the conservator via the relay casing which pushes the vane towards the trip switch, thus disconnecting the PT from the rest of the substation network [99].

To provide adequate protection to the wider substation, CBs will be located at several points to rapidly isolate faults to the area which they occur and to minimise potential damage caused by short circuits to the substation and beyond. Faults on electrical systems are usually caused by the breakdown or failure of insulation and equipment on the network.

Regarding CB types, many follow the same basic operating principle but will use a different insulator to quench the electrical arcs produced by short circuits. Examples of CBs include oil, air, vacuum and SF6. In Figure 23 a diagram of an oil CB is illustrated [100]. When a short circuit occurs and is detected by the CB, an arc will form between the fixed and moving contacts, with the short circuit energising trip coils within the CB which charges a spring mechanism that forces the contacts apart to quench the arc and isolate the fault from the wider network [98].

Beyond PTs and CBs, there is an extensive list of equipment that can be found in use at substations. In addition to PTs, current and voltage transformers will also be present for monitoring purposes. Furthermore, CBs are only one type of protective equipment used in substations, with isolators and lightning arresters also being employed to ensure work can be safely carried on equipment during no-load conditions, and to protect equipment from transient overvoltage during lightning events.

4 Engagement insight

To fully understand the manufacturing considerations and challenges, we engaged with the industry via two mechanisms:

A survey sent out through industry networks. This was to get a broad overview of the sector in its totality and capture the general opinions of suppliers who supply goods and services across the full project lifecycle

One on one interviews with technology developers and key suppliers. This allowed us to deep dive into more specific areas. This included areas that the questionnaire flagged up, and areas of discussion that were discovered via other TIGER work packages.

This section presents the insights gained from these two activities, which ultimately helped us to form the overall roadmap.

4.1. Industry survey

4.1.1 Approach

We created a survey for suppliers of goods and services in the tidal industry. The questions were devised by ORE Catapult, chosen to cover a range of necessary topics while staying relatively concise to encourage participation. Questions covered the following five main areas:

1. **Background company info**. This included organization name, website, number of employees, approximate annual turnover and main industries supplied. These questions were to give an appreciation of the size and type of organisations working in the tidal industry.
2. **Track record in TSE**. We asked for the company's track record and examples of any TSE projects, to give us an understanding of their sentiments and industry expertise.
3. **Components/services supplied**. We asked what products or services they could supply for the tidal sector, what proportion were manufactured in the UK and France and the approximate lead times on these products. This allowed us to identify participants in the UK and French supply chain, and also manufacturing areas where lead times are excessively long at present.
4. **Current drivers**. We asked what key processes or machinery are used to supply each respondents current services, and asked them to rank the most significant factors on lead times from four options. This allowed us to identify potential barriers and supply chain constraints
5. **Future plans and market sentiment**. Lastly, we asked the suppliers if they had any plans for expansion, and whether the tidal industry was a driver behind this decision. We also asked what would make the TSE sector more attractive for the business, and what volume of installed capacity would encourage them to make further investment into the sector.

The survey was created in Microsoft Teams, and promoted through the following channels:

- TIGER project mailing list and through Twitter
- ORE Catapult Twitter page
- RenewableUK membership
- Society of Underwater Technology (SUT) mailing list
- TIGER "meet the buyer" supply chain events. These were live events, set up as part of the TIGER project, to give suppliers an opportunity to meet technology developers.
- By TIGER partners to individual suppliers

In total, 47 responses were collected. These covered a range of industries and expertise, with the quality of responses deemed sufficient for examining manufacturing barriers and opportunities in the TSE sector. The list of companies who responded and gave permission to be listed in report is given in Appendix A:.

4.1.2 Background company info

Figure 24 shows the backgrounds of the companies that filled in the survey. The companies cover a wide spectrum of sizes; from small start-ups with less than ten employees and less than £500k annual turnover all the way up to large multinationals with over 250 employees and £200m+ of annual turnover. The majority of companies (just over 60%) reported turnover in the £1M-£50M turnover range. This midsize was somewhat expected as very small companies had less exposure to the industry channels by which the questionnaire was propagated, and very large companies have less commercial interest in TSE in its early stage of development.

The companies supply a broad range of sectors. A majority operate in the wider energy industry, namely O&G, offshore wind and marine energy. As this study is focused on tidal energy it is no surprise that over 60% of companies stated marine energy as a sector in which they operate. Conversely this means that about 40% of the companies do not operate in this space, a fairly high proportion which indicates the wider interest in the marine energy sector. Sectors mentioned in the "other" category included water, refrigeration, automotive, aerospace, nuclear, shipbuilding and mining. This highlights the wider synergies between marine energy and other industries, including those outside the marine environment.

There was also a varied selection of manufacturing facility locations. There were 70 responses (excluding the "Other" category), showing that on average the 47 companies who responded have more than one facility. This is somewhat skewed by the larger multinational companies, some of whom have facilities in all of the regions (for example one responder indicated that they have facilities in 44 countries worldwide).

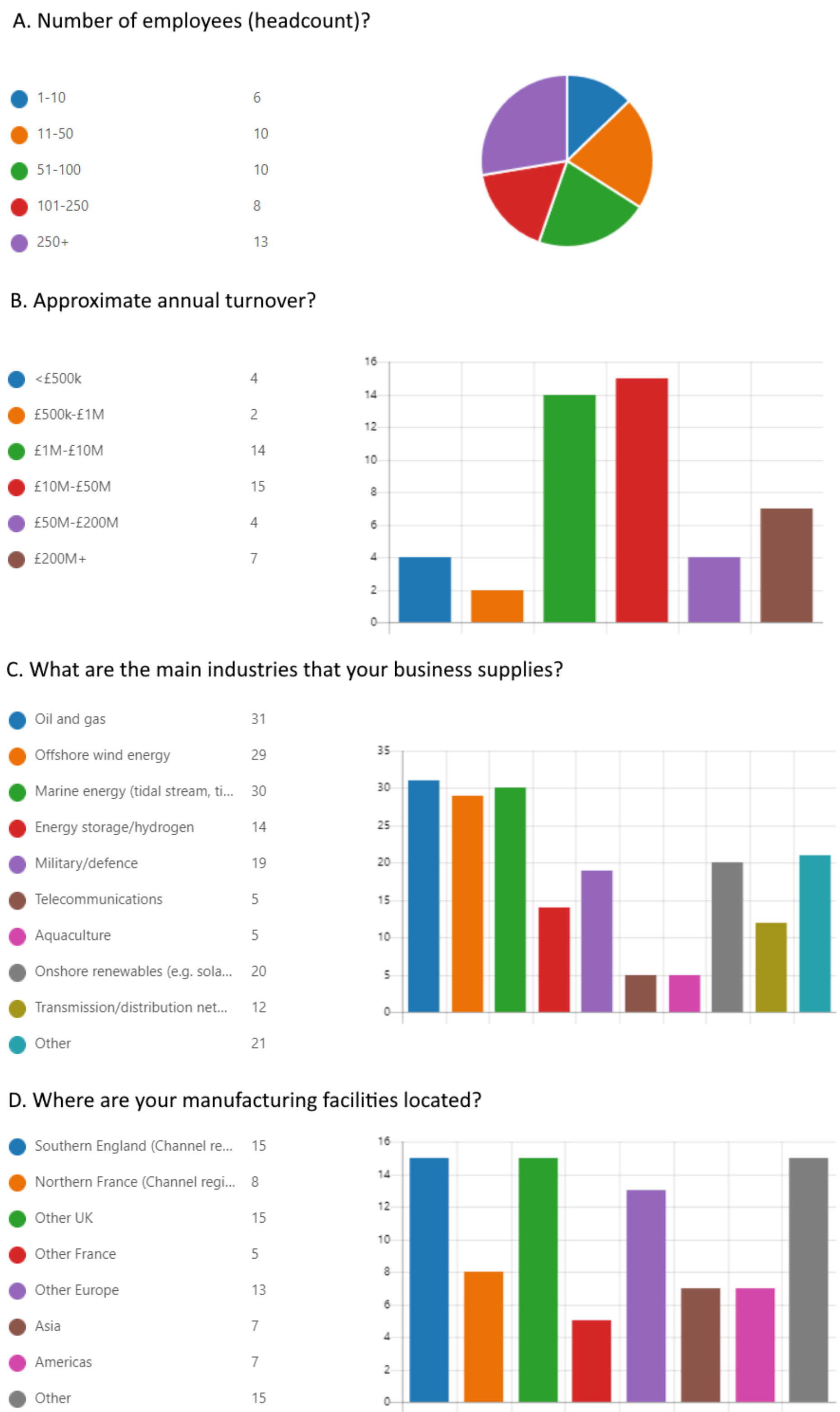


Figure 24 – Survey responses: The sizes (A and B) of organisations who responded, main industries they supply (C) and the locations of their manufacturing facilities (D).

About one third of the facilities are in the Channel region (Southern England/Northern France), the region that is the primary focus of the TIGER project. Seven companies have a presence in the Americas and Asia, correlating with the seven large companies with £200M+ of turnover as indicated in Figure 24B. A majority of “Other” responses were from companies who specialize in consultancy services so do not operate manufacturing facilities.

We asked companies with facilities in the Channel region what components they manufactured/services they supplied in the region. Responses included:

- Radio communications
- Automation, switchgear, electrical components and panels
- Shipbuilding and large steel structures
- Workshops
- Fabrication and machining
- Bearings, seals, lubrication systems
- Mooring systems
- Assembly testing and repairs
- Flexible pipe
- Non-manufacturing services, for example: CAD, assembly and testing services, software development, project management, consultancy services, support staff

The diversity of responses shows that there is a strong and diverse engineering presence in the Channel region, which the developing TSE sector could harness for future large-scale projects.

4.1.3 Track record in TSE

Figure 25 shows questions related to assessing the TSE expertise among the respondents. As for previous questions, there was good variety in the responses: from companies with little to no exposure through to companies already involved in many projects. Overall, 72% of respondents indicated some involvement with previous marine energy projects. Many different projects and technology developers were mentioned, including:

- Work with TIGER partners (SIMEC Atlantis, Orbital Marine Power, Minesto, Sabella, Hydroquest, QED Naval)
- Other active technology developers (Nova Innovation, Magallanes, Andritz)
- Work on feasibility at TSE sites in planning (Morlais, PTEC)
- Past tidal developers (OpenHydro, MCT)
- Work with wave energy developers, past and present (including Pelamis, Fred Olsen BOLT, Aquamarine, AMOG, Bombora, Trident Energy)

The broad range of projects and technologies mentioned indicates the high level and varied expertise among the suppliers. The vast majority of responses mentioned supplying components or services for specific device concepts rather than, for example,

