Cornwall FLOW Accelerator

THE FUTURE POTENTIAL ROLE OF OFFSHORE MULTIPURPOSE CONNECTORS

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CORNWALL FLOW ACCELERATOR PROJECT Innovation in Low Carbon Design and Manufacturability

The Future Potential Role of Offshore Multipurpose Connectors

REPORT - Floating Offshore Wind Electrical Infrastructure and Grid Connections

Photo Source: Multipurpose Interconnectors understanding project risk for wind farm cables | RPS (rpsgroup.com)

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The Pembrokeshire Demonstration Zone (PDZ) project is being led by Celtic Sea Power Ltd, a 100% subsidiary of Cornwall Council. Funded by the Welsh European Funding Office (WEFO) and the Swansea Bay City Deal (SBCD), and the development of PDZ is part of the Pembroke Dock Marine programme. Partners to Pembroke Dock Marine include Port of Milford Haven, Pembrokeshire County Council, ORE Catapult and Marine Energy Wales.

ORE Catapult is a not-for-profit research organisation, established in 2013 by the UK Government as one of a network of Catapults in high growth industries. It is the UK's leading innovation centre for offshore renewable energy and helps to create UK economic benefit in the sector by using its test assets, engineering and ORE market expertise to drive down the cost of offshore renewable energy and support the growth of the industry.

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Front Cover Source: Multipurpose Interconnectors understanding project risk for wind farm cables | RPS (rpsgroup.com

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PREFACE

ORE Catapult is the UK's flagship technology innovation and research centre for offshore wind, wave and tidal energy. ORE Catapult is playing a leading role in the delivery of the offshore wind sector deal (partnership between UK Government and offshore wind industry), including the Offshore Wind Growth Partnership, focused on enhancing the competitiveness of UK supply chain companies for supplying into the domestic and export markets. ORE Catapult has developed and actively maintains technology roadmaps to co-ordinate Research and Development funding and activity across agreed industry priorities. This provides ORE Catapult with a unique broad and objective perspective on the UK and global offshore wind industry.

We are an independent, not-for-profit business that exists to accelerate the development of offshore wind, wave and tidal technologies. Our team of over 300 people has extensive technical and research capabilities, industry experience and a proven track record. Through our world-class testing and research programmes, we work for industry, academia and government to improve technology reliability and enhance knowledge, directly impacting upon the cost of offshore renewable energy. We organise our activities around key areas for future innovation and developing local Centres of Excellence that will support the transformation of our coastal communities. These areas include: floating wind; marine energy; testing and demonstration; operations and maintenance.

The Centres of Excellence champion innovation in robotics, autonomous systems, big data and artificial intelligence, balance of plant – especially foundations – and next-generation technologies. To date, we have supported more than 800 small to medium-sized enterprise, contributed to 328 active and completed research projects, and supported over 180 companies in their product development.

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NOMENCLATURE

AC	Alternating Current
AMSL	Above Mean Sea Level
BEIS	The Department for Business, Energy and Industrial Strategy
B-F	Bottom Fixed
CFA	Cornwall FLOW Accelerator
CoB	Centre of Buoyancy
CoG	Centre of Gravity
CSA	Cross-Sectional Area
DC	Direct Current
FOS	Floating Offshore Substation
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
GM	Metacentric Height
HND	Holistic Network Design
HSE	Health & Safety Executive
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HV GIS	High Voltage Gas-Insulated Switchgear
IAC	Inter-Array Cable
MOS	Multipurpose Offshore Substation
MPI	Multipurpose Interconnector
MT	Metric Tonnes
MV	Medium Voltage
NGESO	National Grid Electricity System Operator
O&G	Oil and Gas
O&M	Operation and Maintenance
ORE	Offshore Renewable Energy

OSS	Offshore Substation
OW	Offshore Wind
OWF	Offshore Wind Farm
PDZ	Pembrokeshire Demonstration Zone
R&D	Research and Development
RE	Renewable Energy
SBCD	Swansea Bay City Deal
SCADA	Supervisory Control and Data Acquisition
SS	Substation
TCE	The Crown Estate
TLP	Tension-Leg Platform
WEFO	Welsh European Funding Office
WTG	Wind Turbine Generator

SYMBOLS AND UNITS

$°C$	degree Celsius
Cu	copper
GW	giga-watt
I_n	nominal current in ampere (A)
I_p	transformer primary current (A)
I_s	transformer secondary current (A)
K	temperature (Kelvin)
$K.m/W$	thermal resistivity (Kelvin meter per Watt)
km	kilometer
kV	kilo-volt
m	meter
mm^2	milli meter squared
MW	mega-watt
MVA	mega-volt ampere
P	active power (W)
P_n	nominal active power of wind turbine in Watt (W)
pf	power factor
S	apparent power volt ampere (VA)
S_n	nominal apparent power of wind turbine (Volt Ampere)
U	phase-to-phase voltage (V)
$U_{correct}$	phase-to-phase voltage correction (V)
$U_{op.min}$	minimum phase-to-phase voltage the turbine can ride through in per unit
U_p	transformer primary voltage (V)
U_n	nominal phase-to-phase voltage (V)
U_s	transformer secondary voltage (V)

EXECUTIVE SUMMARY

The Cornwall Flow Accelerator work package 4 led by ORE Catapult details innovation in low carbon design and manufacturability that lays the groundwork for development of low carbon strategies, across design, manufacturing and operations & maintenance. Within this work package, the goal of this specific task 6 analysis, is for the electrical infrastructure of floating offshore wind in the Celtic Sea to identify opportunities in the UK's South West region.

This research will build on earlier considerations of how floating offshore wind can be integrated into the South Wales and South West UK transmission network, focusing on the introduction of the South West offshore substations, the Pembroke Demonstration Zone development and the substation, 4 GW expansion analysis, and technical bottleneck and promising technologies, i.e., floating offshore substation and subsea substation.

