Mooring and Anchoring Research Report

Mooring and Anchoring Literature Review and Consultation

Scottish Enterprise

Assignment Number: L400395-S00
Document Number: L-400395-S00-REPT-001

Xodus Group
Glasgow, UK, G2 5SG

T +44 (0)141 299 0000
E info@xodusgroup.com
www.xodusgroup.com

Mooring and Anchoring Literature Review and Consultation

L400395-S00

Client: Scottish Enterprise
Document Type: Report
Document Number: L-400395-S00-REPT-001

Contents

EXECUTIVE SUMMARY

This report presents an initial literature review and consultation exercise to understand the current state of the art in anchors and moorings for offshore wind and marine renewables, any currently known risks and challenges, ongoing research and development programmes by the wider industry and ADMA partners, and finally concludes with our recommendations.

In line with the ADMA Energy Partners remit, our primary focus has been to consider anchors and moorings in offshore wind and marine renewables and their capacity to directly benefit the industry through:

> Reducing capital expenditure, installation costs, and maintenance costs;

> Improving reliability, survivability, performance and energy yield, and;

> Reducing LCOE.

For clarity, reducing LCOE is a good umbrella term and metric for measuring the relative success of the other parameters, and we have therefore dedicated a whole section to this specifically. Any reduction in LCOE will result as a collective response to successfully understanding and enabling measures in the other sections.

Methodology

This report is formed of a two-part literature review, a consultation exercise, and an internal workshop to guide our recommendations. The the first stage of the literature review was led by our own knowledge and recent research into floating offshore wind more generally and was used to guide the content and structure of the consultation exercise. The second stage of the literature review was guided by responses to the consultation exercise. Following the collation of all information and responses, an internal workshop was held to assess the findings, agree the main risks and challenges facing the industry in anchors and moorings, and finally to create a recommended path for ongoing research and development to answer some of these main challenges.

Findings

While there are applications for anchors and moorings across the offshore wind, wave and tidal industry, the use case in the tidal industry was low and detailed consideration of this industry was considered of low value and is only reported on by exception. Use of anchors and moorings in the wave energy sector is integral to many designs, but current and future deployment in this industry is low. Therefore, the primary market for industry collaboration, R&D funding and serial production to increase learning and reduce costs, is floating offshore wind. The primary market considered at all stages of this report is therefore floating offshore wind, with the expectation that increased learning and understanding here could be leveraged in other sectors as they progress.

A number of design concepts exist in the floating offshore wind sector, some of which have their own inherent and specific risks and challenges. It is our conclusion that any detailed research into any of these specific areas could result in poor economic return if the selected concept fails in future commercial deployment. Instead it is recommended that initial research and development is focused on risks and challenges common to all design concepts.

Recommendations

ADMA partners should focus on mooring redundancy and anchor mutualisation as challenges common to floating offshore wind and marine renewable energy sectors generally. The primary purpose of this recommendation is to provide open-source knowledge and learning that can inform multiple additional research strands as it continues. In its initial stages, this R&D initiative should look to gather all knowledge from interested ADMA partners and the oil and gas industry relating to mooring failures and root cause analysis, as well as findings relating to anchor mutualisation.

This exercise would then create the beginnings of a benchmarking dataset which can be used for multiple future research strands. As well as providing value to the industry generally, ADMA could look to use this dataset to improve insurance provision, reduce risk and provide quantitative findings to inform supply chain planning.

0 INTRODUCTION

There is growing support for the transition away from traditional fossil-fuelled energy generation towards green energy technologies in a bid to combat climate change. Sustainable energy generation targets have been set in many countries as a direct response to the 2015 Paris Agreement where world leaders agreed global warming was an issue that needed to be tackled collectively.

Renewable energy technologies have the potential to satisfy global energy demands. However, further advances in renewable technology and supply chain can still be made to support industry growth and help progress the energy transition. Floating offshore wind and marine renewables can play a significant role in realising a sustainable energy future. However, these technologies are not yet considered commercially viable at large scale and so additional cost reduction must be found.

Mooring and anchoring systems are a common area between floating offshore wind and marine renewables to be explored in an effort to bring down the levelised cost of energy (LCOE). Through examination of current literature on the key issues in mooring and anchoring systems, this study aims to provide an insight on the options and potential solutions available to help bring lifecycle costs down. For the purposes of this study *marine renewables* refers to offshore wave and tidal devices.

This report discusses the current state of mooring and anchoring systems, identifying the key challenges and opportunities for the technologies and highlighting the current activities underway in Europe. The study was supported through engagement with members of the Advanced Manufacturing for Energy Related Applications (ADMA Energy) pilot to understand their respective area(s) of interest, capability levels in these areas and keys incentives for further technology and supply chain development. This report presents recommendations on future actions to reduce costs and improve the performance of mooring and anchoring systems.

0.1 Method and approach

Our approach to this report consisted of three phases: a literature, in two parts; a consultation exercise with relevant ADMA partners, and; reporting of the combined results and recommendations. The literature review was conducted in two parts to allow our consultants engaging in the consultation to do so with an informed view of the current state-of-the-art in anchors and mooring research and development (R&D).

0.1.1 Approach to literature review

Our team of researchers has already conducted multiple research tasks into floating offshore wind generally in the past eight months and we used this research as an initial starting point, as well as knowledge from specialists in floating structures with experience in the oil and gas industry. It should be noted here that while no new analysis has been conducted for this study, Xodus has performed new analysis for other projects and, where relevant, has included this in the literature as a primary information source. The overall approach to the literature review followed the following steps:

> Identification of reports
- Using our knowledge of the topic, we identified a range of published scientific papers, grey literature, funding calls, technical studies, policy documents and other relevant items.

> Preparation of literature review matrix
- Our consultants followed our in-house method of recording the results of the literature review in a concise and digestible format.

> Consultants conducted the literature review, recording as per the literature review matrix. This included:
- Details of each study reviewed (e.g. study title, authors, nature of project, geographical area, funding body etc.) and embedded study in matrix or project folder;
- Scope of study and key outcomes, detailing issues dealt with, solutions proposed, lessons learned;
- The potential for collaboration, or for planned future work; and
- Other relevant observations, such as comments on funding and linkage with regional, national or international policy.

This approach was followed for both the initial literature review, as well as the second stage of review following engagement with ADMA partners.

0.1.2 Approach to consultation

We worked with Morag Clark at Scottish Enterprise to agree a list of contacts with ADMA partners who should be approached to provide input into this study. An initial questionnaire was drafted to elicit high-level responses and followed up by telephone or email for further detail on specific areas of interest. This approach was adopted based on multiple engagement studies conducted by our team which have shown that participants are generally more likely to respond to an initial information request by email with a short and targeted follow up by telephone. While detailed response rates were low, this was largely a result of multiple partners considering anchors and moorings to be outside their current research areas and it is our expectation that the responses included in the study are from the partners with the most to contribute to any ongoing R&D efforts.

0.1.3 Approach to reporting

Finally, we distilled the findings of both the literature review and the partner engagement into a short, succinct and targeted report detailing our findings, the current risks and challenges in the sector, and our conclusions and recommendations for further study.

1 SUMMARY OF KEY FINDINGS FROM DESK-BASED RESEARCH

1.1 Overview of floating market and potential deployment to 2030

The cost of fixed offshore wind varies with site water depth. Additionally, seabed ground conditions can make it impractical to install fixed foundations in certain areas. As fixed offshore wind projects continue to be developed at shallow, near-shore sites, expectations are growing for floating offshore wind solutions to be utilised to access locations unsuitable for fixed foundations. Floating wind farms can be installed at deep water sites that are uneconomic for fixed offshore wind and may be more amenable for deployment in certain seabed soil configurations. Sites further from shore that commonly have higher and more consistent wind speeds, providing greater and more stable energy yields, are also predominantly deep water locations.

Designs for floating offshore wind foundations vary greatly, with the main differences being in the ballast type and platform configuration. Whilst most foundation concepts are designed to be turbine agnostic some companies are looking to offer package solutions with their own bespoke turbine design. Though no ideal design concept has been identified for foundations yet, some designs are likely to face considerable technical barriers. It is likely that most of the concepts will not be developed past tank testing and small-scale demonstrators, filtering out the commercially and technically viable floating platform options. A smaller range of concepts will also be beneficial for creating a streamlined supply-chain and infrastructure. An example of this filtering process is Nenuphar Vertiwind. In 2015 the company had plans to develop a 2MW prototype in 2016 and a 13 turbine 34MW pre-commercial array in 2018 [1]. By 2018 the company went into liquidation following EDF Energy's and Areva's decision to stop funding. This shows not only the competitiveness of the market, but the importance of up to date information in the fast-moving industry. It also shows that planned projects are not always a reliable indication for future success of a technology. A potential cause of Nenuphar's demise was the choice of a vertical axis wind turbine. Horizontal wind turbines have become the norm for most industry applications, on and offshore. Branching into a non-standard technology in a new industry increased the risk factor for investors. This suggests that the most likely concepts to make the cut will be turbine agnostic platforms. The different platform design concepts and associated risk factors and opportunities are further explored in detail.

In general, it is possible to group the main floating offshore wind foundation designs by the common characteristics of a design and group them into a defined hierarchy, mainly based on their stabilising technology and constructability. Figure 1 provides an illustration of the most common types of floating foundation. Most design concepts are hereditary or share similarities with oil and gas offshore industry thus the lessons learnt can be better applied through the hierarchical structure.

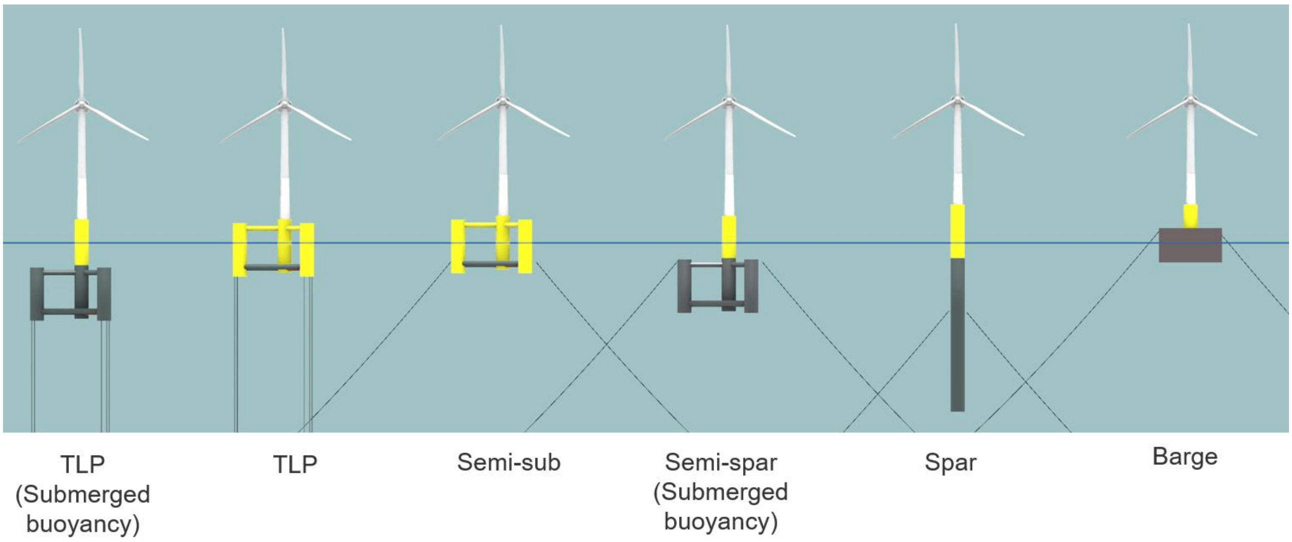


Figure 1: Illustration of the various categories of floating foundation.

Whilst there are a perceived large number of different types, it must be noted that they share a very large commonality with the offshore oil & gas industry. Most, if not all, of the designs have been tried and tested at some point over the last 40-50 years.

A cost benefit of floating foundations is that most designs with a shallow draft can be fully assembled in a dry dock and floated to site using standard tug boats. This leaves anchoring, mooring and connection with the foundation as the only turbine installation work required to take place offshore. Similarly, the foundation and turbine can be floated back to port as a unit for maintenance. This could eliminate the need for expensive heavy-lift vessels and thus potentially reduce capital expenditure (CAPEX) and operating expenditure (OPEX) costs.

Floating wind has only been deployed at demonstrator or pilot-array level to date, with the largest project being the 30MW Hywind wind farm installed off the coast of Peterhead, Scotland in 2017. The floating wind projects that have been deployed with megawatt-scale turbines currently in operation and under construction are described below.

As floating wind technologies mature from demonstrators to commercial scale developments, economies of scale are expected to bring CAPEX reductions. Further reductions to CAPEX, OPEX and LCOE are expected from technological developments, especially within platform design and mooring systems. However, floating wind still trails fixed in terms of cost competitiveness. Where an available location is suited to fixed, floating is unlikely to be a more economic option. There is also a variety of technologies available for floating wind competing against each other. It is expected that only a handful of different floating foundations actively in development, meaning there is currently little standardisation across designs and thus requiring bespoke design and supply chain solutions for each. A streamlined supply chain and financial incentives will be required to support the development of the floating wind industry and to make envisioned cost reductions a reality.

1.1.1 Global overview of pre-commercial arrays and full-scale demonstrators

Scotland is an early mover in floating wind power, with installed capacity reaching 32MW by the end of 2019, attributed to Hywind Scotland and the first phase of the Kincardine project. The second phase of Kincardine will increase total installed capacity in Scotland to 80MW by 2021 [2].

Because of significant government support and incentives, the outlook for France is an increase from 2MW of installed capacity in 2019 to 100MW in 2021, surpassing the UK. Other significant projects are under development in Japan, Portugal, France and Norway. This presents an enormous opportunity to ADMA Partners which are ideally situated as the major hub for offshore energy to capitalise on this market growth.

1.1.2 Future projects – outlook to 2030

The Carbon Trust estimates that based on current market trends, fixed-bottom offshore wind farms will continue to dominate up to 2030 after which, depending on the results from demonstrators and pilot arrays, floating could become could be deployed at commercial scale [3].

The progress of the floating wind market has been slower than anticipated. A 2015 report estimates a global cumulative installed capacity for floating wind of over 200MW in 2019. The figure today is less than half of that. 4C Offshore envisions cumulative installed capacity to reach 7-13GW globally by 2030 [2]. The projects referenced in the earlier sections are high certainty go-ahead. Projects with commissioning dates past 2022 have not reached final investment decision, hence longer-term predictions are subject to high uncertainty. Market forecasts could change further as high-stakes actors such as Saudi Arabia attempt to enter the market. In July 2019, Saipem signed an agreement with Plambeck Emirates LLC to develop a 500MW floating wind farm using their Hexafloat design. This development is part of Saudi Arabia's envisaged 5GW wind market.

Figure 2 shows two scenarios, high and low deployment, for 2030 by country (by state for US markets) [2].

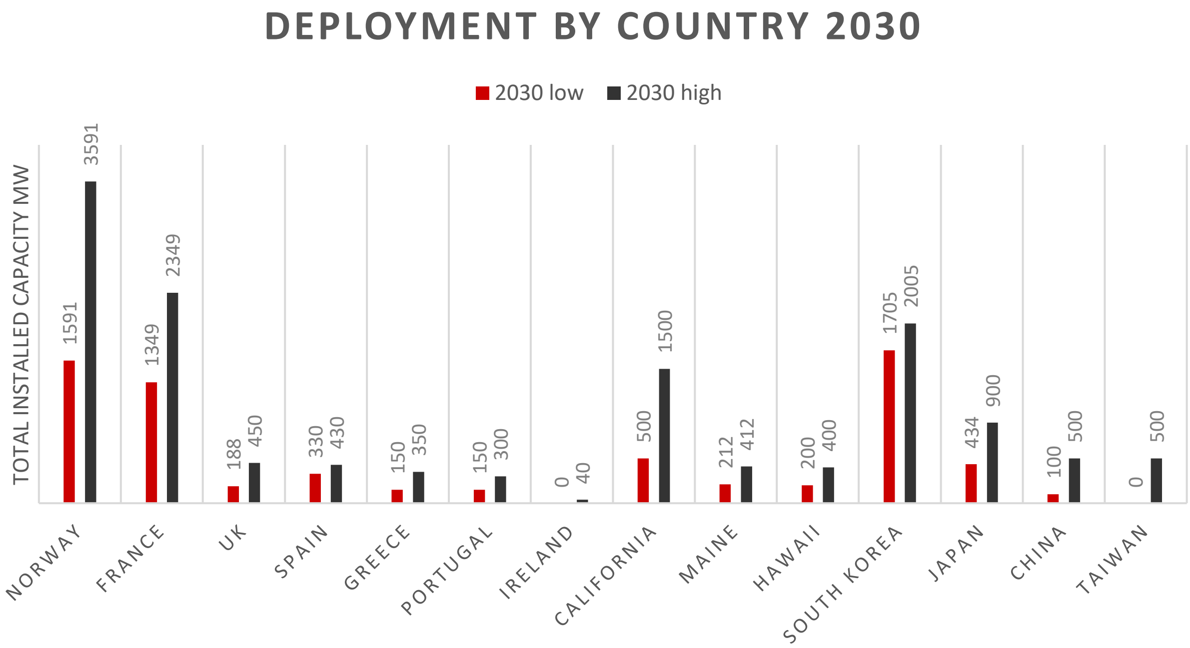


Figure 2: Predicted 2030 deployment by country (high & low scenario). Source: 4C Offshore

1.1.3 Market View: Technology Selection

Figure 3 below shows the current installed and the expected capacity in 2022 by floating foundation developer. Hywind and WindFloat are leading the pack, with the most demonstrated technologies. However, a single large project can make a big difference to these trends.