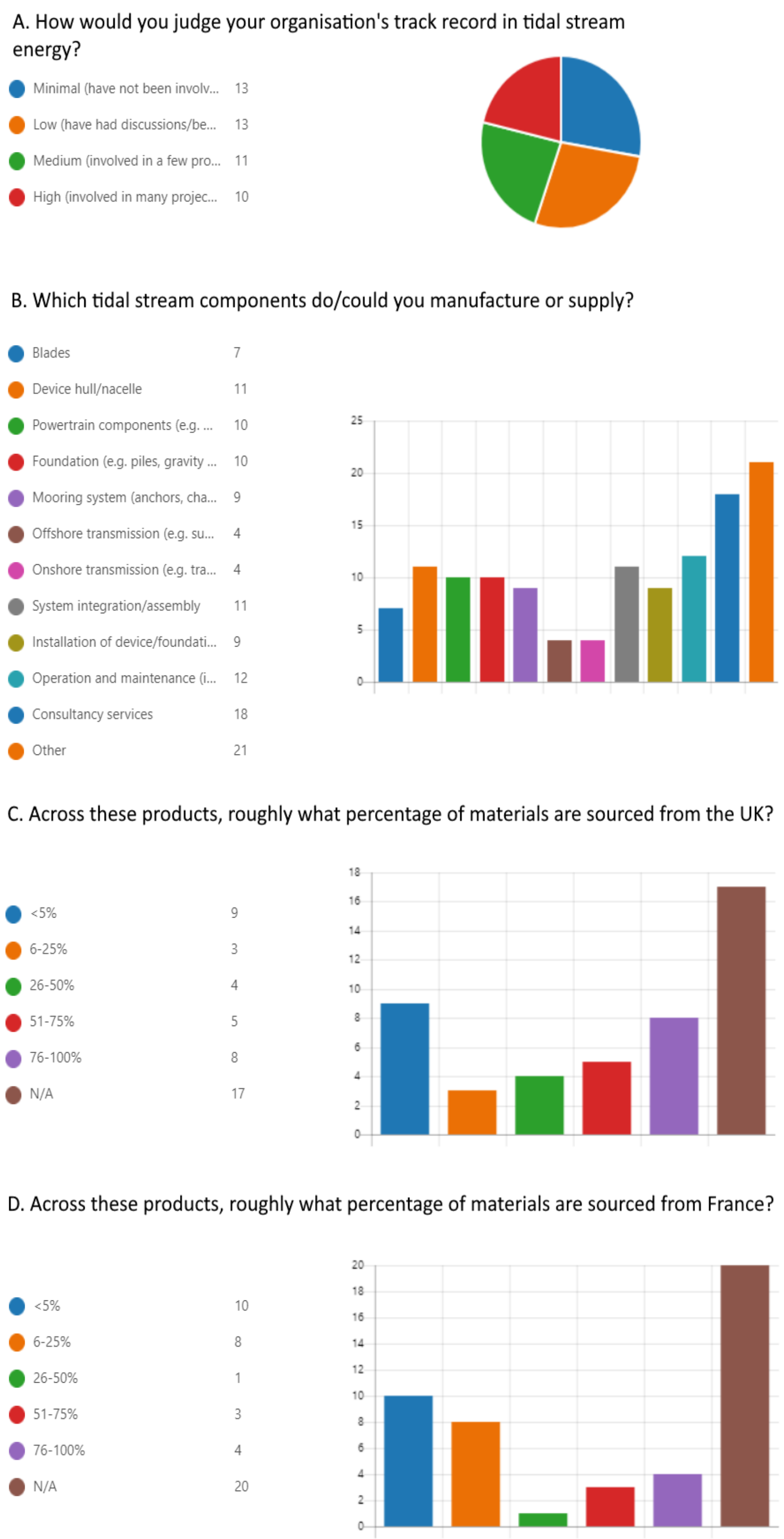


Figure 25 – Survey results: the self-assessed expertise of the organisations in TSE (A), the TSE components that they could supply (B) and their judgement of the proportion of materials sourced from the UK (C) and France (D).

direct involvement in research programmes like Horizon 2020. This indicates that there could be an opportunity to integrate suppliers into research directly, for example as members of consortiums, to better consider the manufacturing implications of specific research areas.

4.1.4 Components/services supplied

We asked the suppliers which services they currently offer, or could offer in the future. Responses covered all of the main system areas, although only four suppliers indicated offering components in the transmission system (onshore and offshore both only had four responses, under 10% of respondents). Transmission is arguably the most off-the-shelf aspect of a tidal farm. For example, subsea cables are also used for offshore wind and substations are an integral part of the wider electricity grid. This segment is very well established, dominated by a few large key players[2] who will typically supply the whole system, and so the opportunities for SMEs will be limited. The "other" responses included aspects like:

- PPE and workwear
- Cast iron shells for applications like cable protection
- General fabrication/heavy engineering
- General metalwork/plastic elements
- Harbour logistics
- Resource assessment
- Software
- Research services

The suppliers generally indicated that the majority of materials are sourced from outside of the UK and France. Only 12 out of the 47 respondents (25%) indicated very high UK/French content of 76%+. This compares to 19 (over 40%) who indicated less than 5%. The large number of "N/A" responses covers companies who mainly offer consultancy and desk-based services rather than manufacturing directly.

We asked suppliers what key machinery and equipment they use and require for the goods and services that they supply. These included:

- CNC machines
- Milling machines
- Welding sets and equipment (traditional and electron beam welding)
- Presses
- Lathes

[2] Major subsea cable suppliers include JDR Cables, Prysmian, Hellenic Cables, NKT. Major suppliers of substations and electrical systems include Siemens Energy, CG and ABB. For more information see the Guide to an Offshore Windfarm: Guide to an offshore windfarm.

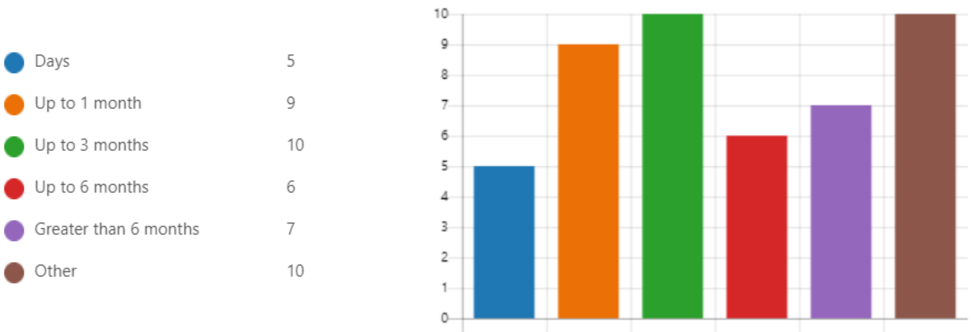
- Rollers
- Radial drills
- Honing machines
- Furnace and foundry processes

4.1.5 Current drivers

Figure 26 shows the typical lead times for products offered and how the respondents would rank the influence of four drivers on the lead time and cost of their goods.

The longer lead time components (up to and exceeding six months) were dominated by suppliers of powertrain components, electrical equipment, large mechanical equipment like bearings, and large scale steel fabrication (i.e. shipbuilding). These responses also tended to be from larger organizations with over £50M of annual revenue. These aspects reflect the fact that these larger companies are involved in large scale projects in other industries which reduces their flexibility and capacity to supply the much lower volumes required by the tidal industry. The shorter lead time services offered tended to be more desk-based offerings, for example consultancy services. Ten out of the fourteen companies suggesting lead times of days or up to one month also stated having minimal or low levels of previous involvement in the sector, perhaps demonstrating a keenness and attractiveness of the sector for new companies who are able to make allowances for what they see as an interesting industry. Many companies indicated that lead times were impossible to make a judgment on, depending largely on

A. What is the lead time for the products/services for a typical order?



B. What are the main drivers that would impact cost and lead times of goods supplied?

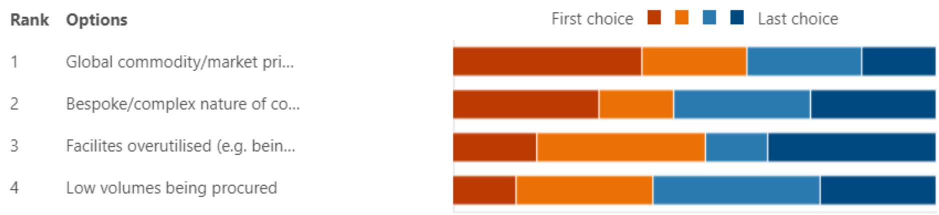


Figure 26 – Survey results: The lead times for the main products offered by the suppliers and their opinions on the main drivers that influence lead time.

other work they had at the time, with a large variety seen across their different product offerings.

About 40% of the respondents ranked global commodity prices as the biggest driver impacting cost and lead times, with about 62% ranking it first or second. These companies tended to be fabricators, shipbuilders and manufacturers of heavy engineering equipment like bearings. The companies that ranked this as least important tended to be companies offering marine services and desk-based services.

Of the 15 companies who ranked “Bespoke/complex nature of components” the highest, a majority offered services related to engineering design. This indicates that many of the tidal devices and components pose challenges from a design perspective, with unique aspects, but this becomes less burdensome at the fabrication stage, where the design changes can be accommodated. Other companies that ranked this category the highest included a designer and supplier of mooring systems, a supplier of hydraulic components and a supplier of rotating machine and generators.

Only six companies ranked “low volumes being procured” as the biggest cost and lead time driver. One of these was a cable supplier, indicating that the low volumes and short lengths required by early-stage tidal projects can be an issue for suppliers. Two other suppliers offered fairly specialized services; composite materials and polyurethane components respectively, which have more common usage in other industries. This implies that such suppliers may become more interested in tidal as it becomes more mainstream.

We also asked suppliers to list additional cost and lead time drivers. The following aspects were mentioned:

- Inconsistent designs, lots of different device types and the high amount of engineering required for one-off devices.
- Lack of access to public funding.
- Short term Covid-19 induced supply chain issues (e.g. high shipping costs being seen at present).
- Lack of access to data.
- High insurance costs for early stage projects and products.

4.1.6 Future plans and market sentiment

Figure 27A shows that about three quarters of respondents are planning to upgrade or invest in new facilities. We asked them about the main drivers for this decision, with responses including:

- Increased market demand and number of customers for their products.
- Aims to target new markets and diversify their business.
- Expansion into growing offshore renewable energy markets.

- An upgrade relating to a specific, large new project.

We asked about how their business could be best supported to grow manufacturing capacity for the tidal sector (Figure 27B). The most popular options were overwhelmingly “more industry collaborations” and “large pipeline of projects”, both reflecting the general desire for a larger, more integrated industry with more direct opportunities. Better access to financing was a secondary option, generally selected by small and mid-size companies. This, combined with the sentiments for expansion of manufacturing facilities mentioned in relation to Figure 27A, implies that companies appreciate the increasing opportunities within the offshore renewable energy sector, and it would be more beneficial to get support in accessing these opportunities rather than financial assistance per se. Of the nine companies who mentioned “recruitment/staff retention” as a factor, seven (almost 80%) judged their track record in tidal energy as “minimal” or “low”. This implies that recruitment initiatives would be more useful to companies less exposed to the sector, which may not be seeing the same level of growth as offshore renewables in general. This was also the case for companies who selected “education/training on sector needs”, indicating that the sector could do a better job of promoting itself to new suppliers and opening up new opportunities. No companies who judged themselves as having “high” tidal expertise answered either of these categories, showing that there is more clarity and understanding between major suppliers and project developers. A majority of answers in the “Other” category desired clear government backing for the sector via revenue support, highlighting the knock-on positive effect that this has for the wider supply chain.

We asked developers what volume of tidal turbines installed per year would be enough for them to consider significant investments to cater to the sector. Of the 46 respondents who answered, over 70% indicated that less than 50 devices per annum would be sufficient. Depending on the sizes of devices this could be equivalent to roughly 20-100MW of capacity. This relatively small number helps strengthen the case for government revenue support for tidal. For example, initial calculations have indicated that about 30-40MW of tidal capacity [101] could receive a CfD in AR4 via the £20M per annum ringfence that has been set by the government. Even this modest amount of capacity is interesting for many suppliers and will help to build the activity and supply chains required for future cost reduction success.

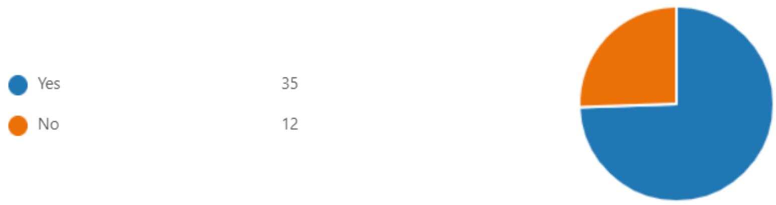
Related to this, we asked for written responses on what other things would make the TSE industry a more attractive target for their business. Responses included the following themes:

- Evidence of sector longevity
- More government support, including more clarity on CfD allocations and public backing for tidal
- Demonstrating that there is a greater share of the overall renewable market

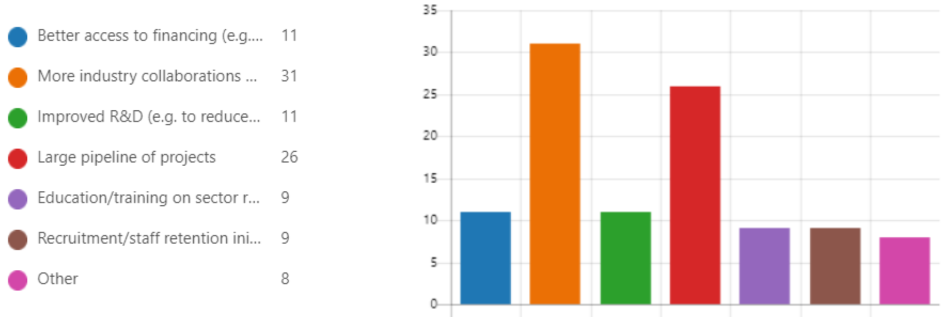
- More opportunities to bid for work, via e.g. competitive processes (invitation to tender)
- A clear project pipeline associated with regular government tenders (like offshore wind)

Several respondents indicated that TSE is already a target business for them.

A. For the products that can be supplied: are there plans to upgrade or invest in new manufacturing facilities in the next 5-10 years?



B. What support mechanisms would best help you to secure and grow manufacturing capability for the tidal stream sector?



C. Considering the combined UK/French market, what volume of turbines per year would be enough to encourage you to make significant additional investment into the sector?