The scope of this study is restricted to high-voltage alternating current substations, and a substation capacity range under the Pembrokeshire Demonstration Zone from 1 to 2.4 GW as the primary focus initially building out to 4 GW with multiple platforms. This work aimed to determine the benefits of fixed jacket multipurpose offshore substations, the comparisons of fixed versus floating substations and when they become competitive at deep water. Some of the key considerations that would influence the decision to build out the Celtic Sea's floating offshore wind ambitions are also investigated.

This research presents a strategic offshore transmission network for the Celtic Sea that considers multipurpose connectors in the form of multipurpose offshore substations and multipurpose interconnectors from the comparison of bottom-fixed jacket substructures and floating structures for offshore substations. Apart from the 'Fukushima Kizuma' floating offshore demonstration substation project, floating offshore substations have not been widely used to date. However, with offshore wind farms moving into deeper water off the Celtic Sea and the global floating wind market expected to grow rapidly over the coming decades, floating offshore substations are a key topic of interest.

Ofgem's multipurpose interconnector programme offers incentives for developing hybrid and multi-use interconnectors to streamline the transmission system and facilitate low carbon activities. Under the current contract for differences policy framework, multipurpose interconnector-offshore wind is not eligible to apply for agreements. Thus, ahead of contract for differences 'Allocation Round 6' (due in 2024), The Department for Business, Energy & Industrial Strategy is consulting on aspects of the auction design, including how multipurpose interconnector-offshore wind should interact with the contract for differences scheme.

The Celtic Sea will likely include a mixture of both high-voltage alternating current and high-voltage direct current technologies. Traditional transmission in the UK has been high-voltage alternating current, with wind turbine generator collection ranging between 33 to 66 kV and the transmitted power at higher voltages between 132 to 275 kV to shore-based National Grid connections. In recent years the UK has also adopted the European solution of direct current transmission with an alternating current collection grid. The extremely high cost of direct current is due to high-voltage direct current converter stations onshore and offshore to interface alternating current of wind turbine collection and grid transmission.

The sizing of an offshore substation depends on the size of the wind farm and the costs associated with the transmission of the electrical power. The rating of an offshore substation design for the Pembroke Demonstration Project is a 1 GW platform capable of connecting projects of cumulative power up to that rating. In this report copper material for cable cores is considered for the 4 GW extrapolation, using the cross-section area of high-voltage cable from 100 to 400 kV, after working out the relevant total current carrying capacity from offshore wind farms to grid connections. Detailed schematics are created to demonstrate the extrapolation to an initial 4 GW from the Celtic Sea. The idea is to build schematic diagrams showing how the maximum current carrying capacity (in amperes) of four 1 GW offshore substations is connected to the shore substations.

Considering the design concepts for floating offshore substations, the suggestion is forwarded to follow similar concepts adopted by floating offshore wind turbines from previous research. These concepts take the form of semi-submersible, spar, tension leg platform, and barge as substructure designs. By incorporating extrapolation and modelling into this report, advantages and disadvantages have been identified regarding the metocean sensitivity to harsh sea state conditions, concepts, and metacentric height boundaries of the platforms. The preferred substructure for floating offshore wind turbines is semi-submersibles and may also be considered for floating offshore substations in the near future. The reason being that semi-submersibles can be deployed in a wide range of water depths suitable for floating offshore winds and has proven to be the best choice for stability.

1 INTRODUCTION

1.1 Background

Electrical energy infrastructures are increasingly being established and discussed for future offshore wind farms (OWF). Moving operations further away from the coast results in both logistics and operations becoming more complex and challenging due to scale, especially for floating offshore wind farms (FOW). Marine infrastructure development and operation exert enormous environmental pressure on the ocean and threaten marine ecosystems. Hence the thinking around multipurpose offshore connectors could be a suitable solution to these issues, as continued demands in offshore renewable energy (ORE) grow. In a single multipurpose unit, the integration of various user functions would be addressed [1]. A significant benefit to a shared infrastructure is the reduction of the carbon output (identified as energy transfer, moorings, material resource, maintenance etc.) for a more robust and sustainable electrical infrastructure. For example, when harvesting wind power, using part of the energy ashore to convert into green hydrogen.

Solutions like the next generation interconnector provides a way to share electricity between countries and devolved nations safely and reliably, with the use of a multipurpose interconnectors (MPI) [2]. Thinking about the future green energy transition, these MPIs could become offshore connection hub clusters for multipurpose connectors, reducing the need for individual offshore wind farms with numerous connections and numerous shore-landing points to a more streamlined approach. Future projects that combine interconnections and offshore wind (OW) will help to reduce the amount of electrical infrastructure developments onshore, meaning that coastal impacts on communities are kept to a minimum. If offshore platforms are to combine numerous functions and share electrical resource infrastructure, there would be significant cost reductions and performance improvements to the future of ORE. The integration of multipurpose connectors will optimise offshore spatial planning and overall footprint to the platform’s operation.

Increased anthropogenic exploitation of the ocean by predicting the expansion of offshore marine infrastructure, for example, requires the implementation of OWFs in an integrated and sustainable manner. Multipurpose platforms and MPIs can limit the impact on fragile marine ecosystems, reduce cost and lower their carbon outputs. Currently there are governance issues when combining operations from different industrial sectors slowing down implementation. It may be easier from the governance perspective to combine different FOW operations with multipurpose connectors [1].

Within this report the floating substation comparison is made to identify the best approach for future options. In addition, the bottom fixed (B-F) near shore options currently being considered for the Celtic Sea are discussed for the Pembroke Demonstration Zone (PDZ) as a multipurpose substation. Building on this criterion the benefits to multipurpose connectors for the Cornwall FLOW Accelerator (CFA) Project are discussed in more detail with possible design requirements and processes to implement the connections. Through further understanding, this report will also be used to guide the MPIs for the CFA project to the next phase in FOW commercialisation for the Celtic Sea.