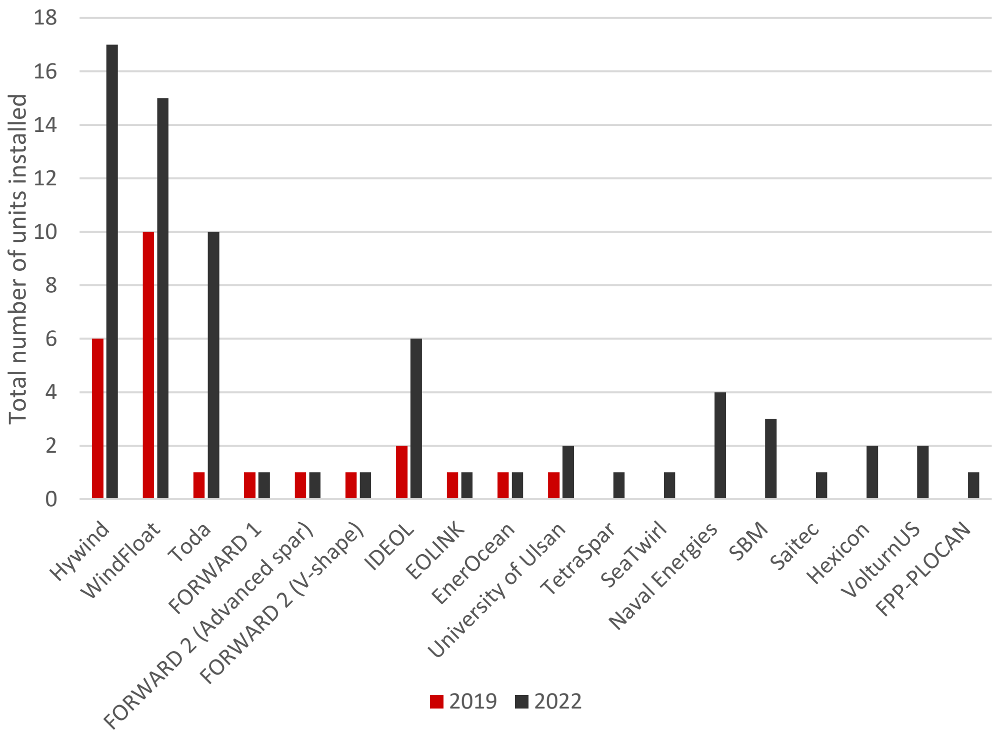


Figure 3: Installed number of units by technology type

The concepts can be roughly grouped based on the floating hull concept used. Figure 4 shows that the spar-buoy and semi-submersible types are the most popular. The potential for cost reduction of these technology options is analysed in section 2.

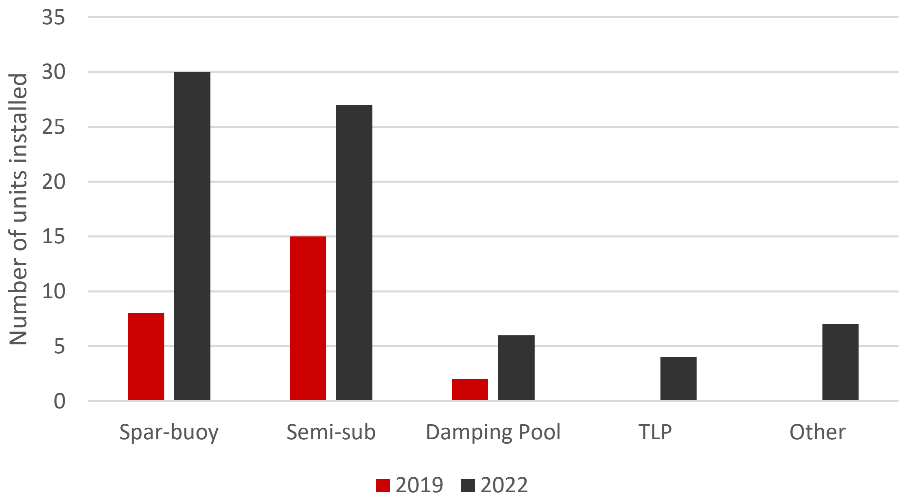


Figure 4: Installed number of units by concept category

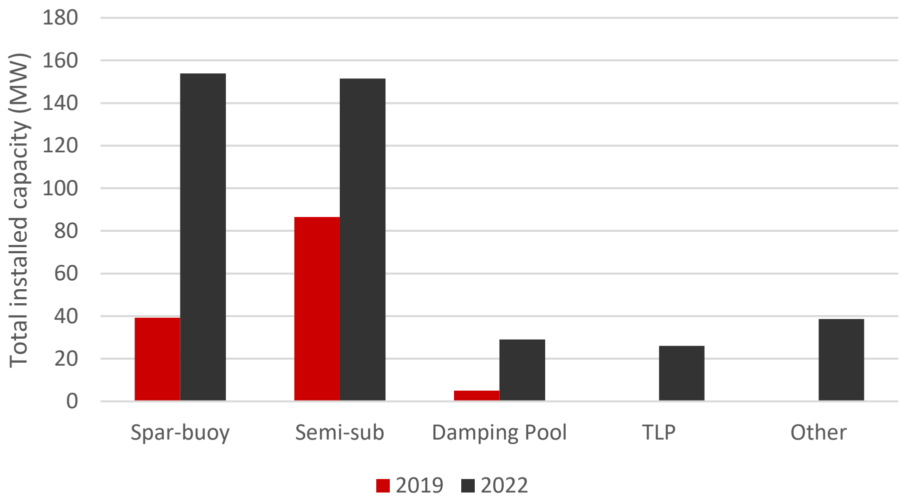


Figure 5: Total installed capacity by concept category

1.2 Overview of marine renewables and potential deployment to 2050

There have been significant technological advances in marine renewables in recent years, with some technologies progressing towards commercialisation [4]. However, a lack of government or investment support for this commercialisation process has meant that the rate of development, particularly with regards to large-scale deployment, has been slower than once anticipated. To reflect this low level of deployment we have adopted the 'pessimistic' forecast from the European Union's (EU) Market Study on Ocean Energy [5] when considering the potential relevance and application of anchors and mooring research in marine renewables.

1.2.1 European overview of pre-commercial arrays and full-scale demonstrators

There are significant tidal stream and wave resources within the UK and many of the technology advances have been developed and tested at the European Marine Energy Centre in Orkney, in the north of Scotland. Over 8GWh of energy generated from MeyGen's tidal array has been connected to the grid as well as Orbital Marine Power's 2MW SR2000 tidal turbine which generated enough energy in seven days to power 7% of the Orkney Islands [6]. Currently more marine renewable devices have been deployed in the UK than the rest of the world combined,

1.2.1.1 *Tidal*

While tidal energy is currently the most commercially developed of the two technologies, it is usually bottom-fixed, making use of gravity-based foundations. Occasionally mooring lines are included in technology designs, but this is by exception. As such, the remainder of this report will consider potential wave energy developments unless it is explicitly stated that there is also relevance to the tidal sector.

1.2.2 Future wave projects – outlook to 2030

The European Union's Market Study on Ocean Energy [5] laid out three potential scenarios for wave deployment to 2030, broadly refelected high, low and medium deployment. Based on the methodological approach and reasoning, as wel as continued stagnation in the sector since the reports publication, we have adopted the pessimitic or low case as our baseline for this research. It should be stated that there is a potential for further growth beyond this, but that current indicators do not suggest that this will be the case.

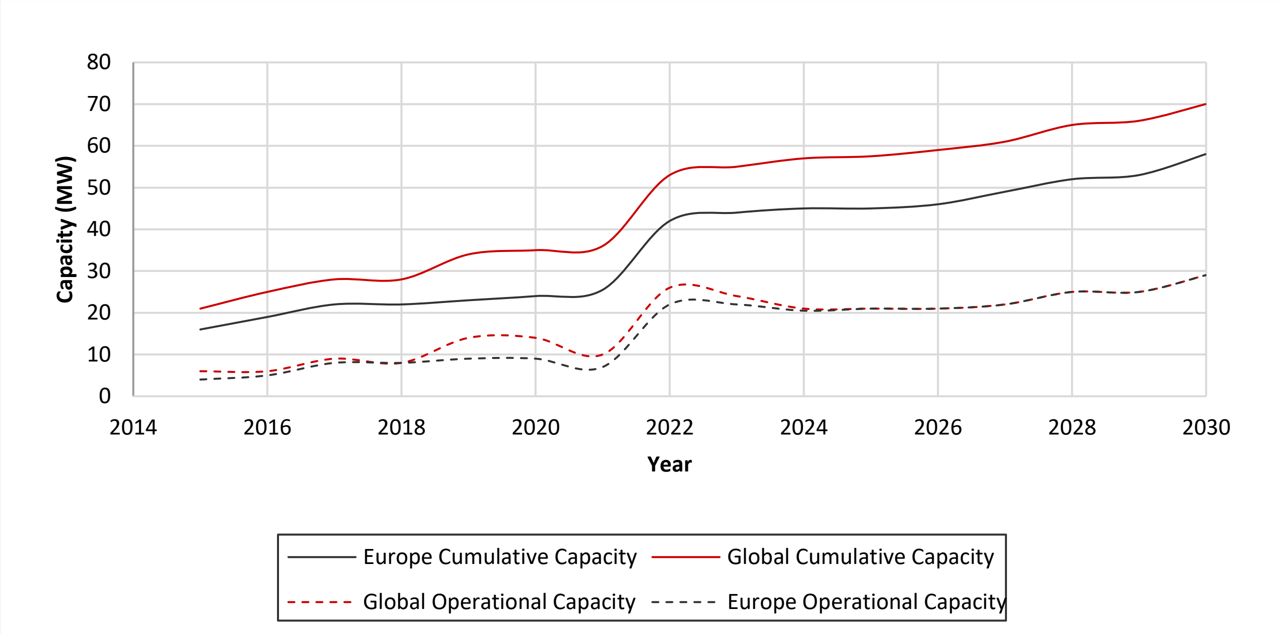


Figure 6 Potential European and Global wave deployment to 2030

Based on these projections, it is clear that wave devices offer a significantly lower opportunity for commercial scale adoption of optimised anchors and mooring solutions. As cost reduction is largely based on initial interest in R&D spend, followed by optimisation in manufacture through serial production, the most likely market for targeted new research initiatives will be floating offshore wind. This idea is considered further in section 2.

1.2.3 Market View: Technology Selection

While there have been significant advances in WEC technology in recent years, the industry has adopted a ‘growing slower to progress faster’ approach to the technology’s development. This may be attributed to lessons learned from Aquamarine and Pelamis going into liquidation, after which the focus has shifted away from building large-scale prototypes possibly too quickly [4]. Instead, companies and investors are employing a step-by-step approach to the development of WECs which typically consists of six phases and funding for the next phase is solely dependent on successful completion of the previous phase. The six-step approach will consist of:

- Design, modelling and control
- Very small-scale separate testing of device, components and sub-systems in small tanks
- Small-scale testing in larger tanks
- Small-scale testing in sheltered sea conditions
- Medium-scale testing in sheltered sea conditions
- Full-scale testing in exposed sea conditions

Following this framework means WECs will continuously be assessed and evaluated, with continual corrections and enhancements made to systems and lessons learned incorporated into the next phase. While this approach means fewer concepts will reach full-scale testing, those that do will have a higher success rate.

One issue that may arise from this approach is the continued investment from stakeholders when the only objective is to generate experience instead of revenue, especially as other offshore renewable technologies move closer to commercialisation. These projects may be more appealing to investors that have to assess what project provides the greatest opportunity cost to their stakeholders, this applies to both the public and private sector.

The Carnegie CETO project in Western Australia was the world's first grid connected array of WECs, but the WA Government cancelled the contract with Carnegie as they claimed the project was financially unfeasible despite pressure from political opponents and groups within the community. The capricious nature of the market is also demonstrated by Tocardo, which entered bankruptcy in October this year as it could not secure a project grant despite successful testing of the T2 tidal turbine device, emphasising the struggle many developers face [7].

1.3 Mooring systems

1.3.1 Mooring lines

Mooring lines connect a floating structure to its anchor on the seabed. The mooring line will typically comprise of different composites for different sections, with different material combinations such as wire, fibre ropes and steel chains [8] [3] [9]. The mooring system used will be determined from structural and hydrodynamic considerations that will impact the system during operation such as platform size, water depth, currents and wave loading.

1.3.1.1 *Catenary*

A catenary mooring system is a basic configuration of slack mooring. The system consists of steel chains (that may also have steel wire or synthetic rope sections) and hangs freely between the floating structure and anchor, forming a catenary shape. The slack in the system allows for some vertical and horizontal movement of the anchored structure. While the upper section of the mooring line may consist of chain and wires or synthetic ropes, the bottom section of the line lies on the seabed, thus increasing its footprint. This added weight next to the anchor acts as a counter weight. This system is relatively easy to install compared to a taut-leg mooring system.

This system is most commonly used in shallower waters because as the water depth and the vertical distance demand increases, more chain/wires are also required along the horizontal axis to maintain the catenary slack in the mooring line. The combined increase in overall length results in higher costs, so the catenary system becomes less economical [8] [3].

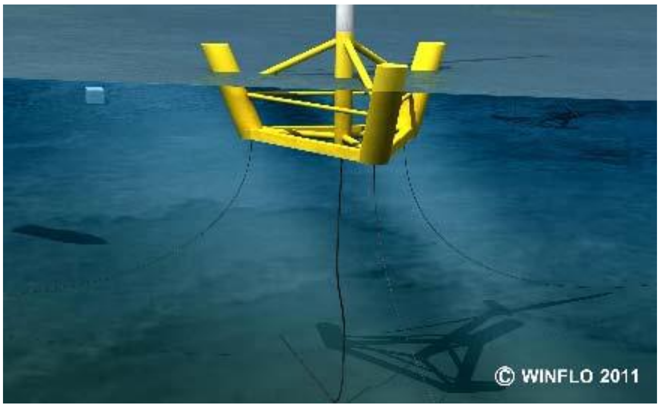


Figure 7: Catenary mooring line

1.3.1.2 *Taut-leg*

Taut-leg mooring systems consist of mooring lines that are pre-tensioned until they are taut. The system relies on the tension created from the buoyancy of the of the foundation or device they are attached to [8] [3], creating a fixed distance between the anchor and the floating foundation. This system uitlises the taut moorings to provide stability to a floating structure which does not usually have this stability built into its design. The advantage of the taut mooring is that the system has a small footprint and is stable, but the mooring line itself is difficult and expensive to install. A taut-leg mooring system does not allow for any vertical movement of the anchored structure. Each mooring line is also critical in maintaining the stability of the structure. The failure of a single line could result in catastrophic instability of the system. Additionally, tensioned mooring lines are subject to greater fatigue loading than catenary systems.

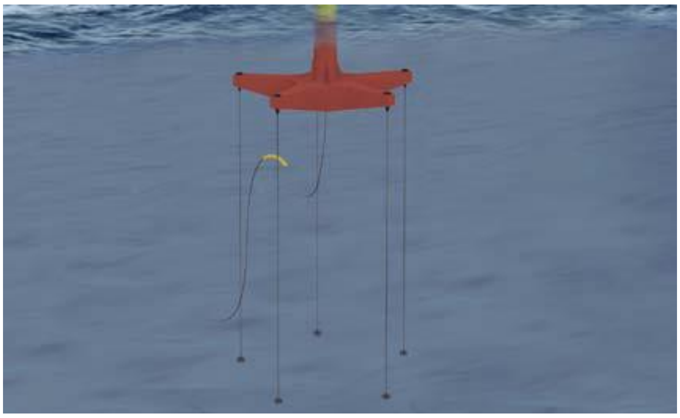


Figure 8: Taut mooring line

1.3.1.3 *Semi-taut*

The semi-taut system is a combination of the taut mooring system and catenary mooring system. This system allows for some vertical and horizontal movement of the structure and reduces fatigue loading, while reducing mooring lengths compared to a catenary system. However, the allowed movement of the floating structure reduces over stability, meaning some of this will require to be compensated within the structures design. The semi-taut and taut systems are more economically suited for deep-water application than catenary system. This is because they both have shorter mooring lines and require less seafloor space than the catenary system [8]. The shorter mooring lines result in material savings, so they are lighter and cheaper to use at increased water depths.

Figure 9: Semi-taut mooring line

1.3.2 Mooring configurations

Mooring lines can also be attached to the floating structure in different configurations. Traditionally, two options for this are available: turret and spread moored.

1.3.2.1 *Spread-moored*

In spread moored systems, mooring lines are connected at several points around the structure, whereas in the turret moored system, all the mooring lines originate at a central turret.

1.3.2.2 *Turret-moored*

Turret moored systems often have the capability of weather-vaning with the wind. For example, some floating wind concepts have been designed without a nacelle yaw motor, relying on this weather-vaning motion to align the turbine with the prevailing wind.