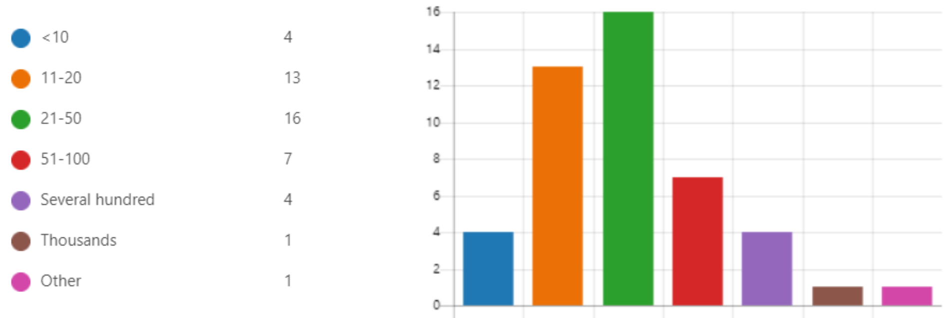


Figure 27 – Future plans of survey respondents, their opinions on the most useful support mechanics and the tidal capacity that would encourage them to make further investment.

4.2. One on one interviews

We interviewed key technology developers and suppliers to ask specific questions about their manufacturing capabilities, the challenges they face and their thoughts on the tidal sector. Companies were selected based on the following criteria:

- Companies with a strong track record in the industry
- Companies who could offer insight into specific areas of interest, highlighted by our TIGER partners and from the industry survey (e.g. blades, powertrain)

We approached about 20 companies in total. The 12 companies we interviewed covered the following areas:

- Tidal turbine suppliers (technology developers)
- Blades
- Device powertrain
- Bearings
- Steelwork, fabrication and assembly
- Subsea cables
- Logistics
- Engineering design

The companies interviewed are kept anonymous for commercial confidentiality reasons, but the general insight and points raised are noted below.

4.2.1 Tidal technology developers

The suppliers we talked to produce horizontal axis turbine designs, at various scales (approx. 100kW-2MW rated) and covered both fixed and floating foundations.

During the interviews, the following points of interest were raised:

- Longest lead time items tend to be blades, electrical powertrain components (e.g. gearbox, generator), transformers and wet mate connectors. Wet mate connectors are an especially significant issue, with one company telling us that their supplier was quoting 22 months at one point for an order. Blade lead time could be up to six months for an order, as a significant time is also required to create the moulds and tooling.
- These also tended to be the most bespoke components. This bespokeness is directly related to the lead time, as the suppliers have little incentive to keep these components in stock, e.g. sitting in warehouses and taking up

space/resources, as demand is so low. This means that they will typically need to manufacture when the order comes in.

- The UK based developers indicated that there is high UK content (65%+). The exception is mainly gearboxes and generators, which had to be sourced from outside the UK.
- One developer told us that there tended to be sufficient competition on most components, with typically three suppliers found who could supply a given component. The majority of components were managed on a competitive basis.
- All developers indicated that the small quantity of components being procured has a big impact on cost and lead time. Manufacturing larger arrays will bring with it improved efficiencies and costs in the manufacturing process. This will also bring suppliers on board who could supply to the industry for the long-term and invest more into facilities as a result, again reducing lead times and costs.

  One component where this is a particularly significant issue is wet mate connectors. As mentioned above, the low volumes in the industry means that there is little incentive for suppliers to design any specialized connectors for the devices. This means that the connectors, while mostly “off-the-shelf”, are not designed for TSE applications and are more expensive and complex as a result. For example, one developer told us that they use three separate wet mate connectors for their device, which could be redesigned into a single connector if the supplier could see the commercial opportunity.

  Small volumes are also an issue for cables. One developer told us that many cable suppliers refuse to supply smaller lengths of cable for early stage tidal projects (e.g. <1km). As devices are close to shore, larger arrays are required to get these volumes to a suitable level where cost savings and increased supply chain competition can be seen.
- The developers indicated that the assembly of a turbine currently takes about 3-6 months, including about a month of testing. Getting all of the components on site from suppliers, prior to assembly, currently takes about 9-12 months. All the developers indicated that this is subject to the suppliers used, and could be reduced into the future, particularly for larger orders.
- Current technology designs have been more focused on getting working prototypes rather than on cost reduction. Several developers touted “value engineering” principles as the next step for future designs, which could lower the device cost by 30%+. Within the TIGER project, ORE Catapult are working with several device developers to look at these issues and examine specific innovations to promote incremental cost reduction.

- Supply of subsea hubs is another area which could benefit from greater knowledge from the supply chain. Feedback from the developers was that traditional suppliers of the technology do not appreciate the strong tidal currents at the sites and the impact that this would have on conventional approaches as used in other industries. It seems that the tidal developers would need to support the design process to ensure a suitable solution. While there are some aspects of the system that might be specialized, for example whether or not to include a transformer/converter within the unit, the basis of the technology could be adaptable to multiple tidal technologies and could be an area for collaboration. There is nothing inherently bespoke in the system.
- Other areas that could benefit from collaboration are subsea cables, which could be standardized across device developers
- One technology developer told us that they have seen some suppliers leaving the tidal industry, as they do not see it growing at a sufficient rate to make a commercial case. They also mentioned that it is not necessarily about volume, as they have one supplier who cannot currently supply an order of more than 10+ components and has no desire to grow their manufacturing capability, even if they received a larger order.

  One developer mentioned a disadvantage in the way that the market is structured: with the turbine suppliers designing the whole system. Cost benefits could come from segmenting up aspects of the device (e.g. one company supplying rotor and nacelle, another the foundation) as the best combinations of each element can be realised for specific sites.

4.2.2 Suppliers

The suppliers that we talked to raise the following points, which were considered when developing the roadmap.

Long lead times

- Suppliers echoed the sentiment from tidal technology developers: that lead times on some components are very long. Components like bearings and powertrain electrical equipment could be 6-12 months, and blades 6-8 months.
- Many companies highlighted the current uncertainty and impacts on the supply chain due to Covid-19. Quotes obtained are currently only valid for 1-2 weeks vs months before the pandemic, meaning that they need to act quickly to secure components at reasonable prices. In this difficult time, components for smaller projects and prototypes are deprioritized compared to larger projects like offshore wind, which take priority as companies have more financial headroom and are more willing to pay inflated prices.

- While a lot of the raw materials and base components come from Asia, particularly China, the direct suppliers tend to be European. Tidal suppliers told us that they tend to have strong relationships with their key suppliers, who they are confident can deliver. Language barriers, regulatory barriers, and a lack of track record (as the industry is predominantly European) means that suppliers from other continents are not usually considered.
- One supplier noted that shorter lead times could be possible if the technology developers were willing to pay more.

Processes

- One supplier indicated that procurement processes could be improved for technology developers. For example, in one case the client did not start the procurement process early enough, meaning that there wasn't time to shop around for different quotes and the final product ended by being about £100k more expensive as a result.
- Offshore wind is increasingly adopting "LEAN" manufacturing processes. One supplier told us that they would like to see TSE also adopting these processes, as current devices do not seem to be designed for mass production.

Intellectual property

- IP issues were mentioned. Many technology developers have their own specific designs and IP, which can be beneficial from a cost perspective, but prevents cross-fertilization and sharing of knowledge into wider industry, which ultimately stifles innovation.

Overengineering and design inefficiencies

- It was mentioned that early-stage projects are often over-engineered to prove their design concept and to ensure operation at sea. While this has been good for demonstrating the technology, the industry now needs to look into more cost effective solutions.

  One example that was given was offshore renewable technologies using mooring system components from the O&G industry (e.g. chains, anchors). These are proven solutions; however, they are also very over-engineered and expensive so are not the solution going forward, but in the present day they offer a way to scale the technology and get devices in the water, reducing burdensome R&D expenses.
- A steelwork fabricator indicated that the earlier protypes that have been seen have not been designed for serial manufacture. One example given was that TSE devices are "fairly space intensive" compared to a more mature technology like offshore wind, taking up more space on the quayside which is more problematic for the port operator which reduces the rate that devices can be manufactured

and assembled. Another general comment was that devices tend to be too complex and the industry should look for the simplest solutions before spending lots of money and resources on R&D.

- One supplier indicated that they are working towards more “plug and play” solutions for the industry, and product classes that could be scaled and used in different turbines.

Blades

- The supplier that we talked to indicated that blade designs can vary a lot between different device concepts. For example, one blade they manufactured was made up of 30+ pieces, compared to about 12 for another.
- There are currently carbon fibre supply problems, which are being made worse by Brexit. Global commodity prices generally account for about 30-40% of the blade cost, and the blade complexity can also play a significant part.
- They indicated that it would not be a problem to manufacture the largest blades being discussed in the industry (able to manufacture 15-20m blades with only minor investment). Future increases in blade length are not likely to be a constraint for the industry.
- The supplier's main business activities in other sectors include: defence, O&G, aerospace, leisure boats. They are very keen on tidal, but the industry is too small at this time to make up a core part of their business.
- The tooling is a significant part of blade cost and lead time, as it takes time to create the tooling.
- There are opportunities for cost reduction in this area, including increased automation in the manufacturing process (e.g robotics automating the lamination process). Aspects like thermoplastic and 3D printed blades could be used in the future but these concepts are still in their infancy and not expected in the near future.
- The main constraint is government support. If there was a pipeline of projects then they could upscale production to accommodate the growing demand.

Subsea cables

- We talked to two cable suppliers – who both indicated that short lengths of cable for tidal can be a challenge for suppliers. For shorter lengths, the “scrap” cable produced during manufacture is a significant part of the overall cable length, thus increasing wastage which can drive costs up.
- While the companies we talked to are able to supply shorter cable lengths, they mentioned that this is not the case for a number of their competitors. While the

cable is standard in design, there are less suppliers for tidal compared to e.g. offshore wind. This reduced competition will increase costs.

- The main cost driver for the cables is generally copper price. This global commodity price is a major consideration for many other industries.
- One cable supplier, a leading supplier for offshore wind, told us that they always have TSE on their radar but the commercial scale is never large enough compared to the other industries that they supply. The minimum length that they could offer is about 1km for a three-core cable.
- Standardising cable requirements across the different project developers would be a significant step in driving down costs. If, for example, several TSE developers pooled together their subsea cable requirements into a single order then this could reduce costs and lead times, as the cable could be manufactured in one production run. The important thing to standardise would be cable voltages and core cross sections, as fibre (for sensors, monitoring, etc.) tends to come in 24 or 48 mode cable and is less of a problem to change.
- Subsea cable could be delivered in 3-4 months. This is an optimistic estimate assuming that the factory has availability. For larger offshore wind projects, the timeframe can be much larger due to more complex designs, larger quantities, and the development of documentation and contracts in advance of financial investment decisions, etc.
- For smaller amounts of cable (up to about 15km), these could be slotted in between larger production runs for e.g. offshore wind projects. For larger amounts, e.g. 50km, this would be able to be booked in as normal at the cable manufacturing facility.

Government support

- The majority of suppliers that we talked to highlight that firm government support would increase their interest and investment into the TSE sector.
- One supplier told us that previous inconsistent government policy had a direct, adverse impact of their business. The decision to remove the marine energy ringfence from the 2016 CfD auction meant that one of their larger orders could not be fulfilled, as no marine energy projects were able to secure a CfD. They had taken on debt to upgrade their facilities for the marine energy projects expected, this debt negatively impacted their balance sheet and made it more difficult for them to get involved in grant funded projects.
- Many suppliers mentioned local content as a key issue for the industry moving forward.

- More than one international supplier mentioned potentially relocating some of their operations to the UK to take advantage of renewable energy support schemes and mitigate the impacts of Brexit. One told us that they would consider partnering with or potentially acquiring a UK company to deliver projects if the UK market was large enough and if there were UK content requirements.
- One supplier mentioned that the industry is at too early a stage to "pick winners" and know which turbines would become the turbines of choice. The sentiment from two leading suppliers was that the industry will converge to "2 or 3" designs. This makes some suppliers nervous about being involved in the industry, as the volumes are not good enough to make a large investment if there is no guaranteed project pipeline. A pipeline of projects will be crucial to bring suppliers on side.
- One supplier mentioned that current financial incentives for suppliers working in renewables are "non-existent". Initiatives like tax relief, business rate relief and greater access to grant funding would help suppliers develop their renewable energy production facilities and ultimately drive down the cost of projects to prioritise these areas over other parts of their business.

Collaboration and combining orders

- Almost all of the suppliers indicated that there should be more collaboration across the industry, and that a lack of collaboration will stifle innovation and lead to higher costs. Turbine developers do most of the design in-house, and do not make use of technologies and ideas from other industries enough (e.g. O&G, offshore wind). One supplier mentioned that a more favourable approach could be for developers to partner with suppliers, to gain their direct knowledge, and create modular products that can be licensed to other technology designers.
- The idea of the tidal industry collaborating to purchase in bulk to secure more favourable prices and lead times was discussed. In general, this is something that suppliers agreed could be beneficial. Examples for collaboration and standardisation included subsea cables (mentioned above), subsea hubs, and paint and coatings.