1.2 Objectives of the research

With OW energy projects located in high energy but remote environments, there are installation challenges along with operation and maintenance (O&M) that make turbines difficult to administer and dependant on weather. Therefore, a viable solution is required to keep the OW installation running as a reliable ORE resource. Failures and fatigue are inevitable due to the dynamic environment, but proper planning and use of the correct multipurpose connector options will increase the solution and result in minimal delays.

This research will build on the baseline development work completed for the PDZ, which aims to be the first 1 giga-watt (GW) OWF to use multipurpose offshore substations (MOS) linked by multi-purpose interconnectors in the Celtic Sea.

This research will address:

- Investigation to multipurpose offshore substations (linked by multipurpose interconnectors) by a strategic offshore transmission network for the Celtic Sea.
- Combined development to support the first round of test and demonstration sites with a total potential capacity of 1.2 GW and the first announced 300 MW pre-commercial project.
- The next stages in the evolution of technical solutions for offshore substations / multipurpose offshore substations.
- Scenarios to extrapolate an initial deployment of 1 GW and then onto 4 GW in the Celtic Sea by the mid 2030's.
- Potential options considered for how the UK can achieve this 4 GW from floating offshore wind to the grid with focus on The Crown Estates 'refined areas of search' ambitions.

2 STRATEGIC OFFSHORE TRANSMISSION NETWORK

2.1 Technical solutions to multipurpose offshore substations

Celtic Sea Power are developing the design for a Multipurpose Offshore Substation (MOS) in the Pembrokeshire Demonstration Zone. MOS will be a shared asset for FOW projects to connect into and help reduce uncoordinated cable landfalls. The project is a response to the rapid emergence of FOW projects in the region and fast changes in the marine offshore renewables market and grid constraint in South Wales. The project is funded by the Welsh European Funding Office (WEFO) through the Swansea Bay City Deal (SBCD). The PDZ project MOS is to ensure that development activity both within and around the zone continues to strive to attract innovation, inward investment and return for its stakeholders.

2.2 Incorporation of multipurpose interconnectors

Interconnectors are high voltage cables which connect the electricity systems of neighbouring countries, in the case of the UK to mainland Europe. In comparison, MPIs could enable interconnection and OW to work together as one combined asset. Proposed projects could connect GWs of FOW farms through subsea electrical cables. The cables would travel between two different regions or two different countries whilst connecting to OWFs at sea. As shown in Figure 1, the import and export cables would connect to onshore converter stations on either end to transform high-voltage direct current (HVDC) into high-voltage alternating current (HVAC) to be fed into the transmission network of each country [2]. Instead of individual wind farms connecting one by one to shore, MPIs will allow clusters of offshore wind farms to connect as green energy hubs. As this approach reduces the electrical infrastructure needed at the point of shore grid connection, it reduces the impact to coastal communities and supports the Celtic Sea goal to reach net zero.

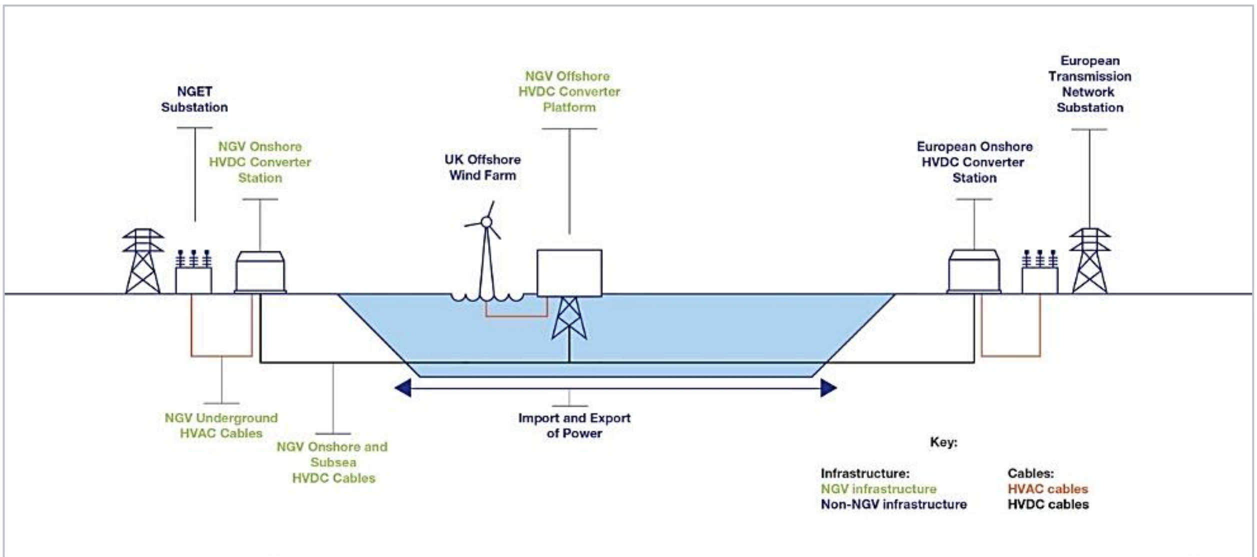

Figure 1: Multipurpose interconnector illustration linking import and export power to different geographical regions [3].

2.3 Role of offshore substations

Conventional substations (SS) are the link between power generation, transmission, and distribution to electrical energy via a point of connection. Power from each individual turbine in offshore wind is transmitted to the offshore substation (OSS). The inter-array cables from turbines range from 33 to 66 kV, but industry thinking is extending this to 132 kV in the future, connecting to the offshore substation. The primary function of the substation is to accommodate the high-voltage (HV) and medium-voltage (MV) electrical components required for transmitting the power generated from the turbines. This HV power is transmitted via offshore export cables from the substation to shore through a collector station and linked to the electrical grid by an onshore substation. In Figure 2, this is an example of a HVAC B-F wind farm transmission system [4].