1.3.3 Mooring redundancy

Another concept that has been explored to reduce the costs of mooring lines is connecting multiple catenary lines to a single anchor. For example, every platform of the Hywind Scotland floating wind farm has four mooring lines to an anchor each. .

1.3.4 Anchor mutualisation

Depending on the turbine layout, three or even six different platforms could be significant, especially for large wind farms. [10] has studied the potential cost reductions, reliability considerations and stress analysis of multiline anchors for floating offshore wind turbines. The results of this analysis showed an 8-16% overall cost reduction of a 100-turbine wind farm

1.3.5 Secondary Components

1.3.5.1 *Mooring Line Connection*

Mooring line to platform connections has been identified as a significant area for development as it is a key location for fatigue stress and failure in systems. One potential mooring line connection is based on ball and taper technology [11]. The design of this system makes it applicable to any system that involves gripping, pulling and holding connections under load and the main advantage of this system is the minimal deformation of its gripping surface, see Figure 24. Also, due to the simplistic design, this connector is easier to install and has more versatile applications than conventional connectors without the use of ROVs [11].

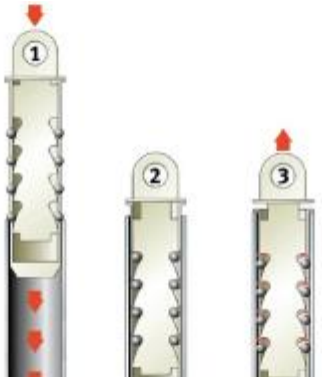


Figure 10: First Subsea Ball and Taper Technology. Source: www.firstsubsea.com

Other companies are investigating means to improve connectors and R&D projects are currently underway to improve the durability of these components. More details on these projects can be found in Section 5 of the report.

1.3.5.1.1 Buoys

Surface or subsurface buoys are used to overcome the weight of the mooring line, thus limiting its influence on the energy device the line is attached to and reduces the effect of vertical load component acting on the system [9] [12]. Similarly, to clump weights, the addition of spring buoys increases the complexity of the mooring system but require minimal maintenance [12].

1.3.5.1.2 Clump weights

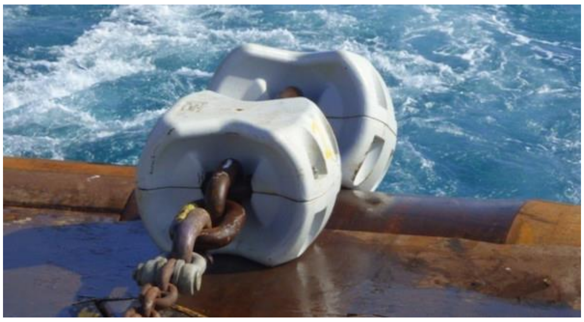


Figure 11: Clump Weight. Source: www.powermag.com

Clump weights are an ancillary mooring component that can be placed on a mooring to increase the stability of the systems by contributing to the restoring force applied by the mooring system on the platform [8] [9] [13]. The addition of clump weights increases the complexity of the mooring system but Ideol identified clump weights a solution to stabilise France's first floating offshore wind farm [13]. Kincardine floating offshore wind farm is another example of where clump weights have been utilised as a stabiliser and other developers are viewing clump weights as a cost-effective solution [13].

1.4 Anchors

Anchors are an essential aspect of the mooring system, securing the system to the seabed for the duration of its use. The choice of anchor is dependent on the mooring configuration and seabed conditions.

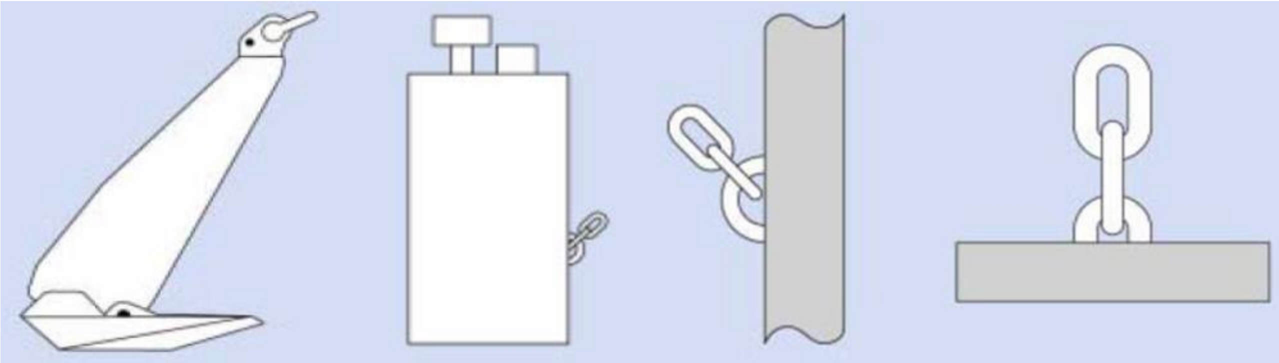


Figure 12: Selection of anchors typically used in offshore energy projects. From the left; Drag-embedded, driven pile, suction and gravity anchor. Source Carbon trust Floating Offshore Wind: Market and Technology Review Prepared for the Scottish Government June 2015

1.4.1 Drag-embedded

Drag-embedded anchors are commonly used and best suited to cohesive sediments, to ensure that the anchor sticks in place though not too stiff to impede penetration [3]. They are horizontal load anchors with the principle holding direction the same as the installation. It is commonly paired with catenary mooring lines and one of benefit of using a drag-embedded anchor is that it is recoverable during decommissioning [3].

1.4.2 Vertical load anchors

This category of anchor includes driven pile/suction anchors, special vertical load anchor and the drilled & grout anchor. Suction piles are the anchor of choice for developments in deepwater. The tubular piles drive into the seabed and a pump sucks out the water and pulling the anchor further into the seafloor [3]. The suction pile is versatile and can be used for different types of seabed such as sand, clay or mud. The only ground type that is unsuitable is gravel [3]. This is similar for the driven pile which is applicable in a wide range of seabed conditions. The CAPEX of vertical load anchors like these is relatively low compared to the installation costs and whilst the anchors are efficient and durable, they are expensive. These anchors are often utilised for mooring systems with TLP's. Most vertical load anchors require drilling and hammering for installation [3]. This causes significant underwater noise and should be considered as a consenting risk especially in areas of high-density marine mammal populations.

1.4.3 Gravity Anchor

Gravity anchors are the simplest system available, generally applied as a horizontal holding anchor which provides a holding capacity through its own weight and abrasion with the seabed [3]. It is for this reason that gravity anchors generally have large dimensions which can be an issue depending on the size of the site. Gravity anchors have relatively low installation costs but is only compatible with medium to hard soil conditions and can be difficult to remove during decommissioning [3].

1.5 Mooring System Selection

Key features need to be considered before choosing what the ideal mooring and anchoring configuration for an offshore renewable energy system might be. Examining the individual components, key design aspects include loading, survivability, fatigue, and corrosion properties of the components. Other key considerations include installation requirements, maintenance, footprint constraints, redundancy and overall complexity of the system.

1.5.1 Design Considerations

When evaluating all available options, one key question to ask is whether to align the design of all components or try maximising each. Drivers for the design, procurement, installation, longevity and ease of replacement are rarely complementary e.g. cheap to buy/expensive to install; simple to install needs replacing early. Often, what I settled on is an optimised compromise. However, to achieve this, we need to have a comprehensive understanding of all the major drivers, many of which are new to offshore renewables.

Figure 13 shows prevalent failure modes of mooring systems. where tension is attributed to only 1% of failures whereas fatigue is responsible for 24%. What is not clear is whether this relationship changes when looking at specific designs such as TLPs, where high tension is inherent in the mooring design.

There is a general lack of data sharing regarding incidents and observations which results in a lack of reliable data. Another issue is that while there is a wealth of experience and observations to draw knowledge from, many of the mechanisms are a function of bespoke system design and unique operating circumstances such as different climates, regions or water depths so it is difficult to apply lessons to different systems. As an a priori observation, Xodus has been in discussion with a leading insurer in the offshore wind industry who is looking to better understand these risks to aid their own position. This would suggest that this information is generally unknown across the sector and not only kept hidden due to commercial sensitivities. Providing detailed research with open source findings and analysis could be hugely helpful to overall research and development.

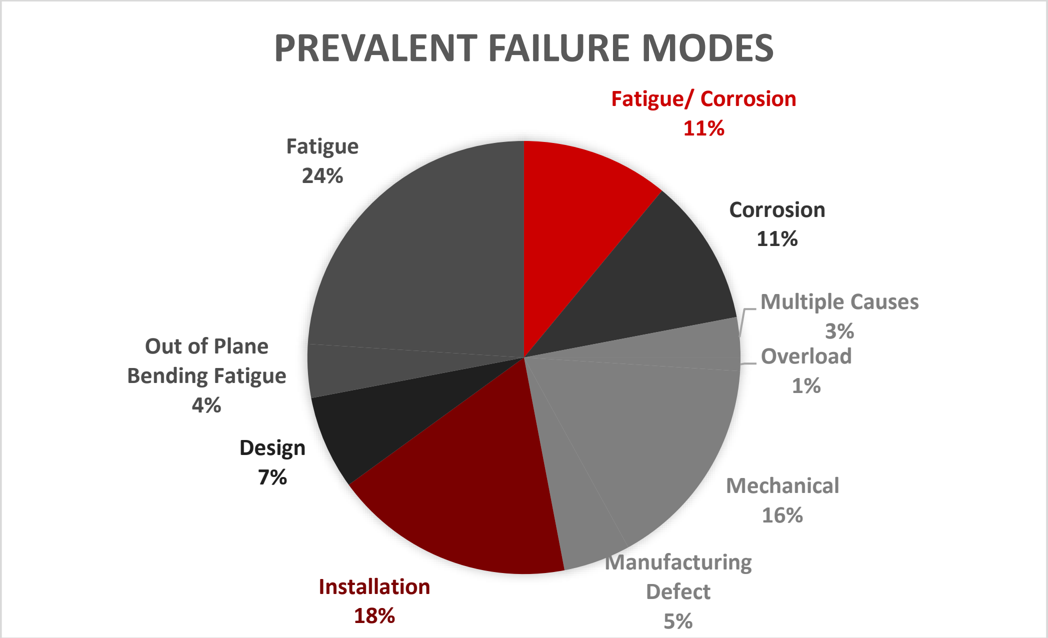


Figure 13: Pie chart of prevalent failure modes in mooring systems. Source: Industry Survey of Past Failures, Pre-emptive Replacements and Reported Degradations for Mooring Systems of Floating Production Units, OTC-25273, E. Fontaine et al.

The next generation of mooring systems is expected to use lower cost nylon ropes, at least in part of it's array. This has not previously been possible for permanent moorings due to the shorter fatigue life of nylon in 'traditional rope constructions'. Increased capabilities in composites manufacture has meant that new designs show real promise in this sector. Nylon moorings will reduce the issue of corrosion and associated surveying and replacement. However, there will also be a reduction on the overall weight of the mooring lines, and this will need to be considered in the overall anchor and mooring design, particularly where mooring weight forms part of the design stability.

2 SUMMARY OF MARKET COST STATUS AND POTENTIAL FOR COST REDUCTION

This section will outline the potential for cost reductions in anchor and mooring systems. Cost reduction in the floating wind sector is necessary if projects are to achieve long-term commercial viability. As the floating wind sector is currently at a pre-commercial stage, this cost reduction will be predominantly deployment driven. Figure 14 below shows three potential deployment rates (low, medium and high) based on current industry projections. All trends show similar steady growth until 2025, after which deployment rates diverge. Due to volume increases, a higher deployment scenario will translate into greater LCOE reduction. As can be seen in the figure, there is large uncertainty in terms of deployment to 2030; the range varies from 6 GW to 20 GW. This is caused by uncertainties in both technology development and market policies related to floating wind. How the range of deployment scenarios will impact floating LCOE is shown in Figure 15.

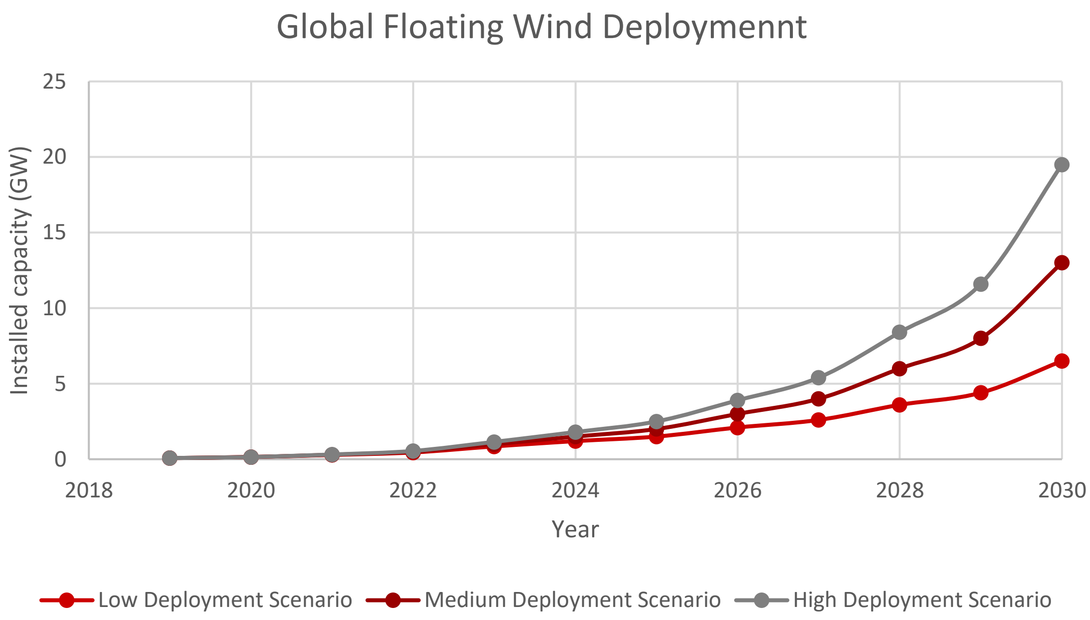


Figure 14: Global Floating Wind Deployment to 2030. Source: Adaptation and rework from 4COffshore

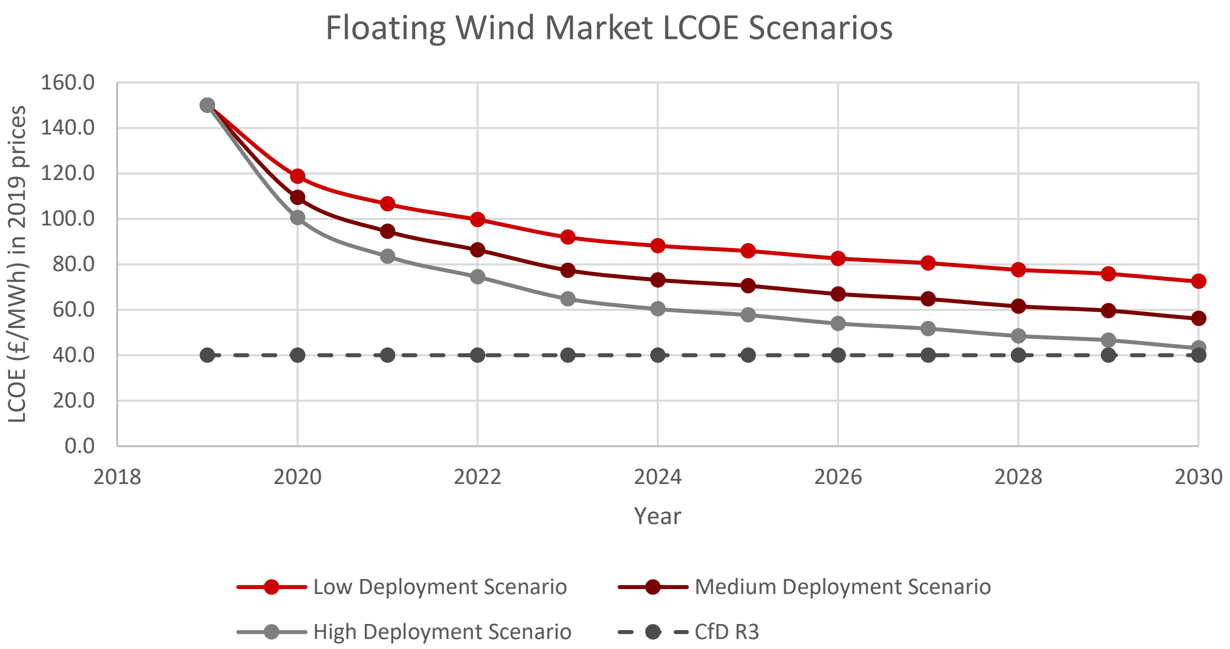


Figure 15: Predicted LCOE for Different Floating Foundation Types. Source: Xodus Modelling

Costs of anchors and mooring systems are expected to come down in the same manner as other floating subsystems; through learning by doing as deployment increases, with production volume increases, and from improvements in supply chain bringing competition. However, some cost reduction will also come via specific technology improvements and design optimisation.