4.2.3 Summary: key points

From the one-on-one interviews, the knowledge gained can be summarised by the key takeaways:

1. Technology developers do most of their design in-house and tend to get suppliers to primarily manufacture rather than involving them in the design process. This introduces some inefficiencies, preventing sharing of knowledge and ideas which could be improved.
2. Lead times are fairly long (6+ months for some key components) and costs high, but the opinions are that these could be reduced significantly for larger orders (e.g., arrays of devices rather than one-off prototypes).
3. Generally, the supply chain is flexible, and will adapt to the size of the industry and pipeline of the projects. Government revenue support will promote a large pipeline of projects which will bring in suppliers keen to capitalise on the opportunities.
4. There could be room for more collaborations in the industry: between the technology developers and suppliers, and between multiple technology developers, for example, to develop industry standards and best practices. This would align the industry better for serial volume production.
5. There are large differences of opinion among suppliers. Some see the tidal industry as a real opportunity for their business, while others (especially those who have been negatively impacted by e.g. the removal of the CfD ringfence in 2016) are more cautious. Despite this, all of the suppliers indicated that they would like to get more involved in TSE projects, if the opportunities were there.

5 Volume manufacturing roadmap

In this section, a roadmap has been formulated which identifies the most prominent barriers to the volume manufacture of TSE turbines and components, and the enabling actions that should be taken to mitigate them. These barriers and enabling actions are presented in Section 5.1.1. In Section 5.1.2, timescales are presented to roadmap the volume manufacturing trajectory of TSE under two scenarios; Baseline and Accelerated Deployment.

5.1. Methodology

5.1.1 Part 1 – Barriers and Enabling Actions

Barriers to volume manufacturing of TSE turbines and components were identified through extensive research of previous publications and through the previously mentioned industry engagement. Despite prior publications stretching back several years, many of the same barriers still persist within the industry with some bearing more severity than others. The persistence of certain barriers became all the more apparent through the industry engagement which gave a deeper insight into these long-standing issues that the TSE industry continues to face.

After industry engagement was complete, barriers were ranked as low, medium, or high in terms of their impact and severity in slowing volume manufacture within the TSE sector. These are shown in Table 3.

Barrier Impact	Description
High	Significant barrier to upscaling manufacturing. Requires appropriate actions to resolve and guarantee required manufacturing levels. Enabling actions critical.
Medium	Mid-level barrier to upscaling manufacturing. Barrier likely to resolve itself over time. However, enabling actions would help accelerate TSE deployment and reach required manufacturing levels sooner. Enabling actions needed.
Low	Barrier poses minimal threat to upscaled manufacture of TSE turbines/components. Enabling actions useful.

Table 3 – Barrier rankings by severity

To distinguish the range of barriers that TSE faces, barriers were assigned into the following categories shown in Table 4.

It should be noted that several barriers have been assigned to multiple categories. For example a barrier could be deemed as being both economic and technological.

Barrier Category	Description	Example mitigating action
Policy & Regulatory	Barriers due to insufficient government policy/burdensome regulation	Improved revenue support and firm capacity targets
Economic	Barriers due to prohibitive TSE costs	Reduce TSE costs via economies of scale and/or economies of volume
Technological	Barriers due to technology not being advanced enough	Improve TSE technology reliability via R&D and demonstrations at scale
Organisational	Barriers due to the way that the industry/individual companies are structured	Improve collaboration between suppliers and developers

Table 4 – Categorisation of barriers to volume manufacture

5.1.2 Part 2 – Volume Manufacture Timescales

In this part of the roadmap, details of two different scenarios are presented. These outline the potential pathways of British and French TSE manufacturing in terms of LCOE, total installed capacity, milestones reached, and the number of TSE turbines/components that are installed/produced per annum by the end of a given timescale. The two scenarios have been designated as Baseline and Accelerated Deployment. The timescales used for each scenario go as follows:

- Current Status (2021)
- Early Expansion (2021 – 2025)
- Early Commercial (2025 – 2030)
- Commercial (2030 – 2035)

For greater context, both scenarios achieve the same annual TSE deployment by the year 2035. What distinguishes the two scenarios is the Accelerated Deployment scenario sees a far higher uptake in TSE in between 2021-2030, while the Baseline scenario begins to see a rapid increase in manufacturing capability from 2030 onwards. Due to the far higher uptake seen during the earlier years in the Accelerated Deployment scenario, the total cumulative capacity by 2035 in this scenario (2.6GW) is far higher than that of the Baseline scenario (1.5GW).

The estimations of LCOE, installed capacity, and the number of TSE components produced per annum were initially extracted from previous publications. These were adjusted with internal models to account for more recent forecasts. From this, the two scenarios were created which allow a reasonable range of uncertainty regarding future TSE manufacturing capacity to be estimated up to 2035. With the pace of development within the TSE industry being slower than expected, the Accelerated Deployment scenario better reflects the expected trajectory of future TSE capacity set out in prior publications released several years ago, while the Baseline scenario has been adjusted to reflect more recent modelling estimates.

5.2. Roadmap Part 1 – Barriers and Enabling Actions

5.2.1 List of barriers

Using all relevant information made available through previous publications and industry engagement; we determined what we perceived to be the eight biggest barriers to the volume manufacture of TSE turbines and their components. These are shown in Table 5.

No.	Barrier
1	A lack of government support in the UK and France
2	The need to move away from bespoke manufacturing
3	The need for improvements in fixed foundation designs
4	The need for advancements in blade manufacture and reliability
5	The need for optimisations in cabling arrangements
6	The need for cost reductions in wet mate connectors
7	Long lead times slowing potential rates of deployment
8	A lack of availability of suitable vessels

Table 5 – Barriers to volume manufacture

5.2.2 Enabling Actions

To remove barriers to the volume manufacture of TSE turbines and components, appropriate enabling actions were devised. These were created by assessing the industry stakeholder engagement, parallels from other industries (e.g. offshore wind) and recommendations put forward in previous publications. In this area of Roadmap Part 1, several barriers will be seen to share certain enabling actions with other barriers which mitigate their impact, with almost all barriers also having multiple enabling actions. The list of enabling actions is shown in Table 6.

No.	Enabling Actions
1	Improved support via market mechanisms
2	A clear pipeline of projects
3	Initiatives to support volume manufacture
4	Greater standardisation of designs
5	Minimise required materials/equipment
6	Research and development into optimised designs and solutions
7	Learning from the experience of other sectors
8	Greater collaboration between competitors and the wider supply chain.

9	A move to localised supply chains where possible
10	Alternative models of vessel ownership

Table 6 – List of enabling actions

5.2.3 Roadmap Part 1 Summary

Table 7 shows a summary of Roadmap Part 1, covering all barriers by category and severity, as well as the appropriate enabling actions required to mitigate each barrier.

No.	Barrier	P	E	T	O	Actions	Approx. timescale
1	A lack of government support in the UK and France	✓				1,2	2021-25
2	The need to move away from bespoke manufacturing		✓		✓	2,3,4	2021-30
3	The need for improvements in fixed foundation designs		✓	✓		5,6,7	2021-30
4	The need for advancements in blade manufacture and reliability		✓	✓		4,6, 8	2021-30
5	Optimisation and standardisation of transmission system components		✓			4,5,6	2025-35
6	The need for improvements in wet mate connector design and supply chain		✓	✓	✓	4,6,8	2021-30
7	Long lead times slowing potential rates of deployment				✓	2,6,9	2025-30
8	A lack of availability of suitable vessels		✓		✓	2,6,10	2030-35

Table 7 – Roadmap Part 1 summary. (Yellow = Low, Orange = Medium, Red = High), (P = Policy, E = Economic, T = Technological, O = Organisational). Action numbers corresponds to the enabling actions in Table 6.

5.2.4 Commentary on Barriers and Enabling Actions

A detailed breakdown of each barrier and its severity is presented here before describing what specific actions need to be taken to accelerate volume manufacture within the TSE sector.

Barrier 1 – A lack of government support in the UK and France (Policy & Regulatory), High Impact, 2021-25.

Both the UK and France have historically provided some government support, which has helped to advance TSE manufacturing in each respective country. Recent developments are:

- In the UK there has been some progress with TSE being included in Pot 2 of CfD's Allocation Round 4, allowing for maximum strike prices of £211/MWh to be met for future projects. In December 2021 it was announced that there would be a ringfence of £20M per year allocated to the sector, a very significant step to guarantee some successful tidal bids. In February 2022, the government announced that CfD auctions would move to an annual basis, again benefitting tidal developers and suppliers by enabling a quicker route to market [102].

- In France there is still no official government support for TSE in France, although (as of December 2021) there has been talk of a feed-in tariff arrangement.

However, far more can be done by both governments. Committing to sufficient levels of revenue support will reduce risk for project developers and investors, increasing the pipeline of projects which would allow future TSE capacity, revenues, and manufacturing demand to be better forecasted. It will lead to suppliers realising the size of the business opportunity, and hence investing in new facilities and equipment to meet the growing demand. Moreover, a capacity target (for example 1GW installed by 2035) would help to focus the industry and give suppliers assurance that the government are committing longer term to the sector.

As mentioned in Section 4.2, suppliers have been damaged by inconsistent government policy before. One supplier told us that they made significant investments into new facilities for marine energy projects in 2016, only for the CfD ringfence to be pulled, meaning that tidal could not compete with offshore wind. This led to them taking on a significant amount of debt, which has had long lasting damage for this business.

Because of inconsistent government policy, the sector has been weakened and is regarded as higher risk for the investment community. The overriding sentiment from suppliers that we engaged with was that they can supply higher volumes if the orders are there: the supply chain will adapt and grow to meet the increasing demand. Because of this, we think that clear government support is a key requirement to grow TSE into a success story for the UK and France.

Enabling Actions – Improved support via market mechanisms. A clear pipeline of projects.

The governments of UK and France are offering differing levels of support at present, meaning different actions should be taken to improve the possibility of project pipelines being realised in each country. For the UK, ringfenced amounts for TSE (as in being done with floating offshore wind) will ensure TSE is not completely overlooked in favour of other Pot 2 technologies with a lower administrative strike price, such as remote island wind. Key will be to keep supporting the industry moving forwards, as sustained support is required to lower the risk in the industry, bring in more private investment and incentivise suppliers into upscaling their own facilities.

Furthermore, a sector deal for TSE, similar to that of the Offshore Wind Sector Deal, would ensure British tidal resource is better utilised and manufacturing demand better forecast. This sector deal would require investment and commitment from project developers, and so we expect that the industry would push for this into the 2030s as projects are installed and as larger project developers enter the space.

For France, a call for tender (as is being done with bottom-fixed and floating offshore wind) would provide greater visibility for the French TSE sector. In France the tidal resource is more localised, with the vast majority of potential in the La Raz Blanchard (2GW has been estimated) [103]. Policy should ensure that there is healthy competition in this area, to prevent a monopoly forming which could stifle innovation. Cherbourg is a very significant construction port for the industry, close to the La Raz Blanchard, for example Naval Energies created a tidal turbine assembly plant in the region in 2018, just before liquidating their subsidiary OpenHydro. Expanding dialogues between PNE, the port operator, tidal developers and the government could be advantageous to ensure that the port can get the necessary investment to support the long-term future of the industry. For example, the UK government has allocated funding for ports to support the offshore wind industry, most recently their commitment to invest £160m into new ports and factories for floating wind [104]. While it is far too early for such an investment in the nascent tidal sector, it could be a significant driver for manufacturing and economic activity in the region as the industry expands.

Barrier 2 – The need to move away from bespoke manufacturing (Economic/Organisational), Medium Impact, 2021-30

For economies of volume to increase, a particular turbine or set of turbine designs need to be successfully manufactured that can operate in a wide range of TSE sites. This is because tidal resource is very location specific, with sites varying greatly in terms of their turbulence, wave loading, seabed geology and ocean climate. If tidal manufacturing fails to embrace a greater degree of standardisation, poorer learning rates will be experienced due to the higher costs associated with reaching the next doubling of capacity.

Other areas requiring increased standardisation are wet mate connectors and subsea cables. One respondent from the engagement exercise insisted wet mates are the "future of tidal" when looking to lower the financial risk and operational expenditure (OPEX) associated with TSE projects.

New designs and solutions will also require in depth testing, to ensure that performance can be met in the field and to reduce risk.

Enabling Actions – A clear pipeline of projects. Initiatives to support volume manufacture. Greater standardisation of designs.