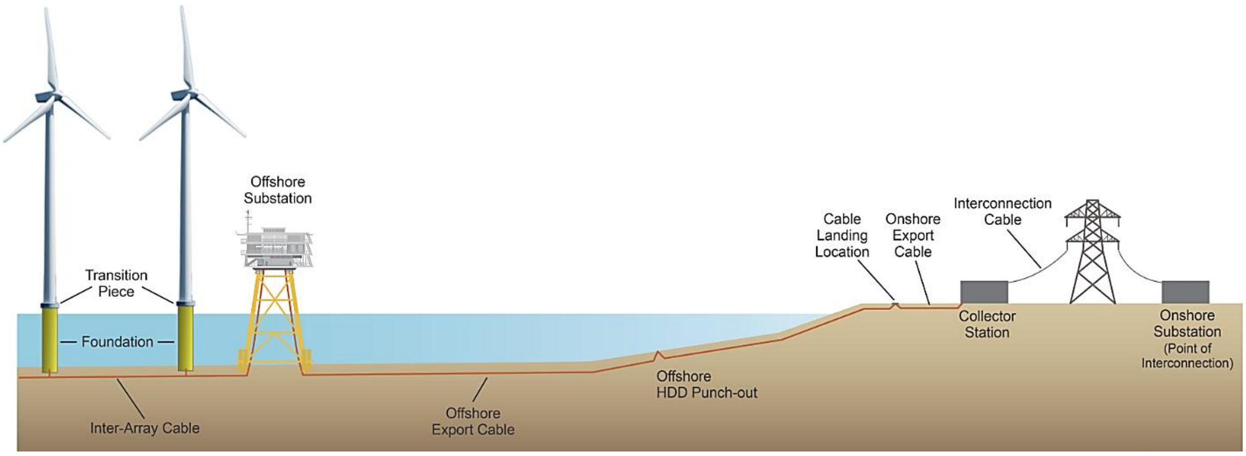

Figure 2: Typical offshore B-F wind farm system in HVAC back to shore through a point of connection to the electrical grid [4].

Reliability and redundancy considerations must take place during the electrical design of the substations. This will include electrical safety from switchgear and circuit breakers to ensure they can be disconnected when faults occur. Step up transformers will convert the cable voltage (HVAC) from 33 to 66 kV (potentially 132 kV) to 132 to 275 kV to balance safety and efficiency of the system. Safety and system efficiency are of the highest priority, and therefore controlling and monitoring equipment will be present within the substation for protection.

HVAC offshore wind farm substations are critical components at utility-scale to operate safely and efficiently, found in Figure 3. The B-F substation (either monopile or jacket foundation) sits on the top of a transition section. Designs vary in size, however, tend to be constructed into four distinct floors (decks), weighing in at a range of approximately 800 to 7,000 tonnes. These are the standard deck configurations found below (Figure 3),

- Deck (1) cable deck used for export cables (pulled-in from offshore);
- Deck (2) main deck to support MV and HV equipment for the HV transformer(s);
- Deck (3) utility deck crew quarters (day rooms) and other auxiliaries;
- Deck (4) roof deck location to main crane for lifting, communication and potential helipad.

Figure 3: Critical components for the representation of utility-scale offshore wind farms in jacket design [5].

2.4 Types of substructures to offshore substations

Support structures comprise of a typical jacket or monopile B-F OSS structure, with piled foundations, which works into the jacket design being considered for the PDZ ranging from the three scenarios (A to C), found in Figure 4. The B-F OSS platform for the PDZ range in size from 1 GW, 1.2 GW to 2.4 GW (Figure 4). Alternately, in comparison a floating OSS (FOSS) support structure will combine a floating substructure, (also known as a floater), and a station-keeping mooring and anchoring system. When considering a FOSS another major difference is the requirement and connection for dynamic inter-array and export cables. Sites like the Celtic Sea under consideration for FOSS, will also have the dynamic cables to consider both for inter-array cables from FOWTs, and export cables from FOSS. At present the maturity and technology for HV dynamic export cables is not currently commercially ready.

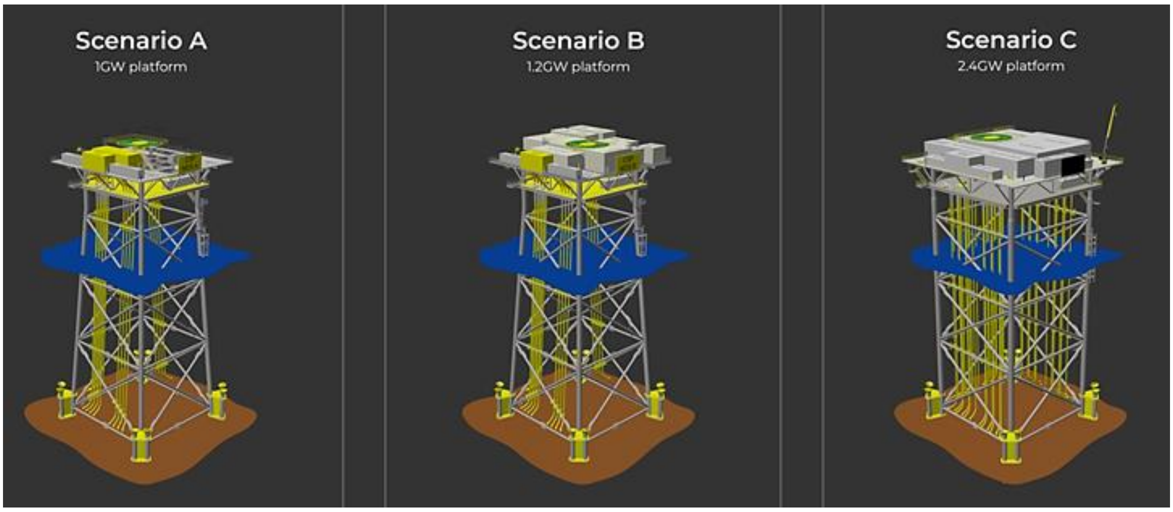

Figure 4: Technical jacket style designs, for a number of transmission solutions for the Celtic Sea, in platforms (a) 1 GW, (b) 1.2 GW and (c) 2.4 GW [6].