Figure 16 compares the areas of technological development which are likely to bring the largest cost savings. The platform, turbine, and remaining balance of plant will have the most significant effect on cost reduction, with improvements in anchors and moorings considered to be able to reduce cost by 4%. Innovations related to anchor and mooring systems will also contribute to the reduction of some installation costs. Much innovation to date has been focussed on platform cost reduction as a priority ahead of anchor and mooring systems due to it being a significantly higher cost component. A further barrier to innovation is the number of different anchor and mooring solutions available to technology and project developers. With low technology convergence to date and a range of systems implemented there has been little room for consideration of standardisation in the sector.

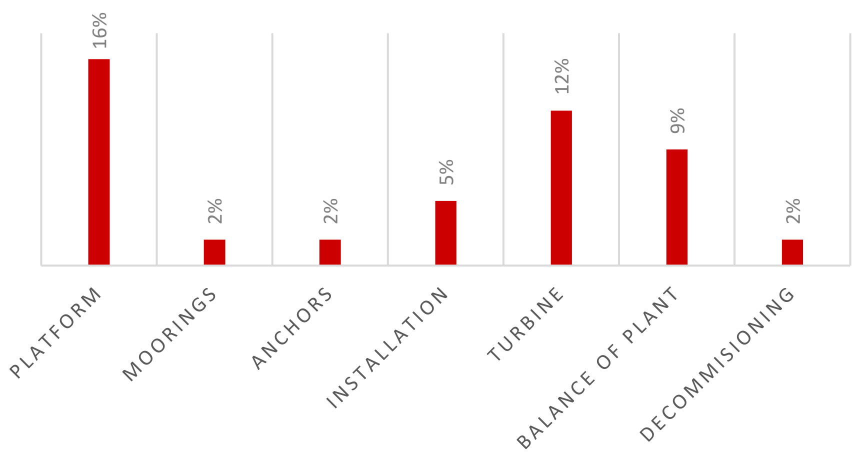


Figure 16: Expected cost reductions based on technology factor. Source: Carbon Trust [3].

3 SUMMARY OF KEY CHALLENGES

Floating wind is currently offering a wide range of potential supporting structures for the wind turbine; however, many are either still at the conceptual stage or very early design and testing or prototype phase. There are few structures which have been deployed successfully and operated long-term. Each of the main concepts can be allocated into a broad design concept, as previously summarised in this report.

Some of the structures proposed clearly have not learnt from the lessons of the offshore industry for marine and oil and gas, with configurations which do not consider the logistical difficulties and/or impracticalities of installation, maintenance or replacement. These risks will be a clear focus of this assessment.

The following section summarises the broad design concept and any identified challenges relating specifically to anchors and moorings. These findings are also summarised in a high-level table at the end of this section which is used to inform the suggestions for further research and study later in the report.

Due to the inherent reliance on a specific form of mooring, Taut-leg Platforms (TLPs) are given a more detailed consideration than some other designs.

3.1 General design concepts from Carbon Trust JIP

Anchor and mooring systems for offshore renewable energy generation have been based on the equivalent systems used for vessels and for offshore oil and gas operations. These systems have somewhat already been optimised as the requirements for moorings of vessels and of oil and gas structures are similar to those for offshore wind. However, cost reductions that further optimise these systems for floating offshore wind can still take place and are likely to come from areas such as additional improvements in design standards, materials, and array layouts.

Phase 1 of the Carbon Trust Floating Wind Joint Industry Project considered the technology challenges in several areas of floating wind, including mooring systems [Reference]. The key findings from the study are summarised in Table 1 below.

Table 1: Key findings from Carbon Trust Joint Industry Project [14]

Category	Finding	Summary
General	Lack of understanding and focus regarding the relevance of mooring systems for floating wind turbines, both technically and economically.	Current mooring system designs used in early floating demonstration projects are based on traditional steel chain designs. These are typically high cost solutions that may be underestimated by technology developers. While learning can be transferred from the oil and gas industry, the coupled behaviour of floating wind turbines and large volume of units means an alternative solution may be required.
	Shallow water is more challenging that deep water for mooring and tendon design.	Floating wind is expected to be technically viable from 40 meters water depth and upwards, particularly beyond the 50-60m limit anticipated for fixed foundations. However, the mechanical properties and dynamic loading on the mooring system mean that at shallow water sites (<100m) fatigue loads can increase, resulting in larger and more expensive mooring systems. For catenary systems increased mooring footprints are also required leading to more expensive systems. Taut and semi-taut systems are less sensitive to water depth but still face challenges at shallower sites.

Fatigue and reliability	Mooring line failures are likely in floating wind, but many failure causes are avoidable with appropriate planning.	Analysis from the oil and gas sector describe that mooring line failures are likely to occur in large scale floating wind farms as observed failure rates are above target levels prescribed by industry standards. This suggest floating wind units will need to factor in acceptable levels of redundancy or utilise advanced reliable designs accounting for floating-wind-specific load characteristics to mitigate the probability of failure. It has been identified that failures in oil and gas are mostly caused by avoidable problems and errors, such as installation damage, manufacturing defects, wear, abrasion, design errors, corrosion, and synthetic material degradation.
	Fatigue of moorings is not well understood for floating wind – there is scope for further research to improve design standards.	Despite considerable track record of deployment from offshore oil and gas, the application of moorings in floating wind is a recent development that introduces new challenges for design and reliability. Namely, the coupled behaviour of floating turbines introduces new fatigue load characteristics that have a material impact on performance and reliability of the mooring system. These load characteristics are not currently sufficiently covered by design standards. In addition, loads in extreme environmental conditions have a significant influence on fatigue life. Improving the accuracy of forecasting extreme conditions and the accuracy of modelling tools to assess their influence could support greater design optimisation.
Materials	Synthetic mooring lines have the potential to reduce costs but need further development for long-term application in floating wind.	Synthetic mooring lines have a long track record in oil and gas and have potential to deliver significant cost savings compared to conventional steel and wire moorings due to lower mass, high fatigue performance, smaller footprint, shorter lines, and lower vessel requirements during installation. However, there are challenges and limitations with synthetic mooring systems to be considered ahead of commercial deployment. There is added complexity and cost of installation due to pre-stretching of some materials and the sensitivity of synthetic lines to damage during handling and load-out.
Installation and logistics	Mooring installation is a significant cost contributor.	Mooring system installation is a technically well-known procedure from oil and gas. However, mooring installation is an important cost contributor, particularly given the large volume of mooring lines and anchors that must be installed, often in challenging offshore environmental conditions. Given the complexity of installation, it is considered that early focus in projects on mooring system design in combination with installation methods will be key for delivering cost reduction.

	Top connectors and anchors have a significant impact on installation	Hook-up is considered the most critical operation during installation. As such, the top connector can have major implications on the installation process, as well as disconnect procedures that may be considered during maintenance and service. Current top connectors from oil and gas are typically large and costly solutions. There is scope to develop simpler, lower cost, but effective connectors that can facilitate rapid connection with minimal impact on the flaoter design and vessel requirements. Anchor designs are fairly well established from parallel sectors, but there is scope for solutions that are optimised for application in floating wind, particularly those that can facilitate rapid installation in challenging conditions. Anchors for challenging seabed conditions is also an area for development.
Operations and maintenance	Monitoring and inspection techniques from parallel sectors are readily available but expensive.	Most standards, adopted from oil and gas, require short inspection intervals for mooring lines. Given the large number of mooring lines to monitor and inspect across a commercial array, there will be a need to develop appropriate risk-based approaches to monitoring and inspection regimes. This is likely to require a relaxation in floating wind specific standards and guidelines. Although suitable technologies for monitoring and inspection exist from oil and gas, these are typically high cost and may not be economical for large-scale floating wind farms. Cost effective technologies and methods therefore need to be developed, including software to streamline the analytics from large quantities of data.
Array layouts	Anchor mutualisation offers potential benefit for cost reduction but is challenging to implement.	Mooring layouts in large arrays are not considered a major challenge for the industry, with sufficient flexibility in layouts able to mitigate risks or mooring clashing, even with overlapping mooring lines. Anchor mutualisation, whereby individual anchors are connected to more than one mooring line, could present opportunities for cost reduction through fewer anchor and installation expenses including fewer geotechnical surveys and inspection requirements. However, the impact of benefits may be marginal in a large floating wind farm and may be challenging to implement in practice.
Seismic loading	Soil liquification is a challenge.	A number of attractive markets for floating wind are situated in seismically active locations that could impact the integrity of mooring and anchor systems. The primary challenge is related to soil liquification that could disrupt anchor holding capacity and result in a loss of station-keeping. Mitigation will include extending anchor penetration in deeper soil layers or the use of larger anchor sizes, adding cost.

Standards	There is a need for bespoke mooring system standards for floating offshore wind.	Current standards applied to floating offshore wind mooring and anchoring designs are largely based on and directly reference existing standards from oil and gas and fixed-foundation offshore wind. Although floating wind-specific standards and guidelines exist, they have not yet been sufficiently developed to fully account for novel floating wind characteristics. Some notable variances include different safety levels and requirements for load calculations. There are also gaps including uncertainties in the definition of redundancy and requirements to submit a mooring integrity management plan.
Learning and information sharing	Lessons learned from demonstrator experience is valuable and should be shared across industry.	Building long-term experience cannot be artificially accelerated. Thus, it is important for the early projects using early commercial scale systems to put an emphasis on monitoring of mooring system behaviour and detailed analysis of lessons learned in order to better understand key challenges.

3.2 Design concept-specific risks and challenges

3.3 Taut-leg Platform

The floating TLP is taken to site as a semi-submersible structure with inherent stability but connected to vertical tethers. Due to the buoyancy being at the waterline the wave action is significantly higher and hence the offsets are larger. This will limit the applicability in terms of site since the ratio of wave height to water depth has a major impact.

3.3.1 Design Principals

The concept of the TLP is relatively simple, whereby having a large amount of buoyancy in the floating structure and pull-down using tendons to give a stable structure in the pitch/roll directions. The structure therefore tends to move from side-to-side only.

The TLP is however a very bespoke design, since for a specific location the wave and current forces may be enough to push the structure to the side such that it dips-down a significant distance due to the gimballing effect.

This may drive the height of the structure higher, increasing the overturning moment and thus increasing the buoyancy required. This can therefore further increase the wave forces.

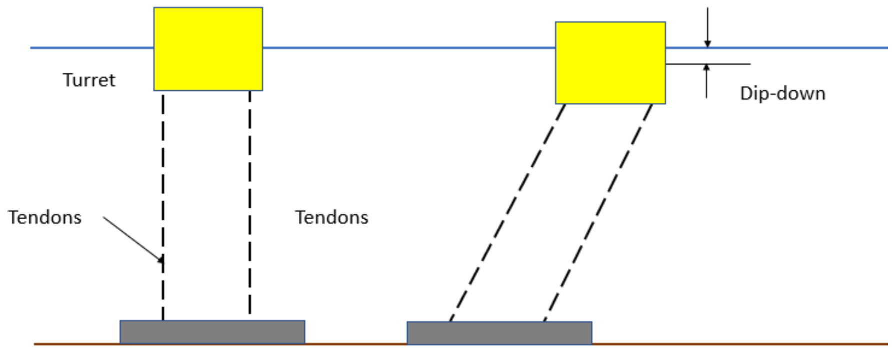


Figure 17 – Principal of TLP

For example, if we assume an extreme wave such as that shown below, the TLP must be increased in both height (to avoid the wave striking the sensitive parts of the access deck) and draught (to avoid an air-gap, which would lead to collapse of the assembly into the water).

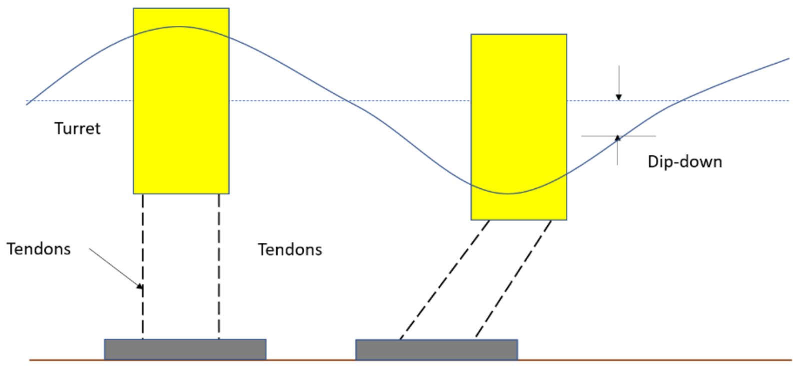


Figure 18 – Effect of Large Waves in Shallow Water on TLP

This clearly increases the size of the structure, but more critically the angle of the tendons increases further due travel along the horizontal plane, which does not account for further movement in three dimensions due to forces from wave, wind and ocean currents.

This situation can be exacerbated further if there is a large tidal range (especially in the southern North Sea and certain areas on the European Atlantic Coast).

One of the unique characteristics of the North Sea, where the majority of short to medium-term opportunities for commercial floating wind exist, is that the water depth generally increases as we move north, but the design wave heights also increase at the same rate. This means that a TLP is highly unlikely to work in the southern North Sea, but if we move to deeper northern waters the wave height still becomes a serious design issue.

The site suitability of a TLP can therefore be broadly indicated by the ratio of water depth to maximum wave height and for the North Sea there are very few areas which are suitable.

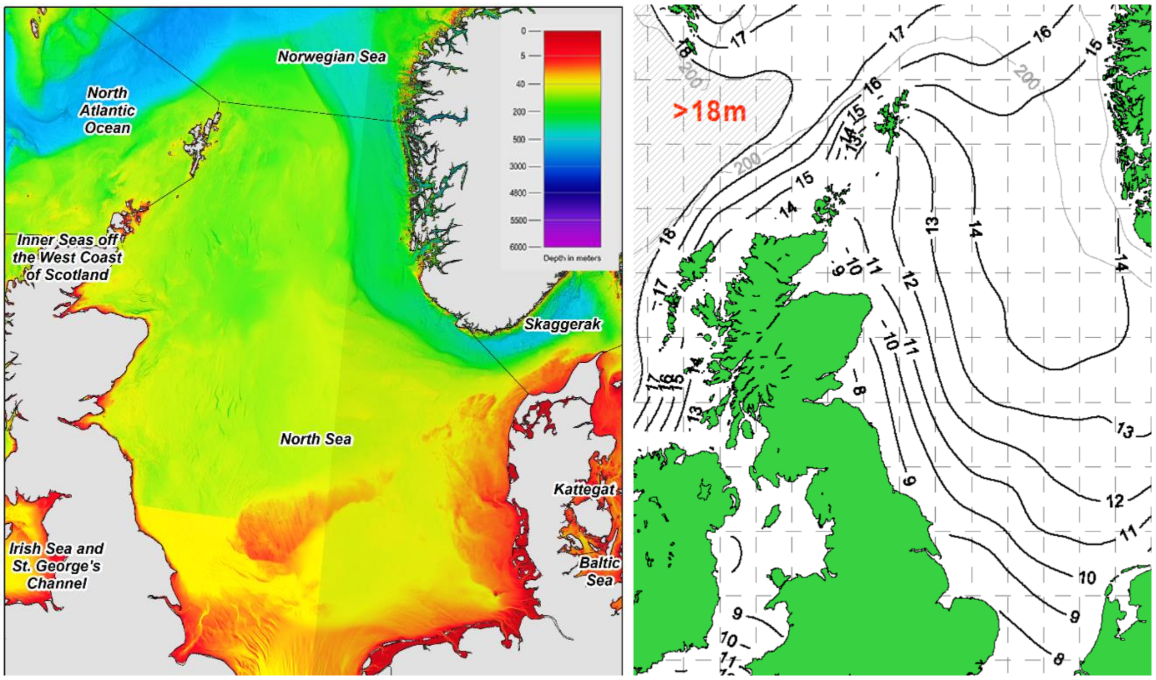


Figure 19 – North Sea Water Depths and 100-yr Significant Wave Heights (UKHSE Report R661)

3.3.2 Surface vs submerged buoyancy

The basic TLP design is that for a surface piercing structure. The design principals and inherent limitation apply to this structure but the tow-out and hook-up of the structure is a safer operation in that without the tether the structure will be stable (this will be a condition of tow-out for insurance purposes).

To minimise some of these effects, the buoyancy can be located completely under the water line; however, the risks with these designs is that they must consider tow-out stability plus how the structure can be pulled down sufficiently to engage the tendons.

Generally, most of these structures are inherently unstable and hence serious questions have to be raised as to how they are transported to the site and safely removed. These are aspects which are rarely elaborated upon in the designs but are fundamental risks and potential show-stoppers.

In addition, during operation the loss of a tether could be catastrophic for the structure, since there is no static stability in the damaged condition and hence the whole structure could tilt into the sea.

Of the designs which are on the market the SBM design offers the most practical and highest potential. The system does not use tendons, but instead uses chain, which can be pulled down in discrete steps. However, due to the difficulty in balancing the tension between multiple chains in each corner, single chains are proposed only. This leads to the risk of a single point of failure and loss of the turbine, due to one corner being released.

3.3.3 Challenges and risks

The key challenges and issues around the TLP design are well understood and can be summarised as follows;

> Tendon technology is not well advanced, especially in terms of the large angles and tension in all directions.

> High wave height to water depth ratios lead to excessive TLP movement resulting in large angle changes on the tendons.

> Redundancy in terms of multiple tendons is required at each corner, but few concepts have this. Without redundancy, the loss of one tendon may lead to loss of the entire system.