Progress has been made in developing TSE turbines which are designed to operate in a wide range of conditions, with recent initiatives also underway to create a route to volume manufacturing over the next decade. Examples of these initiatives include the VOLT project led by Nova Innovation which plans to:

"Develop the first European assembly line to mass manufacture tidal turbines, and trial innovative techniques and tools to ship, deploy and monitor turbines around the world" [105]

and the FORWARD-2030 project led by Orbital Marine Power which seeks to:

"Design and build an optimised fully integrated power train solution, designed for volume manufacture" alongside technical partner SKF [106].

Some companies are also targeting different product scales, unified by the same core operating principles and designs. The idea is that these different products will be able to target different sites and markets. An example is Tocardo, who are developing three sizes of turbines from 100kW to 450kW+, but with the same underlying engineering and design. This will make efficiencies in the manufacturing process, as the same suppliers can be used across the product offerings.

In order to maximise the impacts of these initiatives, a steady pipeline of projects must first be established to allow companies such as Nova Innovation and Orbital to forecast future demand of their products.

The site-specific nature of TSE could be remedied by something as simple as having several blade options of various lengths for the same underlying turbine nacelle. Blade length could be designed to maximise power output for a given site, which avoids standardising the rest of the device and allowing it to be manufactured on mass. This could introduce manufacturing inefficiencies, as new tooling would need to be created for each blade size. This could be another area for industry standardisation: with turbine suppliers agreeing on blade designs and sizes. As blade design is already very siloed, with different developers creating their own designs to maximise energy extraction, it is unlikely for full industry alignment in this area.

Innovations in improving device simplicity and removing bespoke elements will require additional testing. Access to test facilities is vital to accelerate learning on the reliability of new components being pushed towards commercialisation. This will also reduce the likelihood of any defects in the manufacturing process. The use of facilities such as ORE Catapult's 1MW and 3MW drivetrain test rigs serve as a means of reducing testing time and offsetting retrieval costs as any potential design issues can be identified onshore rather than offshore.

Barrier 3 – The need for improvements in fixed foundation designs (Economic/Technological), Low Impact, 2021-30

There are various types of fixed foundations which can used for TSE installations. Gravity bases have been deployed more significantly to date, but there is increasing interest in monopiles to access lower costs and take advantage of offshore wind supply chains.

Both these foundation types have clear areas in which they can improve to reduce the whole-system cost of TSE. For gravity base foundations, steel is commonly used as ballast to ensure the turbine installation remains stable under the harshest of tidal flows. While this approach is effective, it is only economical when looking at very small arrays, with the excessive costs and material inefficiencies associated with gravity base not being suitable when looking at future scaled-up TSE projects. Concrete is also commonly considered as ballast but is very space inefficient and would require large laydown areas at ports which limits the rate that foundations can be manufactured.

Piled foundations require less material and offer greater knowledge transfer from the offshore wind industry with regards to optimising specific components (e.g. monopiles).

Because of the widespread usage in offshore wind, lead times will be shorter. Monopiles are also easier to handle and transport, making them better suited for upscaled manufacture. They are relatively simple structures, with a less labour intensive manufacturing process compared to gravity bases.

The main disadvantage is not in their manufacture but in their installation. The cost of drilling foundations is an expensive process which can be exacerbated further when vessels must wait to for safe weather conditions to carry out the installation. As tidal sites tend to be rocky, drilling will usually be required.

Enabling Actions – Minimise required materials/equipment. Research and development into optimised designs and solutions. Learning from the experience of other sectors.

For gravity base foundations, research and development (R&D) should be considered which focuses on optimised solutions to reduce costs and improve material efficiency. It is likely that current systems are overdesigned, so aiming to make gravity anchors smaller will allow them to be manufactured quicker and more easily. There is also an opportunity to source scrap materials as ballast which could reduce the need for manufacturing at all. For example, this is something that Orbital Marine Power considered for their O2 device foundation, a gravity anchor made up of a basket filled with scrap chain [107].

For piles, the offshore wind industry has found that they can be designed and manufactured with smaller wall thicknesses and lower masses. Initial designs were based on offshore O&G structures, which are subjected to different loading properties. The PISA (Pile Soil Analysis) project was one example of research in this area. It was a £3.5M project which ran from 2013-2016, with the consortium including the University of Oxford, Imperial College London, Orsted (formerly Dong Energy), GE Renewable Energy and the Carbon Trust. They found that the monopile steel requirements could be reduced by as much as 30% for certain ground conditions [108].

Smaller piles requiring less steel will be cheaper and easier to manufacture, transport and install. It is expected that early-stage TSE turbine foundations will be conservatively designed, to ensure stability on the seabed and prevent any catastrophic failures from occurring (which would damage a company both financially and through bad publicity). Over time, however, as these foundations become more common it is expected that the mass of steel can be reduced, and the foundation design optimised.

Monopiles are the most common foundation type in the offshore wind industry, and thus an industry transition from gravity base to monopile seems apparent, as the more adept supply chain will lead to savings in costs and manufacturing timescales. While there are added environmental impacts from piles on the seabed, this has not been a major barrier for offshore wind and so is not expected to play a major role in choice of foundation for TSE. The TSE industry should engage with suppliers of offshore wind monopile foundations to optimise design and ensure manufacturing volumes (examples include Sif, Bladt Industries and Haizea Wind Group).

Barrier 4 – The need for advancements in blade manufacture and reliability (Economic/Technological), Medium Impact, 2021-30

To date, a common reason for TSE deployments being unsuccessful is due to mechanical blade failure [8]. Many existing blades are currently made from a composite mix of glass and carbon fibre, and are often constructed by hand. Mechanical blade failure can happen for a variety of reasons, but some of the leading causes of reduced blade lifespan include turbulence, wake effects, edge erosion and cyclic loading over time. With all this considered, this makes improved blade manufacturing methods and the use of alternative materials two of the most promising areas in which cost reductions and upscaled manufacturing can be achieved within TSE.

Blades are manufactured using moulds. Blade moulds can be created from epoxy paste, which can produce three or so blades, while more advanced composite moulds can produce hundreds of blades but are far more expensive. A challenge for the industry is that the resource is very location specific and there is not a "one size fits all" approach to blade length. Optimising LCOE at a specific location will require devices with a specific blade length, which is also constrained by the depth of the seabed as clearance is required above and below the blades. In this case, different sizes of moulds and tooling would be required for different sites, which would add complexity and cost, as well as increasing manufacturing timescales.

In addition, different developers have their own blade designs. One supplier we interviewed indicated that there is large variation in complexity between technologies. Some blades are simpler and made of fewer individual pieces; compared to others which have many more pieces and may include metalwork and additional reinforcement.

As the industry progresses it is expected that turbine sizes and blade sizes will get larger, with rotor diameters of 24-28m expected for 3MW+ devices. This could create further constraints and limit the suppliers available.

Enabling Actions – Greater standardisation of designs. Research and development into optimised designs and solutions. Greater collaboration between competitors and the wider supply chain.

Blade design could be an area for collaboration, which could lead to standardisation and cost improvements for the whole industry. Due to IP and the competitive nature of the industry, this could be led from the supply chain and research organisations, providing tidal turbine developers with standardised options which scale across different blade sizes. The early-stage nature of the industry means that this would likely have to come through public rather than private funding. A recent project working along these lines is the NEMMO project [109]. This Horizon2020 funded project is coordinated by Technalia, with project partners including Magallanes, BLAEST and Ocean Energy Europe. The aim is to investigate different blade materials, creating a larger, lighter and more durable floating tidal turbine blade which can both improve yield and reduce costs.

Larger blades are not expected to add any manufacturing issues for the sector, with current suppliers indicating that blade lengths of 15-20m (rotor diameters of approximately 30-40m) would be possible with access to larger CNC machines (which could be outsourced). As the industry grows there is also the possibility that suppliers to the wind industry will become interested (for example Vestas, LM Wind Power) so capacity of these components should not be a significant issue going forwards.

To mitigate the manufacturing issues associated with optimised blade lengths per site: a simpler approach could be for developers to create classes of devices with standardised blade lengths, which would improve manufacturing efficiency and lower manufacturing costs, but this could be sub-optimal from a LCOE and energy generation perspective.

Another step that could be taken to upscale blade manufacture is the development and testing of blades made of thermoplastics and other alternative composites. An example of this is the National Renewable Energy Laboratory (NREL) testing thermoplastic blades in New York's East River using a turbine developed by Verdant Power. The blades are set to be retrieved by the end of 2021 to have their structural response assessed. If successful, this testing should provide some validation to thermoplastic composites not only being more reliable in their operation, but also quicker to manufacture. These blades can also be recycled, so if this becomes a requirement for the industry then this and other manufacturing methods will have to be explored.

Barrier 5 – Optimisation and standardisation of transmission system components (Economic), Medium Impact, 2025-35.

Reductions in the amount of cabling required for projects is critical in reducing the LCOE of TSE. With reference to the MeyGen project led by SIMEC Atlantis, the first phase of the project had 4 turbines installed, each with a separate connection to a nearby onshore converter. However, for larger farms of 10+ devices, this would be an inefficient arrangement as it requires excessive amounts of export cable and supporting electrical infrastructure. Several industry respondents also highlighted that procuring cables can be difficult as many cable manufacturers will overlook TSE projects due to the far shorter lengths of cable required compared to that of other industries (e.g. offshore wind). Lastly, there are not established cable standards for tidal stream projects, with project developers opting for different cable voltages and cross sections. The impression from suppliers is that tidal projects are very design and engineering intensive relative to the size of the commercial opportunities.

Enabling Actions – Greater Standardisation of Designs. Research and development into optimised designs and solutions. Greater collaboration between competitors and the wider supply chain.

Subsea hubs are widely regarded as the future for larger farms, to reduce the amount of cabling to shore. An example of this technology has been deployed: by SIMEC Atlantis at Meygen in 2018. They plan to improve the technology in future project phases to reduce cost and installation time. During the industry interviews, one developer indicated that engagement between subsea hub manufacturers and tidal developers is required, to ensure that the devices are designed with the high flow sites in mind. This could form the basis of future research projects, with IP arrangements in place so that the technology could be licensed for other farms and technologies. While the subsea hub technology is relatively off the shelf and simple to manufacture, the lack of track record for TSE is a concern, with SIMEC Atlantis the only company to deploy a working concept. The extreme nature of the tidal location adds design complexities and extra considerations that need to be made. We believe that this is a key area for industry collaboration, to ensure that there is the required manufacturing capacity in place as arrays begin to get deployed from about 2024-25 onwards.

Focusing on cable manufacturers and their interest in tidal; one industry respondent stated that they are open to supplying cables for TSE but much of that interest depends on a solid pipeline of projects being formed for TSE, as at present it is a highly engineering intensive process relative to the size of the project. Furthermore, the same respondent recommended that greater collaboration within the TSE sector would help towards standardisation of the required cable type, thus resulting in cost reductions via economies of volume.

It is possible that TSE developers could group together to buy cable, if the voltages and cable cross sections were standardised. This could reduce costs, for example through less wastage and more competition and interest from suppliers. It would also reduce lead times, as the cable could also be manufactured in a single production run rather than having to e.g. change over the equipment for multiple, small amounts of cabling. This would be best achieved by creating clear industry standards, bringing together a group of TSE suppliers and cable manufacturers. It is expected that 30-40MW of capacity will be allocated for AR4, most likely split between 3 or more projects. These projects would be targeting a similar FID, and so it might be reasonable to procure cabling together.

Barrier 6 – The need for improvements in wet mate connector design and supply chain (Economic/Technological/Organisational), Medium impact, 2021-30.

Wet mates are crucial in reducing the time taken to install and retrieve TSE devices due to their ease of connection and disconnection compared to dry mate connectors. According to developers and suppliers, wet mate connectors are some of the most expensive and bespoke components, despite being paramount to lowering the OPEX of TSE projects. Without collaboration and eventual standardisation, wet mate connectors will be left in a state where its “survival of the fittest” which will slow long-term reductions in the LCOE of TSE. These components are also subject to long lead times.

Enabling Actions – Greater standardisation of designs. Research and development into optimised designs and solutions. Greater collaboration between competitors and the wider supply chain.

There are several companies with their own wet mate designs to serve their specific device designs. More collaboration is needed throughout the TSE sector so more standardised designs and a standard operating voltage for wet mate connectors can be implemented. From industry interviews with developers this is something that they are interested in pursuing, although the differences in the devices (e.g. operating voltages, measurement equipment, sensors) means that this could be difficult, as potentially turbine suppliers would need to redesign their electrical systems and the connections needed. It is more likely that synergies would be seen between similar scales of devices. For example, Nova Innovation and Sabella both have horizontal axis device classes of a similar scale (100kW for the Nova M100 vs 250kW for the Sabella D8). In June 2021 they announced a memorandum of understanding to work in collaboration to:

"…accelerate development of tidal energy sites for both Scottish and French companies… The alliance will include co-operation across French and UK sites, driving down costs, catalysing opportunities for funding, and delivering economies of scale to tackle the climate emergency." [110]

For this kind of partnership, a standardised wet mate design could reduce costs and complexity of both devices and give the companies more leverage through the ability to order larger volumes.