3 DEVELOPMENT OF AN OFFSHORE TRANSMISSION NETWORK

3.1 Electrical layout and expected components for transmission

The Celtic Sea will likely include a mixture of both HVAC and HVDC technology. Traditional transmission in the UK is HVAC, with turbine collection between 33 to 66 kV and the transmitted power at higher voltages between 132 to 275 kV (400 kV potentially) to shore. In recent years the UK have followed in Germany's footsteps with DC transmission with an AC collection grid. HVDC requires converter stations onshore and offshore to accommodate for AC turbines collection and the grid. By introducing MOS systems instead of traditional substations, as there are additional considerations to consider:

1. Higher voltage collection cables will be accumulated from wind farm step-up substations in cases where the farm is larger than one string. These may be at different voltages and must be adjusted for the designed transmission voltage levels at the MOS.
2. The transmission to shore may have more than one grid connection point with varying grid connection capacity.
3. AC-DC or DC/AC conversion may be required at different levels depending on the collection systems.
4. The MOS should be modular to allow for the addition of new systems at a later date, expansion of wind farms or for different decommissioning timescales.

3.1.1 Traditional AC collector substations

The main purpose of AC collector systems is to step up the voltage of the collector system for transmission from the turbine to the grid. Each individual farm layout depends on the operating conditions, substation requirements, grid connection requirements and the wind farm capacity. Most OW platforms (both AC and DC) will also require accommodation, control rooms, working spaces for personnel, and safety aspects (for navigation, and rescue systems).

The electrical components required in an AC substation include but are not limited to:

- at least two MV/HV transformers (including a transformer for redundancy);
- auxiliary transformers for such platform required auxiliary systems like air conditioning, lighting, supervisory control and data acquisition (SCADA) and protection relays;
- appropriate switchgear for both HV and MV;
- back-up generators for potential grid loss or partial/total shutdown of turbines, with, or instead of accumulator batteries;
- HV control and protection;
- Heat and ventilation;
- AC filters to absorb high content harmonic currents to protect the grid;

- shunt reactors to absorb and compensate reactive power.

Many of these systems would also be required for a DC conversion system, as AC step up of the collector system would be required before DC conversion took place.

3.1.2 Traditional DC Conversion Platforms

As DC platforms require AC components (seen in Section 3.1.1) the component layout may require two platforms, an AC collector platform, and a platform specifically for DC conversion. In many cases however, this can be accommodated on one platform such as the 'Sofia' offshore wind farm (the 1.4 GW Dogger Bank, RWE project, in the North Sea) [7].

DC platforms also require accommodation, control rooms, working spaces for personnel, and safety aspects, similarly to AC substations.

The electrical components required in a DC conversion platform include in some cases (like 'Sofia') AC substation components, as well as the additional components listed below.

- Converter unit to convert the power system from AC to DC (convert) / DC to AC (invert), made of converter valves;
- Converter transformers are the interface between the AC and DC sides of the system, that consists of two three-phase windings; the valve windings are designed to withstand AC and DC stresses;
- DC filters preventing DC harmonics, and a smoothing reactor to reduce stresses on the valves;
- High frequency converter to filter electrical noise between the converter and AC busbar;
- DC switchgear and transducers.

There are currently no OW collector designs planned using DC technology. Potentially however, depending on the distance between the farm and the MOS, DC technology may be advantageous. If this is the case, the MOS size may be significantly increased as shown in Figure 5.

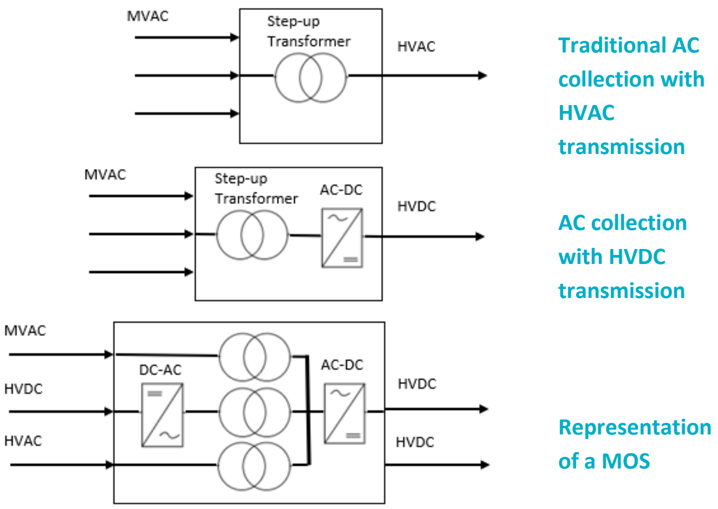

Figure 5: Size comparison of an OSS/MOS and traditional systems.

4 OFFSHORE SUBSTATION CHALLENGES TO COMMERCIAL SCALE

4.1.1 Bottom-Fixed (Jacket) substation technologies

As previously discussed, the majority of wind farm HVAC OSS structures are jacket designs which have been deployed to date (similar to those used for support of B-F wind turbines). Wind farm capacity for these types of OSS ranges from just a small 60 MW up to larger 1.2 GW designs, with larger wind farms having multiple OSSs. These jacket substructures range in weight from 500 to 7,000 tonnes from small to very large OSSs (greater than 1 GW in capacity).

4.1.2 Floating substations challenge to commercial scale floating windfarms

As FOW farms develop to commercial scale, it is extremely important that floating substations are considered as fundamental electrical structures [8]. The OSS will link the inter-array cables from FOWT and the export cable to the onshore substation and grid connection (Figure 6). Government policy helps to steer the FOW agenda because it can access the 80% of ORE generation potential that is in water depths exceeding 60 meters. As FOW transitions to a commercial scale, the project will require voltage increase or power conversion before connecting to the grid, therefore an OSS will be required to host the step up transformers and conversion equipment necessary to export HV power back to shore [8].