> With redundancy the load sharing between very stiff tendons becomes very difficult.

> A significant ballast weight is required on the seabed, which will be difficult to install and require high accuracy in the level to ensure the tendons and turbine are vertical.

> The installation of the TLP is very difficult with additional ballasting or weight required to lower the structure to connect the tendons.

> The connection of the tendons is very sensitive to movement of the TLP due to waves meaning weather downtime for installation may be highly onerous.

3.4 Weather-vaning foundations

There are a number of different types of system proposed which claim to reduce the LCOE by having multiple turbines on the same foundation structure. The majority of these have the yaw control of the nacelle removed and instead rely on the entire structure pointing into the wind direction.

3.4.1 Design principals

Whilst in principal this appears logical and technically an attractive option there are a number of key aspects to consider, such as the large dimensions of the structure and the ability to maintain alignment with the wind, given that the structure heading will be driven by wave and current loading.

The other key aspect of this weather vaning of the structure is that it will require a swivel for both the mechanical and electrical connection. This is address in Section XX as it is an important aspect across all industries

3.4.2 Turret-moored weather-vaning foundations

In any such system the foundation will turn around a central point, but to avoid twisting up of the moorings a turret and swivel will be incorporated. There will be a mechanical swivel and an electrical swivel within, which will be a complex arrangement which needs to consider hull clashing against the mooring line and damage to the area from wave action, together with inspection and maintenance requirements.

The pre-tension in the mooring lines is the only force to turn the turret/swivel and hence the mooring design must consider the breakout torque of the swivel/turret arrangement.

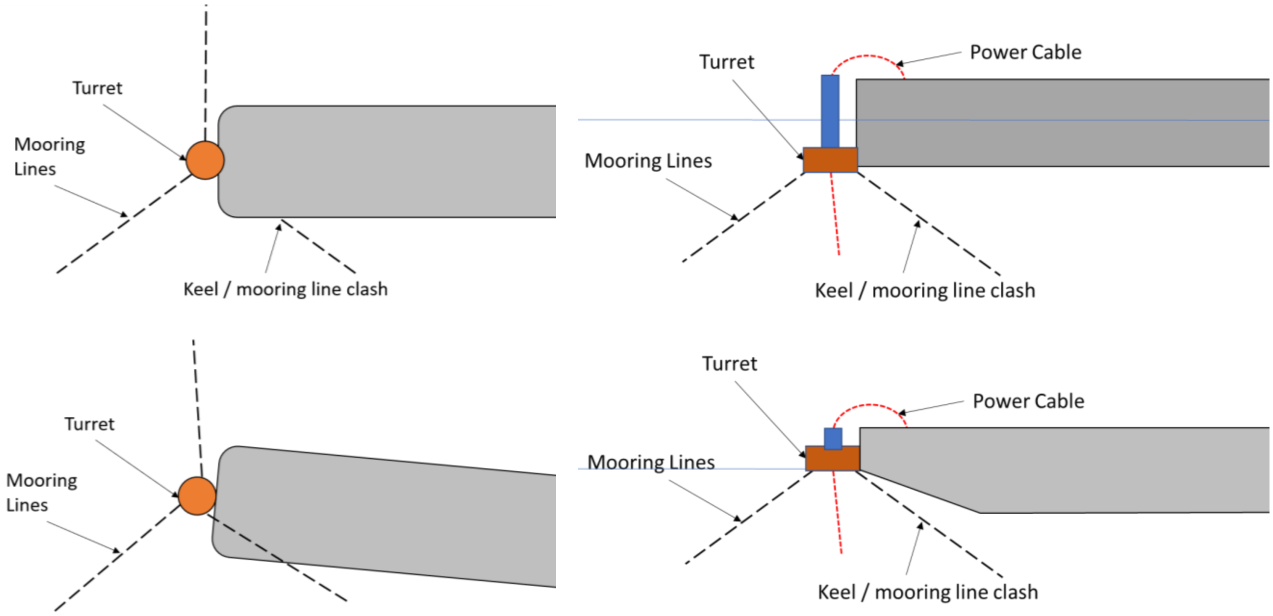


Figure 20 – Plan view and elevation of weather-vaning system..

The biggest challenge is ensuring the weather-vaning of the structure into the wind, as the influence of waves and current is highly significant.

- If the structure is perfectly aligned with the wind direction, the chance of it also being correctly aligned with wave conditions is very low and hence rolling of the structure is a high risk.
- If the wave, wind, and current approach the foundation from different prevailing directions, the turbine could be significantly misaligned with the wind direction (possibly up to 45-60 degrees).

The depth of the turret is a key aspect also, since;

- If the turret is under the keel level the mooring lines are clear, but the turret bearings are underwater, plus the power cable will have to be routed above the water level.
- If the turret is above the waterline the mooring lines clash with the hull, but inspection and maintenance of the system is easier.

In summary the turret mooring of the system has its opportunities, but the heading control of the structure into the wind plus the effect of structure rolling are the biggest issues. These are major technical aspects which if not resolved could lead to reduced yield and serious structural integrity issues.

3.5 Barge

The principal barge design is the IDEOL structure, which has a large open section consisting of a 'damping pool'. This concept has been previously used in the offshore oil and gas industry to dampen out heave motions.

3.5.1 Design principals

The design of the system is relatively simple with arguable a semi-submersible design in principal. It has been categorised as a barge, due to the flat sides and continuous water-plane area.

The righting moment with turbine thrust follows the same principals as the semi-submersible; however, the main difference is the ‘skirt’ at the bottom of the structure which creates drag in the vertical direction. This reduces the heave and pitching from wave action.

> Large wide structure will lead to high mooring loads, especially in high current areas and if the draught is increased to accommodate the larger waves.

3.6 Top-braced floating foundations

There is currently only one vendor of top braced structure, which will rely on a heavy structural connection at the base of the tower to withstand the extreme and fatigue forces.

The Gusto MSC system does not have its mooring connection at the bottom since this would exert high bending moments on the column, instead it is further up the structure.

> This will lead to a navigation hazard for CTV plus lead to accelerated corrosion due to being through the splash zone.

4 KEY ACTIVITES – CURRENT RESEARCH & DEVELOPMENT PROJECTS

Offshore renewable energy technologies are at different stages of development and not ready for commercial deployment, particularly tidal and wave energy. Significant investment and research & development is required to find innovative solutions to issues these industries face to enable them to move towards commercialisation. Horizon 2020 (H2020) is a framework for Research and Innovation in Europe that will fund projects over a seven-year period between 2014 and 2020. The initiative is a financial instrument aimed at securing Europe's global competitiveness through research and innovation to create a sustainable future. The programme awards grants to innovative SME's and help developers access research infrastructure, targeting the development of marine renewable energy. R&D work is also funded through other public trading bodies, developers and consultancies; below are examples of current R&D initiatives that focus on moorings and anchors:

4.1 Floating Wind Joint Industry Project (JIP) – The Carbon Trust

The Floating Wind Joint Industry Project ("Floating Wind JIP") is a collaborative R&D initiative between The Carbon Trust and 14 leading international offshore wind developers: EnBW, ENGIE, Eolfi, E.ON, Equinor, Innogy, Kyuden Mirai Energy, Ørsted, ScottishPower Renewables, Shell, SSE, TEPCO, Vattenfall, and Wpd. Supported by the Scottish Government, the JIP aims to investigate the challenges and opportunities of developing commercial-scale floating wind farms. Since its formation in 2016, the JIP has been delivered through two stages, each consisting of studies to outline the critical needs for the sector to reach cost parity with other energy technologies. Phase 1 of this project consider three specific areas, including anchors and moorings. An in-depth summary of these findings is considered in XX. Phase 1 of this project is fully closed, and Phase 2 does not include a specific ongoing workstream for anchors and moorings.

4.2 OPERA

OPERA (Open Sea Operating Experience to Reduce Wave Energy Cost) was a H2020 funded project which focussed on the collection, analysis and sharing of open-sea operating data of a floating WEC over a two-year period. The project concluded at the end of July earlier this year and aimed to advance the system from technology readiness level (TRL) 3 to TRL though de-risk several industrial innovations for wave energy that bring its cost down. Focussing on de-risking WEC systems, one key objective of the project was to lower mooring costs by over 50% which will be achieved through shared mooring systems and an elastomeric tether. Compared to traditional mooring ropes, elastomeric tethers have load-extension characteristics that significantly reduce peak and fatigue loads experienced by the mooring system and at hull connections, so this will drastically reduce their cost and risk. The outcomes of OPERA have not been released yet so the outcome of the of the projects objectives is unclear. The project cost around £5 million to fund and the research was undertaken by a consortium, coordinated by Tecnalia, a leading technology institute in wave energy development, based in Basque Country.

4.3 CorPower Ocean and Sustainable Marine Energy - UMACK

CorPower and Sustainable Marine Energy (SME) have joined forces on a project funded by Scottish Enterprise and the Swedish Energy Agency to address foundations and mooring issues. The project, called UMACK (Universal Mooring, Anchor & Connectivity Kit Demonstration), was awarded a little under £2 million through H2020 to develop and demonstrate foundation mooring solutions to reduce capital and installation costs as well as improve O&M. The project which began in late 2018 will last 3 years and the aim is reduce costs by up to 50% and the project will also involve mooring experts Tension Technology International (TTI), MRE modelling experts from the University of Edinburgh and testing will take place at EMEC's state of the art facilities.

UMACK is a joint industry venture as CorPower which as stated above is a WEC developer but SME which is a turnkey supplier of integrated tidal energy generation systems, so this project has the potential to progress both technologies onto the next stage towards commercial deployment.

UMACK will develop and demonstrate a remotely operated, technology agnostic, quick connect, technical anchor and smart mooring system for multiple seabed types and coupled with a streamlined marine operations strategy focused on simplifying vessel requirements, reducing cycle time for connection and retrieval of devices while increasing operational windows. This will hopefully lead to a lower LCOE if the project successfully demonstrates how improved strategies and reduced downtime will increase the commercial potential of mooring systems.

4.4 Sustainable Marine Energy and Green Marine – Rock Anchoring Solutions

SME have also been awarded a £90,000 innovation grant in partnership with Green Marine to develop the next generation of rock anchoring solutions. The grant was awarded by Scottish Enterprise, through the European Structural and Investment Funds with the aim to enable SME to continue to develop the next generation of rock anchoring solutions. This builds on the work SME have been doing the past six years, developing, testing and deploying direct embedment anchors that can be utilised in conditions traditional anchoring systems struggle. Green Marine have key capabilities in installing and operating mooring and anchoring systems for subsea drilling rigs. With these capabilities, Green Marine will help SME produce complete solutions as SME continue to expand their range of anchors and ensure that a wider range of geotechnical conditions can be accommodated to help drive down mooring costs across the offshore renewables market.

4.5 Vicinay Marine Group– Mooring Steel Upgrades

Vicinay Marine Group have been working with Gerdau Sidenor and the University of the Basque Country to develop new composite materials for mooring lines. The aim of this research is to develop new steel grades that possess higher strain qualities that will bring important advantages to the industry through a reduction in mooring line weight, better corrosive and wear resistance, as well as an improved fatigue life. A reduction in mooring line weight will subsequently reduce production tonnage as well as the manufacturing footprint. Vicinay targets to develop different degradation systems for different sites as well as environments, learning more about how Thermal Sprayed Aluminium coatings will behave under these conditions.

4.6 Tension Technology International – Reliable Connectors for Reliable Moorings

A feasibility study which focussed on producing state-of-the-art multi-material hybrid end and in-line rope connectors with components that will incorporate a higher strength, lightweight corrosion resistant metal core with a high wear resistant nylon surface, was granted funding of £134k in 2018 by Innovate UK. The research was undertaken by TTI, Nylacast Ltd, EMEC and Brunel University and the project was titles Reliable Connectors for Reliable Moorings (RCRM). Multi-material solutions had not used in these components and so the research investigated how the durability, reliability and productivity of the energy device would improve as well as reducing maintenance costs.

4.7 Tension Technology International – STORM

The STORM project (Specialised Thimbles for Offshore Renewable Marine Energy) was a continuation of RCRM moving beyond the feasibility study to the design of multi-material solutions to current performance limitations of connectors. STORM also comprised of the same partners of RCRM. While a lot of research of mooring ropes has focussed on the reduction of weight, whilst improving their strength, there has been less focus on in-line rope connectors. One consequence of this is that weaknesses occur more often in the rope in-line and end connectors with crucial areas causing chaffing of the rope, resulting in premature failure of the system. The project produced a novel solution to this issue – which offers reduced weight of the component, and the life-span of the connector has increased by 30% due to the ant-corrosion, anti-fouling, and UV resistant properties of both the core and outer shell.

4.8 Tension Technology International – Internal R&D

TTI have recently completed a mooring and foundation landscaping for Wave Energy Scotland, looking at enabling technology and initiatives to bring down the LCOE of offshore energy. They have also been conducting extensive research in mooring R&D with the aim to improve reliability whilst lowering costs. TTI have been examining new mooring system technologies that can be utilised for offshore renewable energy devices which will benefit those that are involved in projects located within shallower waters and extreme environments.

These developments include mooring line made from a special nylon fibre rope that provides superior cyclic tension fatigue endurance to that of conventional nylon ropes. Improved endurance is achieved through coating the nylon rope with a new proprietary coating which has excellent wet yarn abrasion properties. The new design underwent extensive cyclic tension tests replicating typical and extreme conditions that a mooring component will experience offshore. These tests demonstrate that the special nylon rope has essentially the same, desirable stretch characteristics as conventional nylon rope and has much better endurance performance. The unit length cost of nylon is approximately half that of chain with the same break strength. In shallow water moorings, larger chain would normally be used to provide the necessary catenary mooring offset characteristics and so using special nylon mooring lines can achieve significant cost benefits to projects.

TTI have also developed a unique bag anchor system with three partners which is an adaptation of the conventional gravity anchor. The device underwent small-scale testing between 2010 and 2015 before a full-scale model was developed. Continued research is on hold until further funding can be established. It has been specifically designed so that it can be deployed in sand, clay, rock, mud and other sea beds which would be unsuitable for conventional drag embedment and driven piles anchors. Benefits of this design are lowered costs; a bag anchor costs varies depending on the materials used but they are typically in the region of £200 per wet kip (100lb weight in water) with an additional £450 per wet kip for a steel chain. This compares to steel gravity anchors which cost in the region of £800 per wet kip and bag anchors can be transported to sites empty, lowering shipping costs.

Development of the bag anchor system, along with the nylon rope development was funded by the UK Carbon Trust under the Carbon Trust Marine Energy Accelerator Grant and the Scottish Government Marine Renewables Commercialisation Fund.

4.9 Potential funding sources for related R&D

Appendix C provides a full list of potential funding sources for R&D initiatives, as well as links to source pages and application windows.

5 CONSULTATION – ADMA ENERGY PARTNERS

5.1 ADMA Energy

The ADMA Energy pilot was launched in June 2014 as part of the Vanguard Initiative (VI) with the aim of making Europe the leading hub for the development of robust high integrity components for marine renewables and offshore energy. One objective of the pilot is to help strengthen the supply chain, working with medium and large companies through connections with SMEs developing innovative concepts and helping them to grow their business. The initiative comprises of regions from around Europe and is led by Basque Country and Scotland, along with 8 other participating regions: Asturias (Spain), Dalarna (Sweden), Emilia-Romagna (Italy), Flanders (Belgium), Lombardy (Italy), Navarra (Spain), Norte (Portugal), and Skåne (Sweden).

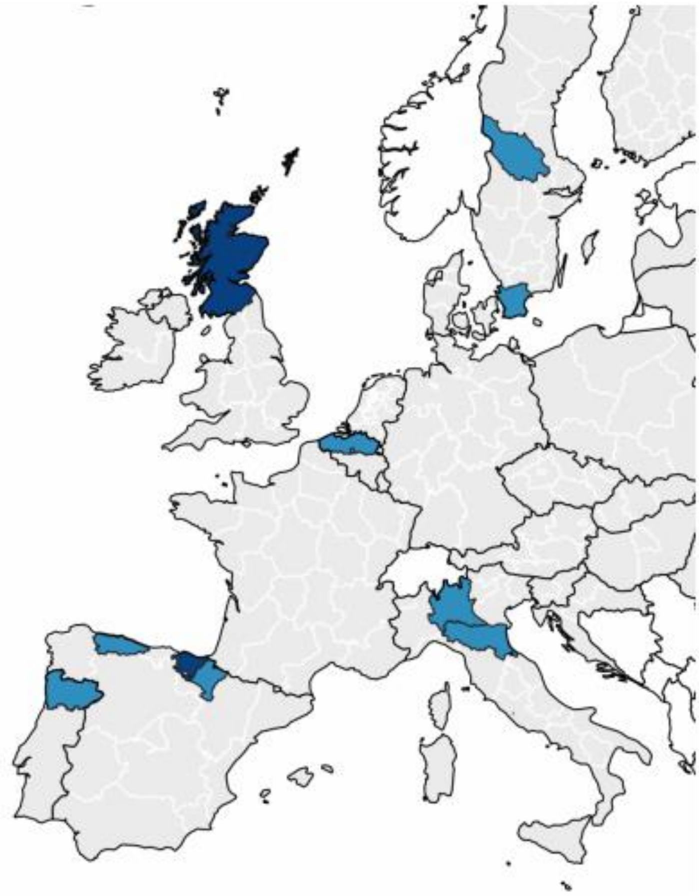
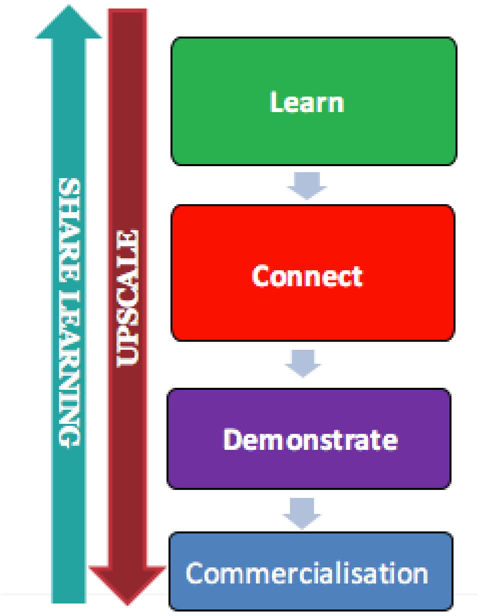


Figure 21: Map of the ADMA Energy Partners. Leading Regions: Dark Blue region, Participating regions: Lighter Blue. Source: www.s3vanguardinitiative.eu

The main aim of the pilot is to facilitate the growth of the marine renewables and offshore energy sectors and creating new business opportunities for those involved. To achieve this ambitious goal, the ADMA Energy pilot has gone through the first steps (“Learn” and “Connect”) of the VI framework, which is structured around four core functions:



> **Learn:** This function includes activities such as data sharing, value chain mapping, exchange of good practices, workshops and study visits, and the development of guidebooks and manuals for business intelligence.