Additionally, one industry respondent mentioned that they need to use multiple wet mate designs on a single device, and because of low order volume at present, they need to go with what is available to them. Once higher order volumes can be achieved the industry respondent believes they will be in a better position to "get what they want" in terms of component design while also seeing cost reductions per wet mate.

Barrier 7 – Long lead times slowing potential rates of deployment (Organisational), High Impact, 2025-30

Long lead times are a significant barrier to upscaled manufacturing at present. Efforts need to be focused on shortening lead times now so that future order volumes can be satisfied and supply chain bottlenecks avoided. Through the industry engagement the issue of long lead times came up on multiple occasions. For blade manufacturing, creating moulds was cited as the most time-consuming process, especially when starting from scratch with a new blade design.

Computer chips were also brought up as being a problematic area for long lead times. One industry respondent informed us that the automotive industry and their demand for computer chips in cars is causing scarcity along the supply chain which is impacting the lead times for other industries such as TSE. A similar situation is seen with wet mates, with another respondent stating that O&G is currently dominating the order books and gaining priority as a result.

Another area of concern when considering long lead times is the time that it takes to source generator magnets. One respondent said that because they can only source their generator magnet from China, they are left to put up with lead times of around a year, with the supplier refusing to commit to set lead times. This, alongside other electrical components they order from China, has left them with a lack of oversight.

While some of these long lead times are due to the Covid-19 pandemic, the lead times for blades and powertrain components pre-dates the pandemic, the low order volumes meaning that these components are not kept in stock and need to be manufactured for each new project.

Although not directly linked to lead times, one respondent brought up their desire for increased modularity in turbine designs which could help improve logistics along the supply chain. Furthermore, the general complexity of powertrain systems and whole turbines has been cited as a big factor dictating lead times.

Enabling Actions – A clear pipeline of projects. Research and development into optimised designs and solutions. A move to more localised and diversified supply chains where possible.

As mentioned above, creating moulds is the most time-consuming process when it came to manufacturing blades. While this is especially time-consuming when dealing with new designs, the need to regularly change moulds on established blade designs is also a contributor to long lead times. For significant reductions to be made in blade lead times, R&D activity into advanced composite moulds should be undertaken to ensure future order volumes can be satisfied. As the industry grows, it is possible that new companies will emerge from the offshore wind industry to supply blades. Companies like Vestas and Siemens Gamesa have UK factories capable of producing hundreds of blades per year and could turn their attention to tidal turbine blades once the commercial opportunities grow.

Where possible, a move to more localised production in the form of supply chain clusters will help reduce lead times by eliminating excessively long supply chains. Examples of supply chain clusters in the field of marine energy include:

- Pembroke Dock (Wales, UK): Significant MRE activity has been created at the dock due to Welsh European Funding Office (WEFO) grant funding availability. Part of the larger Port of Milford Haven, the area is home to organisations like the Marine Energy Engineering Centre of Excellence (MEECE) and the Marine Energy Test Area (META). The Pembroke Dock Marine scheme is seeing £60M invested, including in new fabrication areas, a larger slipway, assembly and maintenance buildings [111].
- WEAMEC (Pays de la Loire, France): The West Atlantic Marine Energy Community (WEAMEC) was founded by Centrale Nantes and brings together over 30 research institutions and 90 companies working in the marine energy sector [112].

It is hoped that similar supply chain clusters will be formed off the back of AR4 results, close to the successful projects, and that these clusters can form the basis of reduced costs for a range of TSE components while maximising local content. High local content will not be possible for all components, such as magnet generators, as the many of the raw materials they are comprised of will be extracted in China. This could change with new, emerging innovations, for example non-rare earth permanent magnet generators. 250kW prototypes have been tested with a focus on the offshore wind industry [113].

While one developer indicated that most of their components go out to competitive tenders, this does not seem to be the case for the industry as a whole. Several respondents to our engagement survey mentioned a desire to witness and participate in more of these tenders, of which there is a general lack of awareness. Having a more competitive tender process will help drive down both costs and lead times, as the optimal suppliers can be found to meet project delivery timeframes. This will also help to bring newer suppliers into the industry, ultimately helping to create a more integrated supply chain. One option could be to have a dedicated portal or email alert system whereby competitive tenders in the TSE industry are shared to the wider supply chain, creating a central point for suppliers to find developers to promote the services required.

The lead time deemed reasonable will depend on the overall project timeframe. As for other barriers, a strong pipeline of tidal projects will help developers plan their deployment timescales and financial investment decision date. From this, suppliers can be chosen who can promise delivery of components by the required dates.

Regarding supply chain scarcity for microchips, as well as other components in a wide range of industry supply chains, much of this will be attributable to disruption caused by the pandemic. However, lessons can be learned so that future disruptions to logistics are handled better by working towards a more diverse range of suppliers.

Barrier 8 – A lack of availability of suitable vessels (Economic/Organisational), Low Impact, 2030-35

There are many different types of tidal devices, which require different types of vessels to install. Floating devices tend to just need tug or multicat vessels, compared to bottom fixed devices which often require heavy lift vessel with dynamic positioning capability.

Many of the vessels used are primarily used in the O&G and offshore wind sector meaning they are often too expensive and/or over specified for use in the TSE sector, especially with the sector at its current stage of manufacturing capability. Furthermore, as offshore wind expands globally, specialised vessels are becoming less available in Europe which compounds to the problem of British and French tidal developers having to compete with offshore wind. Although this does not directly relate to volume manufacturing, the slow pace of installation in future TSE arrays has the ability to impact the rate that components can be procured and devices manufactured, having a knock-on effect on the overall manufacturing process.

Inefficiencies in design and manufacture can compound this effect further. For example, over-sized gravity base foundations will take up more space on the quayside and mean that less foundations can be transported by a vessel, increasing cost and lead times. It will also restrict the ability to use smaller, more available vessels, meaning only larger, more costly vessels can be used which increases the LCOE of projects.

Enabling Actions – A clear pipeline of projects. Research and development into optimised designs and solutions. Alternative models of vessel ownership.

To increase vessel availability and support in lowering costs associated with O&M, a clear pipeline of TSE projects is crucial in allowing future demand to be forecasted for specialised vessels specifically designed for TSE operations.

To maximise the performance of said vessels, measures should be taken to optimise their position keeping ability in harsh sea conditions to increase the weather windows in which they can operate effectively. In addition to optimising future vessel design, reducing the weight of TSE turbines would also assist in allowing smaller vessels to be used as turbines trend upwards in terms of their size and capacity.

One industry respondent also suggested that instead of chartering vessels, TSE project owners/operators should own one or multiple specialised vessels for O&M purposes at their site to get around the issue of delays caused by a lack of available vessels. However, this approach is unlikely to be desirable until larger commercial arrays begin to be installed.

Turbines and foundations should be designed to minimise mass, so a greater variety of vessels can be used. For some foundations, namely gravity anchor, concrete could be a good material to use as it would allow foundations to be manufactured and assembled at quayside, reducing logistical costs.

5.3. Roadmap Part 2 – Volume Manufacture Timescales

By using information made available from previous publications alongside more recent internal modelling done by ORE Catapult; two scenarios have been produced which show the potential trajectory for the volume manufacture of TSE turbines and their components. As mentioned in section 3.4.2, multiple timescales ranging from 2021-2035 have been used to roadmap two scenarios (Baseline and Accelerated deployment) which cover TSE LCOE, total installed capacity, milestones reached, and the number of turbines/components that are installed/produced per annum by the end of a given timescale.

5.3.1 Component numbers and milestones

In Figure 28 and Figure 29 the timescales for the Baseline and Accelerated Deployment scenarios are illustrated. It should be noted that each set of figures represented in each timescale is reflective of what is expected to be in place by the final year of each timescale. In other words, the figures for 2021-2025 are what is expected to be seen in 2025, while 2025-2030 represents figures for the year 2030, and 2030-2035 representing figures for the year 2035.

Generally we expect a fairly modest increase in capacity up to 2025, facilitated by favourable revenue support schemes in the UK and France. In this period we believe that supply can be provided by existing suppliers and associated supply chains. Projects such as the VOLT project and development of 3MW turbines will give insight into the future manufacturing capabilities required for a largescale commercial industry. By 2030 we anticipate 70-160 devices being installed per annum, spread across 5-10 technology developers. We expect that some offshore wind suppliers will enter the industry in key areas such as foundations (e.g. monopiles) and blades; this will be necessary to meet the anticipated device volumes for projects reaching financial investment decision (FID) in the early 2030s. Further into the 2030s we anticipate larger arrays, which will further drive down costs through economies of volume. At this stage the leading technology developers will have dedicated assembly lines set up, capable of assembling 30-50 devices per annum. We also believe that the sector could organise and push for a Sector Deal, akin to the Sector Deal announced for UK offshore wind in 2019, which would provide stability through guaranteed capacity and supply chain investment.

5.3.2 Barrier transition over time

Figure 30 shows how we envision the eight barriers reducing over time, as actions are implemented by government and industry to grow manufacturing capabilities.

By 2025

In the near term we believe that attention needs to be focussed on securing political support for TSE. This political capital is crucial to ensure a healthy project pipeline, which will attract supply chain investment. We also believe that advancements can be made in blades, for example through increased testing and modelling of novel materials like thermoplastics. It is important that blade suppliers are directly brought into these projects, to ensure that learning can be captured and manufacturing considerations properly incorporated. Larger orders that will be required for AR4 could see improvements in the tooling used, for example moulds that can be used to manufacture more blades. Industry collaboration in areas such as cost reduction, blades, foundations and cables will ensure that future manufacturing volumes can be met, for example through standardisation which will ultimately reduce lead times and bring new suppliers into the industry.

While not a necessity for AR4, further R&D and grant investment into subsea hub solutions that can be used for different device concepts will be crucial for unlocking future cost reduction. It is important that suppliers are brought onside early to assist with the design process, as the immaturity of these components will otherwise have implications for project lead times into the future.

By 2030

We expect more interest from offshore wind suppliers, particularly in foundations, as projects move towards monopiles; blades and electrical powertrain components. This will help the industry reduce costs further, and allow lead times to be shortened in these critical components. We also expect increased technology convergence, with a fewer number of technology developers, as the commercial opportunities will still be limited. Further generations of devices and increased collaboration will reduce bespoke manufacturing, with clear classes of devices targeted at well defined site types. With several commercial projects deployed (from AR4 and possibly later CfD auctions) there will be greater standardisation in areas like wet mate connectors and cables, with suppliers more willing to supply larger volumes and keep stock in their inventories, with guaranteed projects in pipeline.

We anticipate that the leading technology developers will have small scale assembly lines, capable of producing 20-50 devices per annum, with plans for larger facilities into the 2030s.

By 2035

By this date the tidal industry will have a notable track record, with 1.5GW deployed. The technology will be at commercial maturity and significantly de-risked, with the benefits of predictability fully understood. As is the case for offshore wind, we believe that the industry will have strong government support which will pave the way for a Sector Deal, guaranteeing project pipeline and implementing local content requirements.

Several technology developers will have production lines capable of producing hundreds of devices per year, with an emphasis on exporting to global markets (such as North America and South East Asia). It is also likely that they will have local manufacturing presence on different continents, close to projects under development/operation, utilising local workforces and supply chain clusters.

We believe that the largest devices will be on the order of 5MW, with modular designs largely based on earlier smaller designs, to take advantage of previous R&D and manufacturing improvements. Modularity will be key in the powertrain electrical system, with manufacturing emphasis on “plug and play” to allow for fast O&M. Commercial arrays of 200MW+ will bring in new, larger suppliers, for example in subsea cables and device integration.

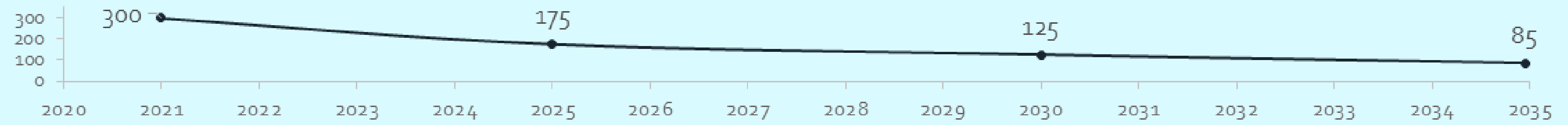
Lastly, we believe by this time there will be interest in purpose built vessels for tidal farms, which could have implications for manufacturing and device design (for example design of quick connection systems and buoyancy systems for device recovery).