As FOW exceeds water depths of 60 m, conventional B-F turbines (with monopile and jacket foundations) would not be economically viable. However, B-F OSS have a critical depth of approximately 100 m and therefore may still be viable for some FOW projects. As the development grows in the Celtic Sea for FOW farms, the tall jacket foundations of B-F substations could limit the risk and inherent costs associated to HV dynamic cables. But in water depths greater than 100 m for OW, B-F substations are just not possible options.

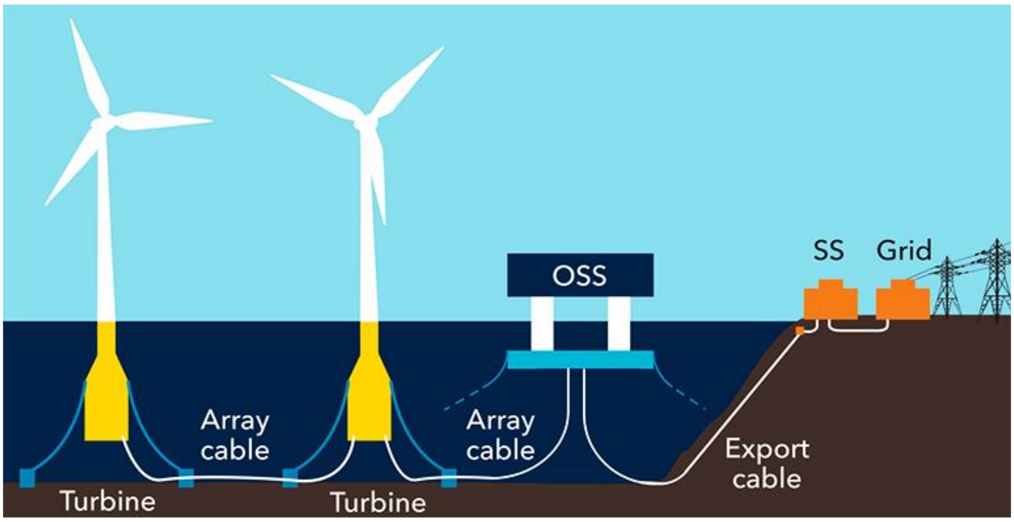

Figure 6: Fundamental components of an electrical infrastructure to a floating offshore wind farm [8].

4.1.3 Design and installation complexity to floating offshore substations

When moving into deeper water, it increases the size and cost to substructures like jacket style platforms. FOSS are technically feasible and to be deployed in water depths greater than 50 to 60 m. Being aware that the average depth of the Celtic Sea is between 90 and 100 m (300 – 330 ft) which is likely that the first FOW farms will be installed at these depths [9]. The water depth will however vary across OW farms, often shallow locations will be identified for OSS installations as the best options. The same approach can be done for the PDZ B-F OSS, for FOW farms that are located at shallower depths making the installation more technically feasible and lowering the costs.

Another design influence on both B-F and floating substructures are the metocean conditions from waves and currents in terms of hydrodynamics and fatigue loading. Since the wave conditions affect the air gap topside to the OSS as a required height above mean sea level (AMSL), it should be designed to avoid the platform from experiencing any overturning forces. As higher electrical current demand will be inevitable as FOSS grows larger, increasing the weight and size of cables needed for the design, putting more strain on the substructure. More cost and complexity also come from electrical equipment needed in FOSS and expensive additional protection to suit redundancy required.

As FOSS will be installed in much higher wind speeds, it is likely to require a stronger substructure due to increased overturning moments as the Celtic Sea has a mean yearly wind speed of ~9 m/s at 100 m AMSL [10]. Anchoring and mooring is outside the scope of this report, however, geotechnical conditions will impact the foundations to FOSS (and that conventional piled anchors will be preferred). Much of the seabed around the UK and the Celtic Sea is no exception, as sand or mud, but there are also a number of potential FOSS locations with coarse substrate seabed to consider.

The weight of the power cables can have some impact, which will all be driven by the OWFs configuration and cable mass as the dynamic cables could potentially clash with the mooring systems to FOSS having disastrous consequences. Typically, a FOSS will be connected via 5 to 10 strings through dynamic array cables in addition to much larger and heavier HV export cables (preferably through subsea junction boxes). All dynamic cables below the FOSS will require sufficient space to move below the floating substructure to avoid underwater damage.

4.1.4 Different floating substation design concepts

In this report the focus will be around MOS, therefore both reference to OSS and MOS will be used throughout this report. The reason behind this will align with the PDZ project currently underway in the Celtic Sea driven by the Cornwall FLOW Accelerator Project, led by Celtic Sea Power Ltd, a 100% subsidiary of Cornwall Council. Funded by the Welsh European Funding Office and the Swansea Bay City Deal, and the development of PDZ is part of the Pembroke Dock Marine programme as discussed.

When considering the design concepts for FOSS/MOS the suggestion is to follow similar concepts adopted by FOWTs. These are, for example, semi-submersible, spar, tension leg platform (TLP), and barge as substructure designs, as shown in Figure 7. This approach isn't to exclude fixed substation but to bring in the thinking around what FOW electrical infrastructures would need to consider. The semi-submersible, spar, and barge are platform designs that use catenary mooring lines, moored to the seabed by chains, steel cables, or fibre ropes connected to anchors. The TLP concept has vertical tension mooring lines with tethers, linking the TLP to the seabed anchoring. Depending on the type of mooring system, soil condition, and expected environmental loading, all floating substation foundations can be used with different anchor types.