> **Connect:** This refers to activities such as industry brokerage, matchmaking events (including virtually), the development of demonstrator ideas, and broadly using the pilot as a collaboration space.

> **Demonstrate:** Under this function, the pilot would serve as a virtual incubator, providing start-up space for demonstrators, serve as a structure for leveraging public and private funds, provide ideas and mobilise inter-regional infrastructure pooling, and deliver projects related to identified common challenges and technology needs.

> **Commercialise:** This relates to the use of the learn, connect, and demonstrate functions and services to promote demonstrators, agenda setting and policy outreach at EU, national and regional levels.

Figure 22: A Technology Roadmap of the Vanguard Initiative's pilot "Advanced Manufacturing for energy related applications in harsh environments".

The initiative is now moving on to the Demonstrate stage. Through the ADMA Energy pilot, research and development (R&D) projects will become more cost effective due to the collaborative effort of partners pursuing a singular aim. This framework will lead to funding for R&D initiatives and support the deployment of offshore renewable energy technologies.

5.2 Engagement

The ADMA Energy partners were approached to better understand their relevant priority R&D areas, funding streams, knowledge of early stage technology, and work to date with regard to mooring and anchoring systems.

All partners were contacted for their input to the study. Responses were obtained from five of the regional partners:

- ASTER (Emilia-Romagna),
- Cluster de Energia (Basque Country),
- Fundación Asturiana de la Energía (FAEN), (Asturias),
- Scottish Enterprise (Scotland), and
- Svenskt Marintekniskt Forum (Skåne)

The predominant sectors of interest in offshore energy to the ADMA Energy partners are the oil and gas, floating offshore wind and wave energy sectors, with little interest shown in tidal energy. There was some interest in the traditional maritime industry in which anchor and mooring systems would be applicable, although it was not considered a particular focus area.

5.2.1 Summary of responses

5.2.1.1 ASTER

Most of the industrial expertise of moorings and anchors in the region comes from Floating Production Storage and Offloading units (FPSO) in the oil and gas sector. ASTER stated that they were not directly involved in any mooring and anchoring R&D initiatives but said that that there are specialist companies in the region, particularly in the city of Ravenna, who design, manufacture and export mooring tensioning systems along with other key offshore energy structures (including platforms, pipelines and valves, and subsea control systems).

Relevant supply chain in the region are all members of ROCA, the Ravenna Association of Petroleum Off-Shore Operators. While the region is currently focused on the oil and gas sector one associate of ROCA, F.lli Righini, which specialise in mooring tension systems are interested in evaluating opportunities and international collaboration for R&D projects on floating offshore wind. F.lli Righini have previously worked with Saipem who have experience in offshore wind EPCI contracting, including for Hywind Scotland.

5.2.1.2 Cluster de Energia

The Basque Energy Cluster reported they are not currently, nor have they been, involved in R&D initiatives relating to moorings and anchors. However, the Basque Country is a world leader in wave energy development, with testing infrastructure in place at the Biscay Marine Energy Platform and collaborations with Tecnalia as part of the H2020 Open Sea Operating Experience to Reduce Wave Energy Cost (OPERA) project. Currently their focus is on different aspects of wave energy development including composites and corrosive testing.

There are no current projects or funding opportunities associated with moorings and anchors in the region identified by the Basque Energy Cluster. Tecnalia, acting as a research and innovation centre oriented around the development of new technology-based businesses, has an alliance with the University of Basque Country and have agreed a framework for a Joint Research Unit to enable R&D and innovation value chains to be created.

5.2.1.3 FAEN

The Asturian Energy Foundation (FAEN) stated the region is most interested in floating offshore wind and wave energy but they are currently not involved in any initiatives to develop mooring and anchoring technology. No companies involved with mooring and anchoring systems were identified. FAEN have test centres that carry out extensive research on materials along with the fabrication and manufacturing of foundations but there is no current intention to become involved in moorings and anchors.

5.2.1.4 Scottish Enterprise

Scottish Enterprise are currently involved in two moorings and anchors R&D projects, providing funding for the UMACK and rock anchoring projects. Scottish Enterprise offer standard innovation funding and company support for those that wish to become involved in innovation initiatives and collaborate with institutes involved in the cutting-edge development of offshore renewable energy technologies, including ORE Catapult, Subsea UK, Oil & Gas UK and the Energy Skills Partnership.

While Scotland has several existing suppliers which can service the floating wind industry, largely through leveraging existing capabilities and activities in the oil and gas, marine, and offshore renewables industries, they are not currently involved in any commercial or demonstration projects associated with moorings or anchors.

5.2.1.5 *Svenskt Marintekniskt Forum*

The Swedish Maritime Technology Forum (SMTF) stated that their region has no current interest in moorings or anchors, but this may change in the future. At present, their main interest lies in traditional maritime industries such as shipping, and this reflects in their capabilities. Sweden has extensive O&M expertise for marine technology but limited knowledge in construction with only one major shipyard remaining. SMTF are not currently involved in any commercial or demonstration projects, however have previous experience supporting wav energy technology developer Minesto.

The Swedish Energy Agency (SEA) is a significant partner of SWTF and supports business development to allow commercialisation of energy related innovations. The SEA is involved in the UMACK project with Scottish Enterprise. SWTF has good links with a subsea test centre near Gothenburg which is currently carrying out work in anti-fouling paints. The work is not intended for mooring and anchoring systems but the SWTF indicated some knowledge will be transferable.

5.2.2 Anchoring and mooring R&D projects

According to responses from the ADMA Energy partners and supporting desktop research, none of the regions are currently invested in mooring and anchoring R&D projects. However, it should be noted that several ADMA Energy partners were unable to contribute to the study and may hold additional insight not captured. Reported R&D research in the regions currently focuses on fabrication of materials and composites, and corrosive testing of components.

Several of the ADMA Energy partners were involved in the North Sea Solutions for Innovation in Corrosion for Energy (NeSSIE) project which was active between June 2018 and April 2019. The project, which was co-financed by the European Maritime Fisheries Fund (EMFF), aimed to develop commercial solutions for corrosion and materials challenges in offshore renewables through demonstration projects in the North Sea. Some of this experience may be applicable to mooring and anchor systems, although this was not raised by engaged members. The partners involved were Scottish Enterprise, Basque Energy Cluster, ASTER, Sirris, SMTF, FAEN, Lombardy Energy Cleantech Cluster and the University of Edinburgh.

Due to the limited number of responses from ADMA partners, it is difficult to identify specific key collaborators for ADMA Energy organisations that are involved in the development of mooring and anchoring technologies. However, each organisation will have a wide network of associates involved in R&D and innovation projects, collaborating with supply chain companies in the offshore energy sector across Europe. There are ambitions in the regions to grow expertise within the offshore energy, particularly for floating wind and wave energy, and develop manufacturing expertise and supply chain to meet market demand. With a large network of academia and supply chain to draw upon it is possible that collaborators for future research initiatives will be found within the regions.

6 RECOMMENDATIONS AND CONCLUSIONS

There is a wealth of information on the integrity of mooring systems available from the oil and gas sector with operations in different climates, regions and water depths, but the information is not publicly available due to the commercially sensitive nature of material. Furthermore, transferring applicable data over to offshore renewables may be difficult as FPSO systems typically use bespoke mooring designs. FOW offers an opportunity to improve on the current knowledge through reliability statistics from the deployment of multiple mooring systems for an array of FOWTs but this must be shared so that the knowledge gained can be used to accelerate the reduction of LCOE of offshore renewables.

Also, due to the relatively low CAPEX and OPEX contribution of anchors and moorings within the oil and gas sector they are not a priority when it comes to R&D. These relative costs are much higher in offshore renewables and the revenue generated from these technologies is also significantly lower than oil wells. Therefore, there is an increasing need for the cost of these systems to reduce; which will only come through innovation, improving their performance and establishing a supply chain that facilitates the serialised production and distribution of mooring and anchoring systems.

From the key findings and innovation needs highlighted by the Crown Estate, as reviewed in section 3.1, there is a role for industry enablers to coordinate initiatives involving technology developers, suppliers, academia, standards bodies and industry working groups in a range of areas. These areas include, but are not limited to:

- **Understanding of fatigue mechanisms.** There is a need to develop an improved understanding of fatigue mechanisms for mooring systems to improve design optimisation, reliability, and cost.
- **Qualification of synthetic mooring lines.** There is a need to develop and qualify synthetic mooring line materials for long-term application in floating wind. Research and development initiatives should asses the suitability of a variety of mooring line materials in taut and semi-taut configurations for various materials in shallow, intermediate and deep-water applications.
- **Low cost installation methods.** There is a need to develop low cost installation methods for large-scale floating wind farms, which are expected to consist of hundreds of mooring lines and anchors. A key enabler will be the development of simple, low cost, but effective top connectors, as well as anchors with improved performance in stability.
- **Monitoring and inspection procedures and technology.** There is a need to develop cost effective monitoring and inspection procedures and technologies that can enable wind farm operators to manage asset integrity at low cost, without compromising risk exposure. This will include: standard development to adopt less conservative risk-based approaches; technology development to support improved performance, reliability, and cost reduction (including sensor technologies, artificial intelligence and autonomous underwater vehicles); and advanced post-processing, data management, and analytics tools.
- **Development of shallow and intermediate water depth mooring systems.** There is a need to develop mooring systems to enable economically viable sites in 60-100m water depth ranges. This will be particularly relevant in North Sea nearshore locations such as those likely to be developed as part of the ScotWind leasing round.
- **Cross-industry data and information sharing.** There is a need to promote experience and lessons learned from early projects using early commercial scale systems to put an emphasis on monitoring of mooring system behaviour in order to better understand and address key challenges
- The Carbon Trust has the second phase of the floating wind joint industry project underway that will investigate monitoring and inspection requirements in floating offshore wind, including recommendations for standard development and technology innovation needs. It is likely that some aspects of this study will relate to optimisations in anchoring and mooring, particularly relating to quick-release concepts that allow for easier O&M access.

Due to the broad array of technology concepts currently in the market, and the likelihood that demonstration testing and commercialisation will reduce the number of concepts being used by the industry going forward, it is possible that any research and development into specific solutions will eventually be nullified if that concept is not picked up for mass deployment. Therefore, an early focus on R&D concepts which answer questions common to all or most of the design concepts is likely to leverage the most advantage going forward. As a starting point, we would suggest that this initial focus is on mooring redundancy and anchor mutualisation.

6.1 Research into mooring redundancy and anchor mutualisation

The primary purpose of this recommendation is to provide open-source knowledge and learning that can inform multiple additional research strands as it continues. In its initial stages, this R&D initiative should look to gather all knowledge from interested ADMA partners and the oil and gas industry relating to mooring failures and root cause analysis, as well as findings relating to anchor mutualisation. Once this dataset is established, it can be interrogated and refined to point at specific findings where information most closely relates to floating offshore wind. This dataset could be open-source, but with the caveat that developers and contractors using the data also commit to sharing desensitised findings on their own designs as a contribution in kind.

This exercise would then create the beginnings of a benchmarking dataset which can be used for multiple future research strands. Indeed, each of the research strands highlighted in the previous section could at least benefit from, if not be initiated as a result of, such a dataset.

Following this, ADMA partners could look to further refine the specific understanding of failure rates and anchor mutualisation through research and demonstration. The findings from this further study could better inform financial models, insurance provisions (and associated access to investment capital), and, importantly, provide robust data to inform the volume of the supply chain opportunity. Robust data on best practice in mooring redundancy and anchor deployment will allow suppliers to align with expected industry demand and define what serial production is on a commercial scale development. Current variations in approach could see the opportunity for anchor supply range between 200 and 400 on a 100-turbine project, and mooring lines of between 300 and 900 on the same project.

Further understanding on mooring redundancy will also be pivotal in decreasing risk for the industry, particularly for technology concepts which rely on moorings for overall stability. Approach to risk cannot be over-stated as low-cost capital has been a primary driving force in the reduction of costs for bottom fixed offshore wind. Low-cost capital is only attracted to low risk investments, therefore this item will be key to reduce operational risks for projects.

6.2 Added Value to Competitive Cost

The main drivers for design, procurement, installation, longevity and ease of replacement are rarely complimentary, for example using cheaper materials to reduce CAPEX, but these materials have a shorter lifespan and therefore increase OPEX costs. There is currently no benchmark for cost-saving for individual systems – the only widely recognised method to bring down costs is shared mooring lines for single anchors. Therefore, without a standardised method, each project must be judged on its circumstances, and stakeholders must aim for an optimised compromise. However, to achieve this we must understand all the major drivers, many of which are new to FOWT's. While tidal and wave energy devices have both experienced meaningful cost reductions in recent years, they are years behind the deployment of FOW and cannot compete with this sector for price-support in the short to medium term. This will likely carry over to R&D projects as stakeholders will produce a return on their investment much sooner and FOW can also draw from offshore knowledge through experience with bottom-fixed turbines. The uncertainty of future revenue increases the risk and thus the cost of financing wave and tidal projects despite the progress that has been made. Tocardo and Carnegie Clean Energy are two examples of this, both of which failed to secure funding despite successful testing and demonstrations.

This is why innovation and R&D projects are so important, the lessons learned from these initiatives will allow stakeholders to better understand cost implications of improving the current mooring and anchoring technology, build confidence in the renewable technologies and hence encourage investment in these areas. There is a lot of R&D potential of FOW from an insurance perspective. The cost of a fundamental flaw in a mooring design is much more significant for an array of FOWTs if this flaw impacts every mooring line opposed to an oil and gas system which is typically bespoke. Funding R&D projects in this instance is a more justifiable position. More knowledge and understanding will also make it easier for trade bodies and government initiatives such as ADMA Energy Pilot to develop the much-needed supply chain for offshore renewables.

6.3 ADMA Energy Pilot

From the consultations it is clear anchors and moorings are not a priority area for development. Most of the ADMA partners that participated in the consultations have an interest in offshore energy technologies and their capabilities align with these interests, but Scotland is the only partner to have engaged with moorings and anchors projects. Scottish Enterprise have been involved with two projects, UMACK which brought together wave and tidal developers to develop and demonstrate foundation mooring solutions to bring down costs and improve O&M methods. They also funded another collaborative effort from SME (which are involved in UMACK) and Green Marine to develop rock anchoring solutions which SME have working on for the past six years. However, from the questionnaire presented to Scottish Enterprise it seems they are unaware of their involvement in R&D initiatives relevant to mooring systems as they stated were not involved in any mooring and anchoring R&D projects whilst the UMACK and Rock Anchoring Solutions projects are ongoing.

There is engagement from ADMA partners on different R&D topics for offshore renewables such as materials. These partners are involved in composites, new materials and materials testing as well as fabrication of components, but there is no direct involvement in any mooring and anchoring projects. However, it seems likely some of the learnings from the research of these topics will be transferrable to moorings and anchors. This is also true for partners and regions which mostly operate within the oil and gas sector. Corrosion is another key focus; in an industrial survey from 2015 conducted within the ADMA Energy Pilot, 80% of respondents considered corrosion in water and corrosion protection as a technological challenge that needed to be addressed. Vicinay Marine Group have stated that 39% of mooring failures are related to corrosion. ARTER and Emilia Romagna are heavily involved in the development of components for FPSOs, have extensive capabilities and a supply already in place for worldwide distribution. One company has already expressed an interest in offshore renewables and the commitment of major oil and gas contractors and developers such as Saipem commit significant resources to FOW will accelerate the transition in Italy. It is therefore important that any findings from the adjacent Nessie study be made available for consideration as part of research studies also looking at FOW.