Tidal Volume Manufacturing Timescales – Baseline (UK & France)

TIGER TIDAL STREAM INDUSTRY ENERGISER

Current Status (2021)	Early Expansion (2021-2025)	Early Commercial (2025-2030)	Commercial (2030-2035)

LCOE (£/MWh)



Cumulative installed capacity (MW)

Milestones

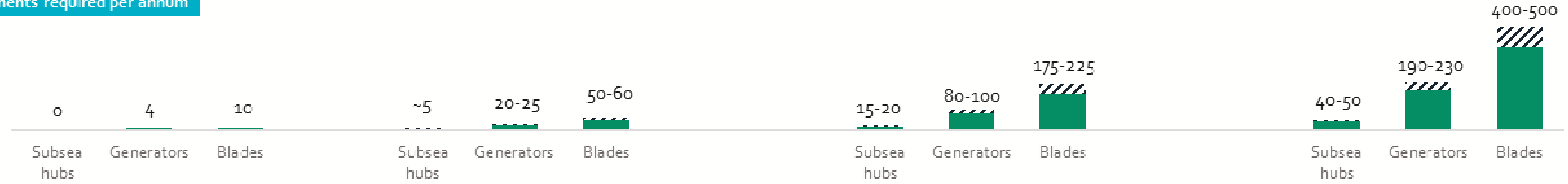
In 2021
- CfD Pot 2 for TSE
- Ringfenced budget amount allocated to TSE

By 2025
- Formal support for TSE by French gov.
- Development of European assembly line for turbines (VOLT)
- Manufacture of 3MW turbines
- Export of UK/French turbines globally for commercial projects

By 2030
- Integration of TSE with wind, energy storage and H2 production (forward-2030)
- Standardised wet mates
- 30m+ tidal rotors
- Dominance of monopiles for fixed devices
- Tidal farm developed by major utility

By 2035
- Manufacture of 5MW+ Turbines
- Arrays of 200MW+ capacity
- UK Sector Deal for TSE
- 1.5GW installed capacity across UK & France
- Purpose built vessel for tidal technology is commissioned

Components required per annum



- 2 devices installed (actual)
- 15-20 devices installed per annum
- 70-90 Devices installed per annum
- 160-200 Devices installed per annum

Figure 28 – Baseline scenario roadmap

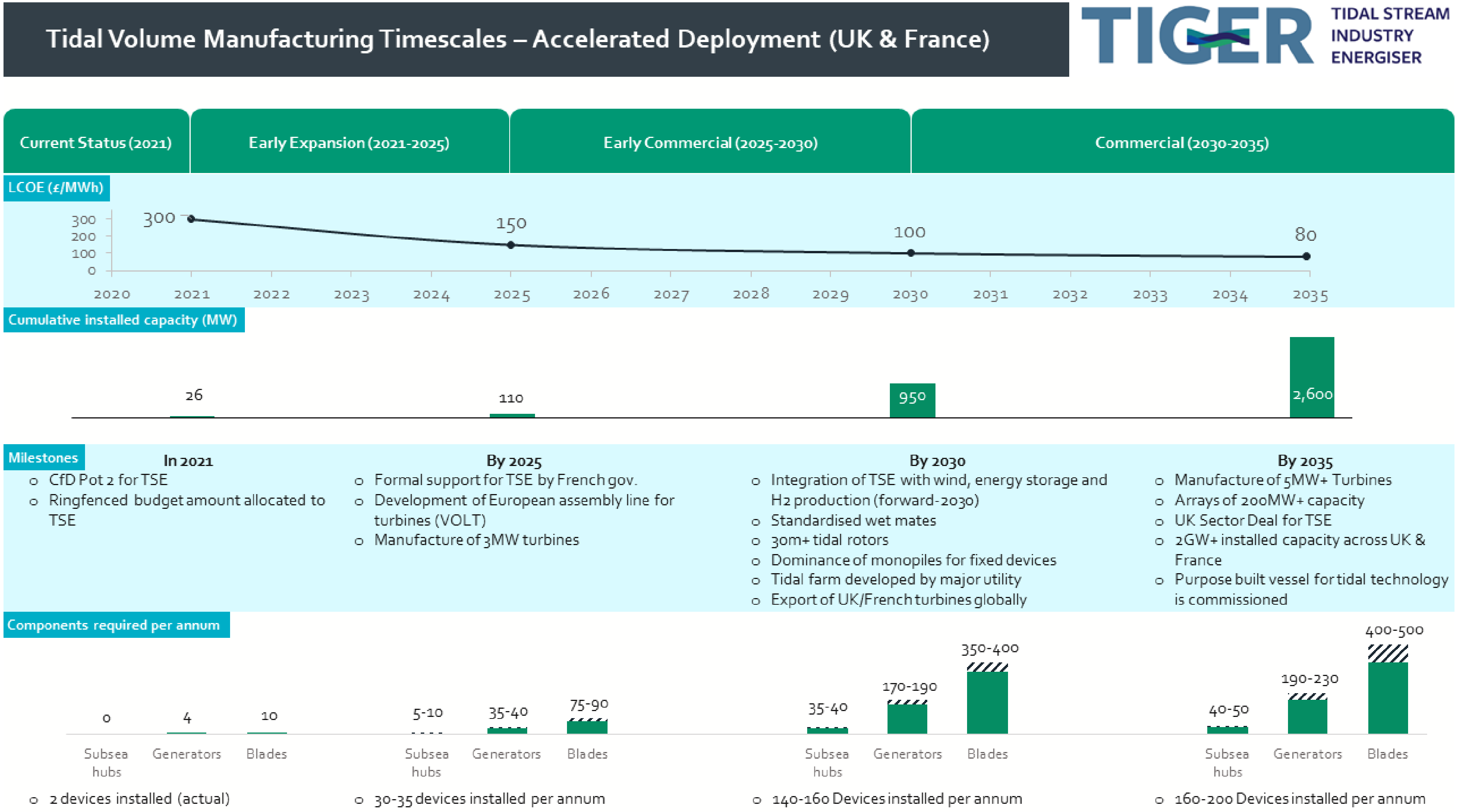


Figure 29 – Accelerated deployment scenario roadmap

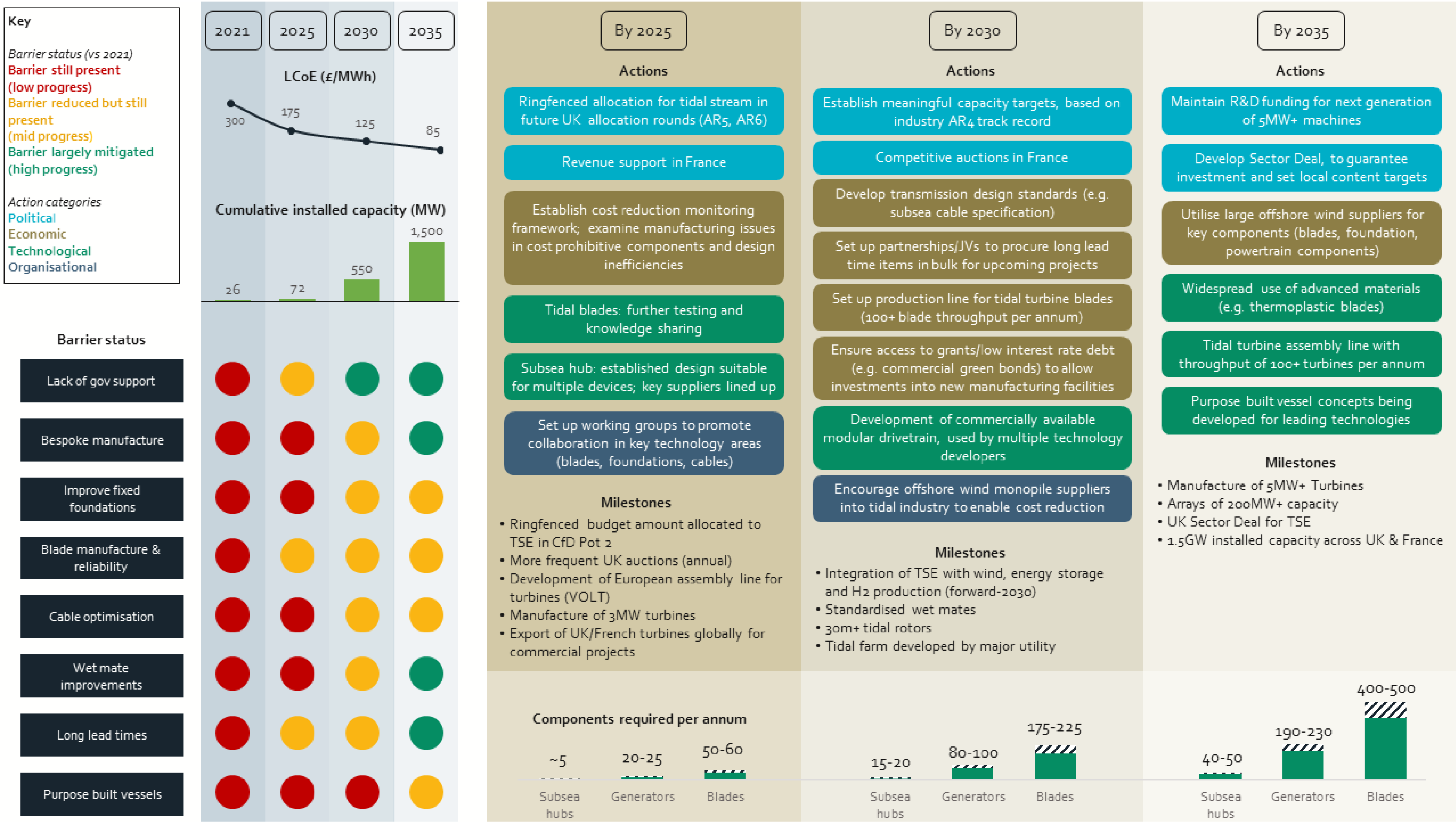


Figure 30 – Progression of the eight barriers to volume manufacturing (left), alongside the actions that could ensure that the barriers are reduced (right).

5.4. Non-Manufacturing Related Barriers

Throughout the development of this roadmap a wide range of barriers were considered for inclusion in this report. However, despite each barrier examined being problematic to some extent when considering the growth of the TSE industry, several of these barriers did not directly relate to manufacturing issues. For the purpose of giving a broader overview of the current issues that TSE faces, these non-manufacturing related barrier are listed below.

Barrier – The need for improvements in moorings for floating tidal turbines

Reductions in O&M costs for floating turbines can be achieved due to them being far easier to retrieve than fixed ones. However, retrieval may become more difficult when floating turbines are configured in large arrays in the future. Another aspect that increases the cost of moorings is the need to over-size components to combat the effects of bio-corrosion.

Mooring system components are typically off-the-shelf and used in many other maritime industries (for example aquaculture, shipbuilding, floating wind, navigation). Because these components are manufactured in large volumes already, with developed supply chains, it was not considered a manufacturing barrier.

Enabling Actions – Minimise required materials/equipment. Research and development into optimised designs and solutions. Learning from the experience of other sectors.

To solve potential issues associated with densely packed chain and mooring configurations that make maintenance of turbines and subsea cables more difficult, one solution is to install multiple turbines to a single platform to reduce the total mooring apparatus required over a large-scale array. Conversely, multiple platforms could be shared between the same mooring lines, again reducing the infrastructure required.

By seeking innovations in moorings that use materials more resistant to bio-corrosion, greater material efficiency and cost reductions can be achieved. Examples include synthetic mooring lines and taut moorings. Alternatively, anti-biofouling coatings being applied to moorings may offer some assistance to improve the reliability of current designs [114].

The offshore wind sector are also looking into alternative mooring designs and materials to accommodate floating wind turbines. One example which demonstrated the use of alternative materials is BW Ideol and their use of nylon mooring lines on the Floatgen project [115]. Additionally, companies such as Marine Flex have developed elastic mooring lines which they claim would be suitable for TSE as well as floating solar arrays [116].

Barrier – A complex & costly environmental impact assessment process (Policy & Regulatory), Medium Impact

Environmental impact assessments (EIA) are often far too costly and technically challenging in proportion to the size of current TSE projects. Reductions to environmental impact is an area in which innovation can be achieved, but prohibitive assessment costs and unclear data requirements reduce the incentive to innovate. Regarding EIA costs in proportion to project size, this has been particularly problematic for developers testing turbine prototypes in prior years, with these excessive costs leaving less funds available for other R&D activities. The low environmental impact of these prototypes can also be disregarded when developers attempt to test other prototypes at new sites. Despite all this, the TSE industry recognises that environmentally responsible development will be of high importance when larger arrays are developed in the future [7].