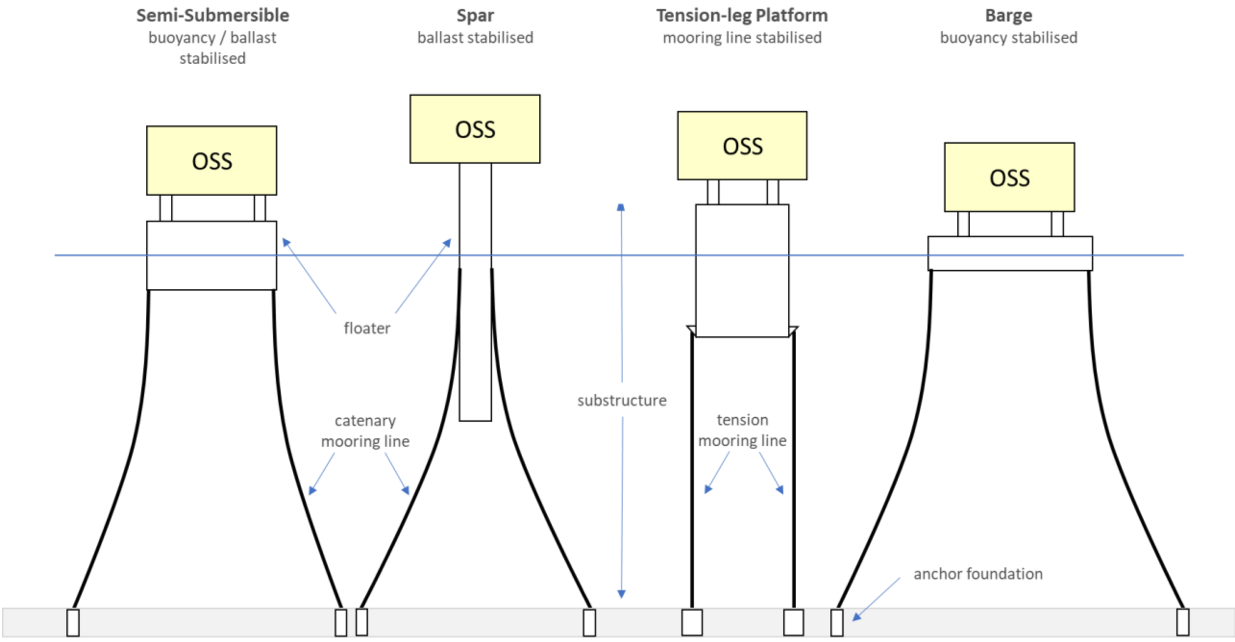

Figure 7: Different concepts of floating multipurpose substations; semi-submersible; spar; tension-leg platform; barge [8].

It may be seen as advantageous to take the synergies in design, construction, installation and O&M, between MOS and FOW. MOS as mentioned before, can be considered in both fixed and floating, as there are similarities between floating OSS and MOS, or between floating turbine structures and floating MOS. Firstly, the weight of a HVAC MOS is approximately 2,000 to 4,500 metric tonnes (MT) so are substantially top-heavy structures. HVDC substations in comparison are much heavier due to the required conversion equipment. The overall weight distribution and centre of gravity (CoG) are noticeably different in comparison to FOWTs. Secondly, the MOS could have a large number of subsea cable connections, some array configurations have in excess of 10 strings and one export cable linking the substation. It is this configuration sensitivity that can be single point of failure both in cable connections and moorings that would require redundancy options to be in place. There are concerns of having too many dynamic cables connecting to the substation that can inflict damage to each other, by each dynamic cable hitting off the other. To mitigate this the configurations must sit at different heights in the water, therefore by increasing the mechanical protection when approaching the floating OSS this could support the redundancy.

The 66 kV ‘Fukushima Kizuna’ demonstration project, a 25 MVA substation, shown in Figure 8 demonstrates the current state-of-the-art for floating substations which was designed in 2012 [11]. The substation substructure was an advanced spar. An advanced spar has a shorter draft than a conventional spar using subsea sections as well as a larger cross-sectional area allowing for better stability by dropping the centre of gravity [11]. The bottom hull can be towed in the upright position as it is filled with concrete, to once again lower the centre of gravity, and motion by wave energy has been reduced through the demonstrator’s unique shape of the hull (cob, middle, and lower hull). The substation had to overcome many challenges using an integrated grid system, and by using waterproof risers with larger capacities to reduce cable fatigue. In addition, implementation of an advanced technology for floating offshore transformer systems had to be designed for protection against severe metocean conditions (using inclination and vibration testing for validation). The "Fukushima Kizuna" demonstration project prior to decommissioning used three turbines to demonstrate the operation of the entire system.

Figure 8: The 'Fukushima Kizuma' floating offshore demonstration substation project, rated at 25 MVA, (left) FOSS being towed out to site [11].

4.2 Future innovation and proven substation technologies

With deep water MOS the dynamic movements even under the TLP rigid configurations, all floating platforms inevitably will move. Proven technology and lessons learned from the O&G sector have provided risk management for FOW. However, HV subsea (dynamic cables and connections) equipment will require substantial R&D to be deployed as OW and multipurpose floating structures develop. All HV export cables for B-F OSSs are 'static' design but floating MOSs export and collection cables will need to be dynamic in operation. The displacement and lifetime (greater than 25 years) cyclic movements require OSSs to endure extreme storms with sufficient fatigue tolerance over the life cycle.

More research is required to investigate HV equipment, namely the main power transformer and the high voltage gas-insulated switchgear (HV GIS) on floating MOSs. The investigation should include a study of their movements and equipment vibration, with special focus on potential oil spilling from the transformer's compensator tank, or gas loss from deteriorated seals of the HV GIS. Current cable manufacturers also face a primary issue to the lead sheath protecting cable core from moisture ingress, and poor fatigue endurance. This will require further research to establish suitable alternatives to dynamic cables within FOW. Another factor manufacturers need to consider for dynamic cables connecting FOWTs to a floating MOS is the loss of bending stiffness over the cable lifetime, due to the use of bitumen between armour layers and sheaths which become dislodged and more unstable when subject to dynamic motion. The bitumen is solid when the cable is manufactured and installed, so bending stiffness is high. But after repeated bending, it breaks apart and dislodges the armour wires from each other, decreasing the stiffness and increasing slippage between component layers.