Development of FOW is the driving force in innovation for anchors and moorings in offshore renewables as it is the closest technology to commercialisation, but there has also been significant interest in WECs as it has been mooted that wave energy will have the capacity to generate 10% of the world's energy needs once fully commercialised. This research could come from both ADMA and industry as they seek to find innovative solutions to bring down the LCOE of wave energy. Experts within industry state there is a skills and knowledge gap in this area and many stakeholders do not appreciate the full extent of the challenge lowering the cost of mooring and anchoring systems. TTI along with other industry consultants and developers are investing in the development of mooring technologies, the details of those activities are detailed in Section 5 but there are also R&D initiatives underway that are not publicly available. Scottish Enterprise and other ADMA partners should engage with industry stakeholders within their regions to assess potential collaborations in the future.

6.4 Continued development of mooring and anchoring systems

With the results from the H2020 funded OPERA not released yet and many other R&D initiatives still ongoing, it is difficult to say what the course of action moving forward should be. It is prudent to wait and review the outcome of those projects added value to competitive cost. Scottish Enterprise should also engage with the other ADMA partners to corroborate the findings of ongoing projects ADMA partners are involved in which can be related to and benefit anchors and moorings. They can also open up a dialogue to the impact cost reductions in these technologies will have on the LCOE of offshore renewable technology. There are obvious opportunities in Emilia Romagna where the region has extensive expertise in mooring systems and other structural components crucial to the successful deployment of offshore renewable technologies. Further engagement with ARTER is recommended to assess the level of commitment to renewables both currently and what the region's plans are for the future.

Increasing market visibility will reduce technology risk and gain access to capital at a lower cost, and insurance will also play a significant role. Insurance could be used to reduce technology risk by making access to capital easier, but commercial insurance products covering early development do not exist but FOW may change this due to the cost implications of a fundamental within a mooring line design that is attached to an array of turbines. The relative costs from increased R&D into mooring technologies will be greatly exceeded by the costs of a failure in the mooring system of an OWF.

Communication is crucial to the successful development and deployment of offshore renewable energy technologies. Grant funding is vital to this and transparency between institutes and stakeholders will help ensure that ‘spending’ and allocation of money can be optimised. For example, public expenditure rewards innovative success and R&D activities are not being duplicated. Also need to identify early opportunities when private investment can bring a financial return. This will also help raise technologies visibility within the market.

7 REFERENCES

[1] 4C Offshore, “VertiWind,” 2018. [Online]. Available: https://www.4coffshore.com/windfarms/turbine-technip---n%C3%A9nuphar-vertiwind-tid118.html. [Accessed 3 October 2019].

[2] T. Russell, “Floaitng Wind: Changing Gear,” 4 July 2019. [Online]. Available: https://www.4coffshore.com/news/floating-wind--changing-gear-nid13899.html. [Accessed October 2019].

[3] Carbon Trust, “Floating Offshore Wind: Market and Technology Review,” 2015.

[4] ETIP Ocean, “Powering Homes Today, Powering Nations Tomorrow,” 2019. [Online]. Available: https://www.oceanenergy-europe.eu/wp-content/uploads/2019/04/ETIP-Ocean-Integrated-Strategy-2019-LR.pdf. [Accessed 23 September 2019].

[5] Union, European, “Market Study on Ocean Energy,” Brussels, 2018.

[6] Scottish Renewables, “UK Marine Energy 2019,” 2019.

[7] reNEWS, “Tocardo Tidal Power declared bankrupt,” 11 October 2019. [Online]. Available: https://www.tocardo.com/bankruptcy-tocardo-tidal-power/. [Accessed 22 October 2019].

[8] J. B. Thomsen, F. Ferri, J. P. Kofoed and K. Black, “Cost Optimization of Mooring Solutions for Large Floating Wave Energy Converters,” *Energies,* vol. 11, no. 159, pp. 1-2, 2018.

[9] L. Johanning and G. H. Smith, “Consideration of the cost implications for mooring MEC devices,” EquiMar, 2009.

[10] C. Fontana, “A Multiline Anchor Concept for Floating Offhsore Wind Turbines,” 2019. [Online]. Available: https://pdfs.semanticscholar.org/91cc/8d5ba4aef9fe17664da5220847bb8c503268.pdf. [Accessed 1 October 2019].

[11] First Subsea, “Balla and Taper Technology,” 2019. [Online]. Available: http://www.firstsubsea.com/about-first-subsea/ball-taper-technology.html. [Accessed 7 November 2019].

[12] Oregon Wave Energy Trust, “Advanced Anchoring and Mooring Study,” 30 November 2009. [Online]. Available: https://tethys.pnnl.gov/sites/default/files/publications/Advanced_Anchoring_and_Mooring_Study.pdf. [Accessed 21 October 2019].

[13] Power Magazine, “Clump Weights in Offshore Mooring Systems,” 5 January 2019. [Online]. Available: https://www.powermag.com/clump-weights-in-offshore-mooring-systems/. [Accessed 21 October 2019].

[14] The Carbon Trust, “Floating Wind Joint Industry Project - Phase 1 Summary Report,” 2018.

[15] Equnior, “Equinor—the world’s leading floating offshore wind developer,” 2019. [Online]. Available: https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us.html. [Accessed October 2019].

[16] Principle Power, “WindFloat,” 2019. [Online]. Available: http://www.principlepowerinc.com/en/windfloat. [Accessed 15 October 2019].

[17] IDEOL, “A floating foundation that pushes the boundaries of offshore wind,” 2018. [Online]. Available: https://www.ideol-offshore.com/en. [Accessed 1 October 2019].

[18] Naval Energies, “Offshore Wind Energy,” 2018. [Online]. Available: https://www.naval-energies.com/en/our-offer/offshore-wind-energy/. [Accessed 1 October 2019].

[19] Minesto, “Power to change the future,” 2019. [Online]. Available: https://minesto.com/. [Accessed 22 September 2019].

[20] Orbital Marine Power, “Orbital O2 2MW,” 2019. [Online]. Available: https://orbitalmarine.com/technology-development/orbital-o2. [Accessed 22 September 2019].

[21] Orbital Marine Power, “FloTEC,” 2019. [Online]. Available: https://orbitalmarine.com/flotec/flotec-project/. [Accessed 22 September 2019].

[22] CorPower Ocean, “HiWave-3,” 2018. [Online]. Available: http://www.corpowerocean.com/hiwave-3/. [Accessed 23 September 2019].

[23] CorPower Ocean , “HiWave-5,” 2019. [Online]. Available: http://www.corpowerocean.com/commercial-projects/partners-projects/. [Accessed 23 September 2019].

[24] CorPower Ocean, “Commercial Projects,” 2019. [Online]. Available: http://www.corpowerocean.com/commercial-projects/. [Accessed 23 September 2019].

[25] Marine Energy, “Waves and tides form stronger tie-up,” 2018. [Online]. Available: https://marineenergy.biz/2018/11/01/waves-and-tides-form-stronger-tie-up/. [Accessed 23 September 2019].

[26] Wello Oy, “Clean Energy from Ocean Waves,” 2019. [Online]. Available: https://wello.eu/. [Accessed 23 September 2019].

[27] Wello Oy, “The Basque country welcomes the Wello Penguin wave energy converter to its shores,” 6 September 2019. [Online]. Available: https://wello.eu/2019/09/06/the-basque-country-welcomes-the-wello-penguin-wave-energy-converter-to-its-shores/. [Accessed 23 September 2019].

[28] Wello Oy, “Offshore giants Saipem sign Memorandum of Understanding (MoU) to optimize Penguin WEC technology,” 8 October 2019. [Online]. Available: https://wello.eu/2019/10/08/offshore-giants-saipem-sign-memorandum-of-understanding-mou-to-optimize-penguin-wec-technology/. [Accessed 15 October 2019].

[29] Laminaria, “LAMWEC,” February 2017. [Online]. Available: file:///C:/Users/jamie.mcmorran/Downloads/201702_lamwec_leaflet%20.pdf. [Accessed 23 Septmeber 2019].

[30] Laminaria, “LAMWEC,” [Online]. Available: http://www.laminaria.be/lamwec.html. [Accessed 23 September 2019].

[31] Carnegie Clean Energy, “CETO 5 - Perth (WA),” [Online]. Available: https://www.carnegiece.com/project/ceto-5-perth-wave-energy-project/. [Accessed 2 October 2019].

[32] R. Turner, “Troubled wave energy company Carnegie Clean Energy has a 'rebirth' on the ASX,” ABC News, 30 October 2019. [Online]. Available: https://www.carnegiece.com/project/ceto-5-perth-wave-energy-project/. [Accessed 7 November 2019].

APPENDIX A FLOATING OFFSHORE WIND TECHNOLOGY DESIGN CATALOGUE

Appendix A.1 Equinor - Hywind

The Hywind foundation is developed by Norwegian oil developer Equinor. A 2.3 MW demonstrator of Hywind began operations in 2009 in Norway. Commissioned in 2017, Hywind Scotland was the world's first floating wind park [4]. Still under development, Hywind Tampen would provide 88MW, 35% of the total energy demand, to oil filed Gulfaks and Snorre in Norway.

Hywind Scotland	**UK**
Total capacity (MW)	30
No. of turbines	5
Foundation technology	Hywind (spar buoy)
Anchors	3-catenary
Developer	Equinor
Depth (m)	95-129
Commissioned	2017

Hywind Tampen	**Norway**
Total capacity (MW)	88
No. of turbines	11
Foundation technology	Hywind (spar buoy)
Anchors	3-catenary
Developer	Equinor
Depth (m)	95-129
Commissioned	2022

Appendix A.2 Principle Power - WindFloat

The WindFloat design was developed by offshore technology company Principle Power. A 2MW WindFloat demonstrator operated in Portugal between 2011-2016 [5]. WindFloat Atlantic will be commissioned by the end of 2019, and another large project Les Eoliennes Flottantes du Golfe du Lion, is underway in France. WindFloat was also selected as the foundation of choice for the Scottish Kincardine wind farm after Cobra's semi-spar was dropped from the project. A pilot 2MW WindFloat unit has already been installed and is operating as part of the project and five more 9.5MW units are to be installed by 2020.

WindFloat Atlantic	**Portugal**
Total capacity (MW)	25
No. of turbines	3
Foundation technology	WindFloat (semi-submersible)
Anchors	3-catenary
Developer	Respol/WindPlus S. A
Depth (m)	85-100
Commissioned	2019

Kincardine	Scotland
Total capacity (MW)	50
No. of turbines	7 (one 2MW, five 9.5MW)
Anchors	3-catenary
Foundation technology	Semi-submersible WindFloat
Developer	Marubeni
Depth (m)	60-80
Commissioned	2020

Golf du Lion	France
Total capacity (MW)	24MW
No. of turbines	4
Anchors	3-catenary
Foundation technology	WindFloat (semi-submersible)
Developer	EOLFI/CGN
Depth (m)	70-100
Commissioned	2020

Appendix A.3 Fukushima - FORWARD

The Fukushima FORWARD is a Japanese consortium of 11 organisations, leading the diversification of the Japanese energy mix following the Fukushima nuclear disaster. Japan has a vested interest in floating wind as most of its coastline is unsuited for fixed foundations. As part of the FORWARD initiative, three floating wind turbines and a floating substation were installed off the coast of Fukushima. Phase 1 saw the installation of a 2MW demonstrator of the 4 column “Compact” foundation. Two different types of foundations were used for phase 2.
Phase I of the FORWARD project is a 2MW demonstrator, installed in 2013. This initial demonstrator had a four-column semi-submersible floating foundation.

FORWARD – Phase 2	Japan
Total capacity (MW)	12
No. of turbines	2 (one 5MW, one 7MW)
Foundation technology	3-col. V-type & Advanced Spar
Anchors	3-catenary
Developer	Marubeni
Depth (m)	100-150
Commissioned	2015

Appendix A.4 IDEOL Damping Pool

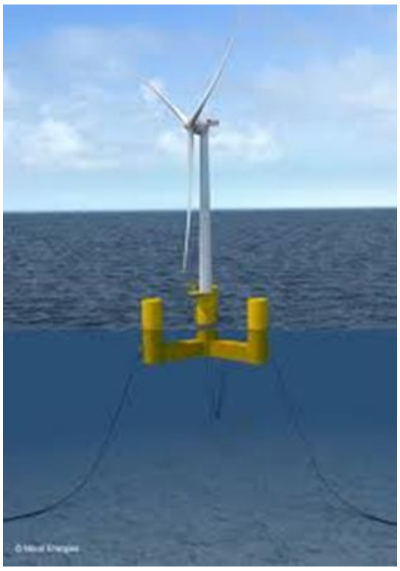
Ideol is a French floating offshore wind foundation developer established in 2010 [6]. Two demonstrators of the patented damping pool foundation are in operation: 2MW in France and 3MW in Japan. A pre-commercial array EolMed is being developed in France.

EolMed	France
Total capacity (MW)	24
No. of turbines	4
Foundation technology	Damping Pool
Anchors	6 nylon semi-tai
Developer	Quadran
Depth (m)	55
Commissioned	2021

Appendix A.5 Naval Energies

Naval Energies develops marine renewable energy systems. The company originated as part of Naval Group, a naval defence engineering organisation [7]. Naval Energies is currently developing a pilot farm in France.

Groix et Belle-Ile	France
Total capacity (MW)	24
No. of turbines	4
Foundation technology	Semi-submersibles
Anchors	3 pairs of tensioned fibre and chain moorings
Developer	EOLFI/CGN
Depth (m)	55-70
Commissioned	2021



Appendix A.6 TODA Hybrid Spar

Japanese TODA corporation has developed the hybrid-spar type floating foundation. A prototype has been installed outside Fukue Island. The 22MW Goto Sakiyama Oki Oki will be the first privately funded floating wind pilot array.

Goto Sakiyama Oki Oki	Japan
Total capacity (MW)	22
No. of turbines	9 (eight 2.1, one 5.2)
Anchors	3-catenary

Foundation technology	Toda
Developer	Hybrid Spar
Depth (m)	100-150
Commissioned	2022

Appendix A.7 VolturnUS - Aqua Ventus I

Aqua Ventus I is the University of Maine's DeepCWind Consortium's pilot project for their VolturnUS floating technology. A 1:8 scale prototype of the technology has been successfully tested at sea.

	USA - Maine
Total capacity (MW)	12
No. of turbines	2
Foundation technology	Semi-submersible
Anchors	3-catenary
Developer	UMaine
Depth (m)	61-110
Commissioned	2022

Appendix A.8 Floating Power Plant

Floating Power Plant intend to deploy a demonstrator of their P80 floating wind and wave power platform at the Oceanic Platform of the Canary Islands (PLOCAN).

	Spain (PLOCAN)
Total capacity (MW)	8
No. of turbines	1
Anchors	3-catenary

Foundation technology	Hybrid Semi-sub
Developer	Floating Power Plant
Commissioned	2022

APPENDIX B MARINE RENEWABLE ENERGY CONCEPTS

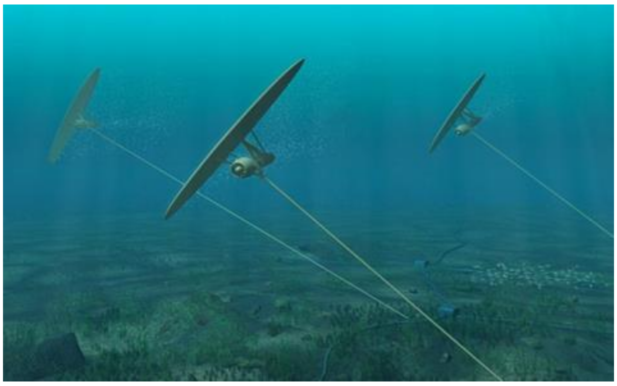
Appendix B.1 Tidal Stream Energy

Appendix B.1.1 Minesto – Deep Green 500

Minesto have developed a tidal kite which produces electricity with low-flow streams at 2.5m/s and below [12]. The technology is currently being tested off the North West coast of Wales, operating at depths 60-120m, tethered to the seabed by a mooring system [12].

This is a unique design and Minesto's Deep Green project is the first to develop a commercially viable low-flow tidal turbine with successful demonstrations of a 500kW commercial -scale unit.

Deep Green 500	**Wales**
Power Rating (MW)	0.5
No. of Turbines	1
Rotor Diameter (m)	1.5
Cut in tidal speed (m/s)	1.2
Rated tidal speed (m/s)	2.4
Foundation technology	Mooring system
Developer	Minesto
Commissioned	2018

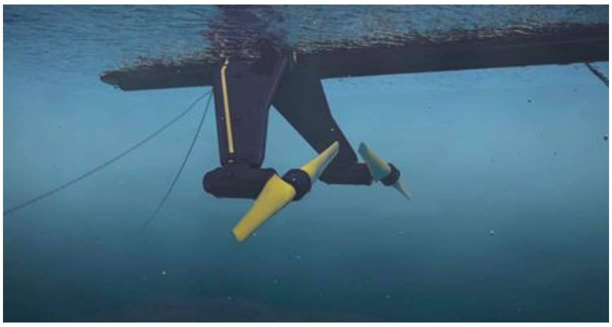


Appendix B.1.2 Orbital Marine Power - FloTEC

Orbital Marine have been at the forefront of the development of floating tidal stream turbines since its inception in 2002. Over the past 15 years, the Orkney based company has persisted with R&D and testing of floating tidal technology, and with the help of funding from the European Union's Horizon 2020 programme, has led to the development of the Orbital O2 2MW turbine [13].