Enabling Actions – Further research into the adverse effects of tidal on marine life. Standardisation and simplification of the assessment process.

Development of models for predicting the noise effects of multi-device arrays based on standardised approaches will improve understanding of the impact TSE has on local marine species. Once larger TSE arrays can be sufficiently monitored in terms of their impact on the local marine environment, clearly defined requirements from regulators should be put in place that allow future TSE developers to acknowledge the due diligence that is required of them.

Barrier – A lack of understanding of optimal spatial arrangements for larger arrays

For TSE to achieve commercial viability against more established forms of renewable energy, reductions in LCOE can be achieved through improved array design. Many tools have been created which can predict and maximise the yield of TSE arrays for given array layouts. Optimal array design can result in higher yields from the intelligent micro-siting of turbines which reduces blockage effects. It can also reduce costs, e.g. reducing the amount of cabling required.

Enabling Actions – Building on the findings of different turbine configurations.

Building on the findings of projects such as EnFAIT can help achieve a better understanding of optimal spatial arrangements. During EnFait, Nova Innovation intend to change the positions of their M100-D turbines to monitor the effect this has on turbine efficiency and the overall yield of their array in the Bluemull Sound in Shetland.

The tidal resource varies greatly for different sites, depending on aspects like the local bathymetry. More ACDP deployments, to monitor the flow regime, and validation with 2D and 3D models will improve understanding of the flow at specific sites, and give developers a better idea of how to arrange their devices.

Barrier – Intellectual property concerns reducing levels of collaboration.

During industry engagement, several suppliers mentioned that optimising their components for use on turbines was made more difficult due to developers limiting the amount of information they were willing to share because of concerns surrounding IP. While the desire of companies wanting to protect their IP is a very legitimate one, this has been flagged as an area where innovation is potentially being stifled due to a lack of cross-fertilisation and knowledge transfer.

Another scenario where innovation is slowed in this area is when a tidal developer faces bankruptcy, which has been a common theme for many companies in this nascent industry. When a company faces insolvency, their IP falls into the hands of a relevant administrator where it can then be acquired by another company at a later date. This was the case for wave company Pelamis who, after facing insolvency, eventually had their IP purchased by Wave Energy Scotland. However, there is the possibility of valuable IP being acquired by a company without the knowledge to utilise it, or staying in the hands of administrators, thus preventing its full value to be realised.

Conversely, there are arguments which favour the notion of strong IP rights strengthening innovation. An example of this was seen during the early 2000's when the wind energy sector was beginning to develop into a major global industry. Before the 2000's there was a far more relaxed attitude to IP rights and patenting, but as the sector grew and competition increased between companies, patenting became far more commonplace.

Enabling Actions – Greater collaboration between competitors and the wider supply chain.

There are some areas where it is unlikely that IP could ever be shared, for example device control systems and blade designs as these give commercial advantages against rivals. However, systems where IP could be more readily shared include foundations, wet mate connectors and subsea hubs.

For some developers there could be a commercial advantage to sharing their IP as they could receive royalties from the party using it. An example could be SIMEC Atlantis's subsea hub, which contains fairly generic components in its basic form and yet is more advanced than other designs in the industry.

There could be benefits from bringing more suppliers into publicly funded research projects, ensuring that findings can be licensed by these companies and hence used for other clients in the sector to encourage competition and reduce LCOE.

There could be a rationale for a public entity/cross industry consortium to obtain IP of companies that get dissolved. This would ensure that any knowledge is used and disseminated to the wider industry. The mechanism would have to be established and expertise could potentially be brought in from organisations who have acquired such IP (such as the aforementioned Wave Energy Scotland). An interesting recent example of public dissemination of IP was when the airborne wind developer Makani was shut down by parent company Alphabet in 2020. The company decided to upload a significant amount of their modelling data, code and sensitive information online to be used by the wider airborne wind industry [117]. They also released a “non-assertion” pledge, stating that parties are free to use their IP and patents freely, without risk of legal recourse [118].

Another potential area for collaboration is data. Potential applications include a centralised database of resource data (both experimentally collected and simulated e.g. hindcast data) that could be accessed by TSE developers. As the industry matures, a similar approach to the SPARTA portfolio could be adopted [119]. This scheme is run by the ORE Catapult. It collects operational data from several UK wind farms (e.g. capacity factor, interventions per year), anonymises it and makes the findings publicly available. Such an approach for the TSE sector would help give investor confidence in the sector and give project developers a good way to benchmark their technology to help drive down costs.

Conclusions

To conclude, this report provides insight into the main barriers that the TSE industry faces regarding volume manufacture for turbines and components. The wider industry issues currently facing TSE were addressed in the literature review while providing context into measures that were taken by offshore wind, solar PV, automotive and aerospace to upscale and futureproof their manufacturing capability at earlier stages in their development. Of all these measures, several could be adopted by the TSE industry to aid its manufacturing growth, such as improvements in material choice and turbine designs to decrease O&M requirements, as was done with turbines in the offshore wind industry. Other measures include the formation of localised supply chains as was recommended by IRENA to support the future growth of solar PV. In the case of TSE and TIGER this would mean maximising UK and French, or even European content in the TSE supply chain. When looking at actions taken by automotive and aerospace, increased automation and digitalisation appears to be the pathway these industries are taking to enhance their future manufacturing processes. These industries are very mature and much more developed than TSE and so, while the same actions can be taken by TSE into the future, this is further into the future as initial focus should be on demonstrating cost effective and reliable energy production by deploying arrays.

In the engagement insight section, a breakdown and analysis of each industry response was provided to make sense of current industry trends, as well as the relevance and experience that each respondent had within the TSE industry. Through feedback that was obtained via the questionnaire, companies that were deemed to have the most relevant insight into issues surrounding volume manufacturing were then contacted for follow-up discussions so that a range of potential barriers could be discussed in more detail.

After discussions with a range of industry stakeholders the roadmap was formulated with barriers being ranked as low, medium, or high. Of all the barriers, a lack of government support and long lead times were ranked as the most severe high impact barriers. Medium impact barriers included the need to move away from bespoke manufacturing, the need for advancements in blade manufacture and reliability, the need for improvements in wet mate connectors, and the need for optimisations in cabling arrangements. The need for improvements in fixed foundation designs and the need to increase vessel availability were rated as low impact.

The main conclusions from this study can be summarised as follows:

Government support

It is highly encouraging that the UK government are supporting the sector through a £20M per annum ringfence in AR4. We believe that more support should be provided as the sector progresses in the coming years, including access to future CfD rounds.

As project sizes, supply chain capacity and developer revenues increase over the next decade, a sector deal similar to the Offshore Wind Sector Deal should be considered so that TSE can continue to expand and evolve well after the point of reaching full-scale commercialisation. Before any talk of a sector deal become realistic, government needs its support commitments to hold true so that companies which make investments on the basis of such support do not incur future financial damage when such support is pulled. Regarding France, a call for tender for TSE, or following a similar support path to the UK will provide a degree of visibility for French tidal developers.

Long lead times

For long lead times, many components in the wider TSE system have manufacturing lead times which can be reduced considerably with the appropriate actions. If or when alternative blade mould materials become economically feasible for TSE, moving to such materials will allow more blades to be produced per mould and hence reduce lead times considerably, with the tooling of moulds currently cited as the most time-consuming element of the blade manufacturing process. Low order volumes are also a key factor contributing to long lead times. This is because higher order volumes of a given component are needed to create the demand that warrants serial production and a move away from bespoke manufacturing. Larger orders from other industries (e.g., oil and gas, offshore wind) are often being prioritised over the lower TSE volumes when procuring components such as wet mate connectors.

Bespoke manufacturing issues

When it comes to moving away from bespoke manufacturing, a range of components within the wider TSE system would benefit greatly from greater standardisation to support serial production. This includes blades, foundations, wet mate connectors, subsea power cables and subsea hubs. Standardisation of turbines across different device scales is being targeted by developers such as Torcado, SIMEC Atlantis, Minesto and Sabella. Nova Innovation recently secured public funding from the Scottish Government via the Volt project to develop a European assembly line for the serial manufacture of turbines.

Wet mate connectors

Greater collaboration between different TSE developers has the potential to contribute towards greater standardisation in wet mate operating voltages and general design. The development of a standardised wet connector, compatible with multiple developers' devices, would reduce the supply cost of the wet mates as they could be purchased in larger quantities. It would also reduce O&M cost, with learn-based improvements from more widespread deployment of the technology. The lack of standardisation, combined with low order volumes, has left TSE developers in a position where they have less leverage in getting the exact wet mate design they want from suppliers. A standardised wet mate, designed through greater collaboration among developers and the supply chain, will result in a more optimised, easier to manufacture design.

Blades

For blades: to maximise their production and reduce costs, standardised blade lengths that are suited for performing reliably with differing turbine designs at varying site locations would improve manufacturing efficiency. These standardised blade sets may not be optimal from the perspective of LCOE compared to blades which are tailored for a specific turbine at a particular site. In this case, a trade-off needs to be made between blade manufacturability through a range of sizes and maximised blade performance, with this trade-off being best decided by developers with support from supply chain partners. There is also a role for academia to assist through research channels like blade shape optimisation, simulations (for example computational fluid dynamics), testing and research into emerging materials like thermoplastic blades.

Subsea cables

Among cable suppliers there is clear interest in supporting TSE. However, progress has been slower than anticipated, with limited commercial opportunity for these suppliers who are more used to supplying in large volumes for industries like offshore wind and telecoms. We expect that more suppliers will signal interest as the pipeline of commercial projects grows, which will lead to improved competition and a reduction in costs.

By standardising cable voltage and cross-sectional area throughout the TSE industry, multiple project developers could make joint orders. This would satisfy both cable suppliers and project developers by reducing lead times and wastage via greater amounts of cable being produced per each TSE related production run.

Other barriers

Other barriers were identified, for example fixed foundation design and vessel availability. We believe that these issues will largely resolve themselves as the industry grows and more commercial opportunities become available to the supply chain.

Volumes and timescales

After providing commentary and enabling actions to each of the mentioned barriers, timescales were then presented under two different scenarios: a Baseline and Accelerated Deployment (AD) scenario. These road mapped LCOE, total installed capacity, milestones, turbines installed and components manufactured between 2021 to 2035. The Accelerated Deployment scenario assumed more rapid growth in earlier years, with 950MW installed in the UK and France by 2030. This aligns with the current vision for the industry from industry bodies like the MEC, Ocean Energy Europe and Renewable UK.

Table 8 summarises the number of devices and components that we expect to be installed per year for three years: 2025, 2030 and 2035. Both the Baseline and AD scenarios are shown. Generally the uncertainty is large, and will depend on the revenue support available and how quickly the industry can bring costs down to be more competitive with alternative technologies. While the number may seem high, these are low compared to offshore wind, and we believe that the supply chain will largely flex to meet the demand as the commercial opportunity becomes apparent.

Table 8 – Projected devices and components installed per annum for three future years: 2025, 2030 and 2035. The accelerated deployment (AD) scenario sees faster growth in earlier years, with the two scenarios seeing equal capacitors of tidal stream deployed by 2035.

Year	2021	2025	2030	2035
Devices per annum	2	15-20 (Baseline) 30-35 (AD)	70-90 (Baseline) 140-160 (AD)	160-200 (Both)
Blades per annum	10	50-60 (Baseline) 75-90 (AD)	175-225 (Baseline) 350-400 (AD)	400-500 (Both)
Generators per annum	4	20-25 (Baseline) 35-40 (AD)	80-100 (Baseline) 170-190 (AD)	190-230 (Both)
Subsea hubs per annum	0	~5 (Baseline) 5-10 (AD)	15-20 (Baseline) 35-40 (AD)	40-50 (Both)

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Appendix A: Engagement Respondents

Below are the companies we surveyed who were happy to be publicly mentioned in this report. Other companies who took part in the industry engagement questionnaire wished to remain anonymous so are not listed.

Amo Specialkabel AB

Apollo

Blackhill Engineering Services

Crack Map Ltd

ECP

Ennis Safety Wear Ltd

Exceedence Ltd

Fern Communications Ltd

FMGC

Hydac Technology Limited

Leask Marine Ltd

LHM Group

Manor Renewable Energy Ltd

Metalast Ltd

Optimus Aberdeen Limited

PPI Engineering Ltd

Scientific Management International Ltd

Shoreteam

Sogebras

Southampton Marine Services Ltd

STIndustries

Swagelok Bristol

TechnipFMC

UMBRAGROUP

UW-ELAST AB