Through the Floating Tidal Energy Commercialisation (FloTEC) project, this tidal turbine is set to be deployed at the European Marine Energy Centre in 2020 as the world's most powerful operational tidal turbine and demonstrate that floating tidal systems can be commercially viable [14]. Orbital have partnered with SKF and their technologies and expertise will help lower the LCOE through asset performance management [14].

FloTEC	**Netherlands**
Power Rating (MW)	2
No. of Turbines	2
Rotor Diameter (m)	20
Cut in tidal speed (m/s)	
Rated tidal speed (m/s)	2.5
Foundation technology	Mooring system
Developer	Orbital Marine Power
Commissioned	



Appendix B.2 Wave Energy Conversion

Appendix B.2.1 CorPower – HiWave

CorPower is leading a project to deploy a commercial certified WEC with four partners and after the successful testing of the half-scale model between 2015 and 2018 [15]. After the successful completion testing CorPower are now focussing on the develop a full-scale model and continue testing with the aim of enabling the successful deployment of the WEC into the market by the end of 2023-2024 [16]. The project focuses on reducing the cost of the WEC and so while the device aims to maximise its energy output, the HiWave is able to ‘detune’ during extreme waves, to increase survivability and reduce capital costs [10].

The overall goal of HiWave is to enable successful introduction of certified and warrantied WEC products in the market by end of 2023-2024, making wave energy a bankable technology that can attract mainstream renewable energy project finance [17].

CorPower along with TTI Marine Renewables are involved in mooring and anchoring research project, UMACK (Universal Mooring, Anchor & Connectivity Kit Demonstration), which is funded by Scottish Enterprise and the Swedish Energy Agency. The project examines the current issues of marine renewables such as cost, survivability and installation. The project is in the demonstration stage and aims to bring CAPEX of mooring systems down by 50% [18].

HiWave	**Sweden**
Power rating (MW)	2
Developer	CorPower Ocean
Commissioned	2015

Appendix B.2.2 Wello Oy – Penguin

Wello have developed their first full-scale commercially ready WEC, the Penguin WEC2, which has been deployed in Orkney to demonstrate the technologies capabilities [19]. The WEC1 protype had been successfully tested in the Orkney waters since 2012 and the WEC2 has been deployed in Basque country as well with the support of EVE and BiMEP [20]. Wello have also signed a Memorandum of Understanding to develop future initiatives within the wave energy sector with Saipem, who aspire to become a key player in marine energy production [21].

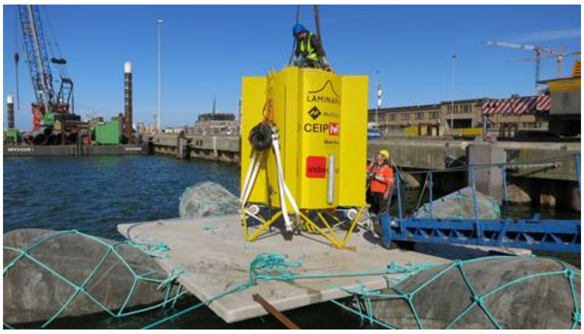
Penguin	**Finland**
Power rating (MW)	1
Developer	Wello
Commissioned	2011

Appendix B.2.3 Laminaria – LAMWEC

Laminaria has developed a full-scale prototype of LAMWEC 200kW WEC, progressing the model from TRL stage 5 (technology validated in relevant environment) to 7 (system prototype demonstration in operational environment [22]. One of the concerns for Laminaria and a key focus as the technology develops is the survivability of the device. That is why the WEC features a pulley system to drag the system down closer to the seabed, moving the tip of the WEC away from the surface in extreme weather [23].

The LAMWEC project is made up of a consortium of ocean energy experts with over 30 years of combined practical experience in the sector. The consortium is led by Laminaria, and includes EMEC, Innosea, Ghent University, and TTI Testing [23]. The LAMWEC project is being funded through OCEANERA-NET, an initiative looking to address research and innovation challenges in ocean energy, coordinated by Scottish Enterprise [23].

LAMWEC	**Belgium**
Power rating (MW)	0.2
Developer	Laminaria
Commissioned	2019

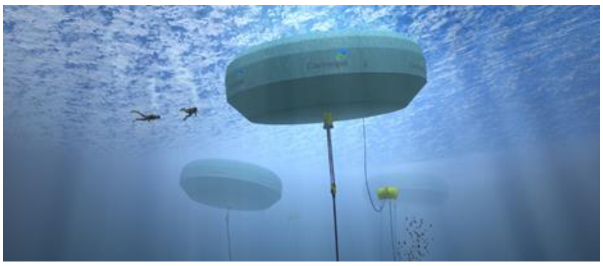


Appendix B.2.4 Carnegie Clean Energy

Carnegie have developed the first grid connected wave energy system, CETO 5 which consists of three units operating in array [24]. CETO produced power for the Australian Department of Defence to supply Australia's largest naval base, HMAS Stirling in Western Australia. The CETO 5 units were installed off the base's location in Garden Island in late 2014 and operated for a period of 12 months while the system produced fresh water as well as power. CETO is the only WEC in the world with this capability.

CETO 5 operated for 14,000 cumulative hours producing a total of 12,000kWh over the demonstration period. Carnegie found an excellent correlation between the modelled performance and the measured data and building on the success of the demonstration, Carnegie had plans to develop and deploy a prototype, CETO 6 unit, which would move the system towards commercial level until the Australian government cut the projects funding and now the company faces financial uncertainty, narrowly avoiding financial uncertainty earlier this year [25].

CETO	**Australia**
Power rating (MW)	6
Developer	Carnegie Clean Energy
Commissioned	2014



APPENDIX C POTENTIAL FUNDING SOURCES FOR R&D INITIATIVES

Industry Segment	Fund	Enabling Body	Country Code	Website Link	Application open	Application close
All	Energy Investment Fund (EIF)	Scottish Government/ Scottish Investment Bank	UK	https://www.scottish-enterprise.com/support-for-businesses/funding-and-grants/accessing-finance-and-attracting-investment/energy-investment-fund		31-Mar-20
All	Community and Renewable Energy Scheme (CARES)	Scottish Government	UK	http://www.ukerc.ac.uk/network/funding/community-and-renewable-energy-scheme-cares.html		24-Jun-19
Wave and tidal	Quick Connection Systems	Wave Energy Scotland WES	UK	https://www.publiccontractsscotland.gov.uk/search/show/search_view.aspx?ID=AUG362941	12-Aug-19	17-Sep-19
Wave and tidal	Quick Connection Systems Call	Wave Energy Scotland WES	UK	http://tiny.cc/QuickConnect	24-Jul-19	16-Nov-19
Wave and tidal	External Experts Sought for Control Assessments	Wave Energy Scotland WES	UK	https://www.publiccontractsscotland.gov.uk/search/show/search_view.aspx?ID=DEC340428	19-Dec-19	08-Feb-19
Wave and tidal	Saltire Tidal Energy Challenge Fund	Scottish Government	UK		29-Mar-19	

All	Cluster facilitated projects for new industrial value chains INNOSUP-01-2018-2020	Horizon 2020	EU	https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/innosup-01-2018-2020;freeTextSearchKeyword=;typeCodes=1;statusCodes=31094501,31094502;programCode=H2020;programDivisionCode=31047887;focusAreaCode=null;crossCuttingPriorityCode=null;callCode=Default;sortQuery=openingDate;orderBy=asc;onlyTenders=false;topicListKey=topicSearchTablePageState	07-Nov-19	02-Apr-20
All	ERA-NET on materials, supporting the circular economy and Sustainable Development Goals	Horizon 2021	EU	https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/ce-nmbp-41-2020;freeTextSearchKeyword=;typeCodes=1;statusCodes=31094501,31094502;programCode=H2020;programDivisionCode=31047862;focusAreaCode=null;crossCuttingPriorityCode=null;callCode=Default;sortQuery=openingDate;orderBy=asc;onlyTenders=false;topicListKey=topicSearchTablePageState	03-Jul-19	05-Feb-20

All	Materials life cycle sustainability analysis	Horizon 2022	EU	https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/ce-nmbp-42-2020;freeTextSearchKeyword=;typeCodes=1;statusCodes=31094501,31094502;programCode=H2020;programDivisionCode=31047862;focusAreaCode=null;crossCuttingPriorityCode=null;callCode=Default;sortQuery=openingDate;orderBy=asc;onlyTenders=false;topicListKey=topicSearchTablePageState	03-Jul-19	05-Feb-20
All	Multi-technology tender scheme	Danish Government	DK	europa.eu/rapid/press-release_IP-18-5042_en.htm	01-Oct-18	01-Dec-19
All	InnovFin	European Investment Bank	EU	www.eib.org/products/blending/innovfin/	31-Dec-14	31-Dec-19
All	InnovFin Energy Demo Projects	European Investment Bank	EU	www.eib.org/attachments/documents/innovfin_energy_demo_projects_eligibility_questionnaire_en.pdf	22-Jun-15	31-Dec-19
All	SBRI: modernising energy data access and information, phase 1	Innovate UK	UK	apply-for-innovation-funding.service.gov.uk/competition/491/overview#dates	16-Oct-19	02-Jan-20
All	Innovate UK Smart Grants: October 2019	Innovate UK	UK	apply-for-innovation-funding.service.gov.uk/competition/446/overview	17-Oct-19	08-Jan-20
Offshore wind, wave and tidal	MARINET2 – Call 5	European Commission	EU	www.marinet2.eu/	25-Jun-20	07-Aug-20
All	European Maritime and Fisheries Fund (EMFF)	European Commisi	UK	ec.europa.eu/fisheries/cfp/emff/	01-Jan-14	31-Dec-20

Wave and tidal	Ocean Power Innovation Network (OPIN)	Sustainable Energy Authority of Ireland (SEAI)	IR	www.nweurope.eu/projects/project-search/opin-ocean-power-innovation-network/	01-Jan-18	31-Dec-21
All	ENERGIX programme – Large-scale programme for Energy Research	Research Council of Norway (RCN)	NO	www.forskningsradet.no/prognett-energix/Home_page/1253980140022	01-Jan-13	31-Dec-23
Offshore wind, wave and tidal	R&D Tax credits	Department for Business, Innovation and Skills (BIS)	UK	www.gov.uk/guidance/corporation-tax-research-and-development-tax-relief-for-small-and-medium-sized-enterprises#rd-tax-credits	Ongoing	Ongoing
Offshore wind, wave and tidal	Regional Selective Assistance (RSA)	Scottish Enterprise	UK	www.scottish-enterprise.com/services/attract-investment/regional-selective-assistance/overview	Ongoing	Ongoing
Offshore wind, wave and tidal	Research and Development (R&D) Grant	Scottish Enterprise	UK	www.scottish-enterprise.com/services/develop-new-products-and-services/rd-grant/overview	Ongoing	Ongoing
Offshore wind	National Renewables Infrastructure Fund (N-RIF)	Scottish Enterprise	UK	www.scottish-enterprise.com/services/develop-new-products-and-services/nrif/overview	Ongoing	Ongoing
Offshore wind	Offshore Wind Expert Support Programme	Scottish Enterprise	UK	www.scottish-enterprise.com/services/develop-your-organisation/offshore-wind-expert-support-programme/overview	Ongoing	Ongoing
Offshore wind	Scottish Innovative Foundation Technologies Fund (SIFT)	Scottish Enterprise	UK	www.scottish-enterprise.com/services/develop-new-products-and-services/sift/overview	Ongoing	Ongoing
Offshore wind,	Innovation Vouchers	Innovate UK	UK	www.gov.uk/government/news/innovation-vouchers-for-all	Ongoing	Ongoing

wave and tidal						
Offshore wind, wave and tidal	Collaborative Business Network Programme (CNP)	Invest Northern Ireland	UK	www.investni.com/support-for-business/skills-development/collaborative-working.html	Ongoing	Ongoing
Offshore wind, wave and tidal	Industrial CASE	Engineering and Physical Sciences Research Council (EPSRC)	UK	www.epsrc.ac.uk/skills/students/coll/icase/	Ongoing	Ongoing
Offshore wind, wave and tidal	Programme Grants	Engineering and Physical Sciences Research Council (EPSRC)	UK	www.epsrc.ac.uk/funding/howtoapply/routes/capacity/programme/	Ongoing	Ongoing
Offshore wind, wave and tidal	Research Base Funding	Engineering and Physical Sciences Research Council (EPSRC)	UK	www.epsrc.ac.uk/funding/howtoapply/routes/standardresearch/	Ongoing	Ongoing
Offshore wind, wave and tidal	Co-Fund NI	Invest Northern Ireland	UK	www.cofundni.com/	Ongoing	Ongoing
Offshore wind, wave and tidal	Export Development Service: Renewable Marine Energy – Offshore Wind/Wave & Tidal	Invest Northern Ireland	UK	secure.investni.com/static/library/invest-ni/documents/exporting-can-transform-your-business.pdf	Ongoing	Ongoing
Offshore wind, wave and tidal	Finance Voucher	Invest Northern Ireland	UK	secure.investni.com/static/library/invest-ni/documents/access-to-finance-finance-voucher-overview.pdf	Ongoing	Ongoing
Offshore wind, wave and tidal	Growth Loan Fund	Invest Northern Ireland	UK	www.whiterockcp.co.uk/growth-loan-fund.aspx	Ongoing	Ongoing

Offshore wind, wave and tidal	NI Small Business Loan Fund	Invest Northern Ireland	UK	www.nisblf.com/	Ongoing	Ongoing
Offshore wind, wave and tidal	The Development Funds	Invest Northern Ireland	UK	www.investni.com/support-for-business/funding-through-loans-and-equity.html	Ongoing	Ongoing
Offshore wind, wave and tidal	SMART: SCOTLAND – Feasibility studies	Scottish Enterprise	UK	www.scottish-enterprise.com/services/develop-new-products-and-services/smart-scotland/overview		Ongoing
Offshore wind, wave and tidal	SMART: SCOTLAND – R&D Projects	Scottish Enterprise	UK	www.scottish-enterprise.com/services/develop-new-products-and-services/smart-scotland/overview		Ongoing
Offshore wind, wave and tidal	European Structural and Investment Funds (ESI)	European Commission	EU	ec.europa.eu/research/infrastructures/index_en.cfm?pg=structural_funds		Ongoing
Offshore wind, wave and tidal	EUROGIA2020 (EUROGIA+)	EUREKA	EU	www.eurogia.com/eurogia/about-eurogia.html	Ongoing	Ongoing
Offshore wind, wave and tidal	Low Carbon KEEP (Knowledge-East of England-Partners) Programme	European Regional Development Fund (ERDF) and the East of England Development Agency	UK	www.anglia.ac.uk/business-employers/knowledge-exchange/keep-plus	Ongoing	Ongoing
Wave and tidal	Propel Cornwall	Cornwall Marine Network (CMN)	UK	propelcornwall.co.uk/	15-Mar-17	Ongoing
All	Open grant funding competition	Innovate UK	UK	apply-for-innovation-funding.service.gov.uk/competition/243/overview	10-May-18	Ongoing

All	Energy Entrepreneurs Fund	BEIS	UK	www.gov.uk/government/collections/energy-entrepeneurs-fund		Ongoing
Offshore wind, wave and tidal	Uncertainity Reduction in Smart Energy Systems (URSES)	Netherlands Organisation for Scientific Research	NL	www.nwo.nl/en/funding/our-funding-instruments/magw/urses/urses.html		Periodic deadlines
All	Emerging Renewable Power	Natural Resources Canada	CA	www.nrcan.gc.ca/energy/funding/20502	28-Mar-18	Rolling
All	Scottish-European Growth Co-Investment Programme	Scottish Enterprise	UK	www.scottish-enterprise.com/services/attract-investment/scottish-european-growth-co-investment-programme/scottish-european-growth-co-investment-programme-overview	03-May-18	Rolling
All	Scottish Enterprise: Research and Development grants	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/growing-your-business/research-and-development-grant		Rolling
All	Scottish Enterprise: Make it to Market grants	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/growing-your-business/make-it-to-market		Rolling
All	Clean growth fund	The Department of Business, Energy and Industrial Strategy (BEIS)	UK	www.gov.uk/government/publications/clean-growth-equity-fund	17-Oct-18	Rolling
All	Scottish Co-Investment Fund	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/accessing-finance-and-attracting-		Rolling

				investment/scottish-co-investment-fund		
All	Scottish Venture Fund	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/accessing-finance-and-attracting-investment/scottish-venture-fund		Rolling
All	By Design grants	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/growing-your-business/by-design		Rolling
All	Regional Selective Assistance (RSA)	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/growing-your-business/regional-selective-assistance-grant		Rolling
All	Workplace Innovation Fund	Scottish Enterprise	UK	www.scottish-enterprise.com/support-for-businesses/funding-and-grants/growing-your-business/workplace-innovation-fund		Rolling
All	Brexit Support Grant	Scottish Enterprise	UK	www.prepareforbrexit.scot/updates/brexit-support-grant		Rolling
All	Innobooster	Innovation Fund Denmark	DK	innovationsfonden.dk/en/programmes/innobooster		Rolling
Offshore wind	SUPERGEN: Wind Energy Technologies Consortium (Phase 2)	Engineering and Physical Sciences Research Council (EPSRC)	UK	www.supergen-wind.org.uk/	01-Jan-10	Unknown