5 EXTRAPOLATION OF AN INITIAL 4 GW DEPLOYMENT IN THE CELTIC SEA

The Celtic Sea has potential to generate multi giga-watts of energy from floating offshore wind by the mid-2030s with only about 1 GW collectively planned for operation. To meet the 4 GW, targets the Celtic Sea must have planned for the accommodation of the electrical infrastructure and the additional power to be exported for onshore regions or neighbouring countries. Remembering that the collection platform will still be used at each wind farm, and the platform connection cables required will resemble short export cables. A generalisation to a typical infrastructure would be wind turbine generator (WTG), inter-array cables (IAC), collection platform, OSS (potentially MOS), and onshore grid connection. All the IACs are not able to come to one central OSS (MOS) since there would be too many cables to deploy. The inclusion of an OSS (MOS) provides a modular aspect to the electrical infrastructure. Therefore, it provides an opportunity for further systems to be added or removed while limited in the interaction with onshore gid as seen in Figure 9, detailed as a schematic example of an OSS (MOS) electrical infrastructure.

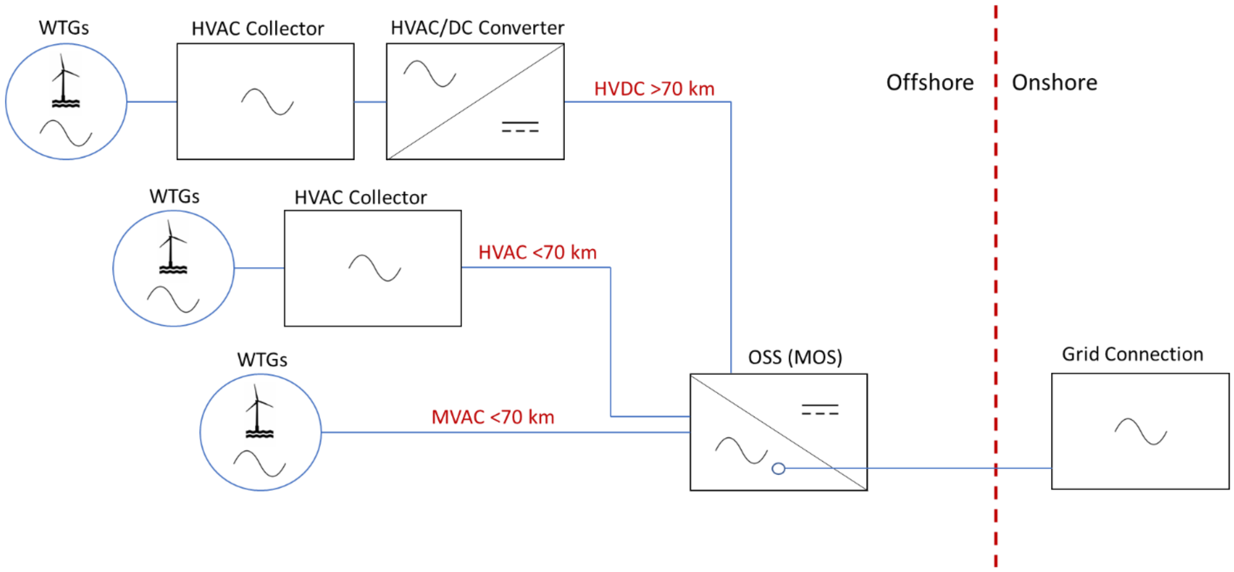

Figure 9: Schematic example of an OSS (MOS) electrical infrastructure design.

The logistics behind such multipurpose substations require collaboration between project stakeholders, owners and partner companies. One possible solution is for the owner of the OSS (MOS) to essentially "rent" connections to wind farm projects, which will be more economical for both parties than developing their own substations and long-distance export cables. OWFs with several strings of WTGs still require a collector system with its own OSS. But instead of directly connecting this OSS to the onshore grid via a long export cable, it could connect to a MOS with single OWF cable connection. It provides a possible way to connect all IACs to one central OSS (MOS).

5.1 Current projects in the Celtic Sea

The current projects in the Celtic Sea are Erebus, Valorous, Whitecross and the Pembrokeshire Demonstration Zone as offshore wind farms with capacities ranging respectively, as 96 MW, 300 MW, 100 MW and 90 MW (with the vision for the PDZ to be 1 GW). The Erebus wind farm is connected directly to shore via a single export cable of length 49 km [12], with no need for an offshore substation due to the wind farm comprising of just ten WTGs and shortest distance to shore of 35 km. Due to the number and size of WTGs used in the Valorous 300 MW project, an offshore substation is required which will be either fixed or floating, however dynamic cables with voltage ratings above 66 kV need to be developed and commercially viable for large OWF string capacity to connect to an OSS. This offshore substation will have two HVAC export cables between 220 kV and 275 kV [13]. The Whitecross wind farm is a 100 MW floating wind farm approximately 50 km off the Cornwall/Devon coast consisting of eight WTGs.

The total capacity deployed in the Celtic Sea would be 496 MW (all depending on the PDZ commercial scale) from the above-mentioned projects, with each wind farm connected to shore separately. If these wind farms were connected to a single offshore multipurpose substation the export cables and substation costs already installed could have been greatly reduced. Therefore, it is a real positive consideration for the future of the Celtic Sea.

5.2 Sizing a scenario of numerous multipurpose offshore substations

The sizing of an offshore substation depends on the size of the wind farm and the costs associated with the transmission of the electrical power. The rating of an OSS (MOS) design for the PDZ is a 1 GW platform capable of connecting projects of cumulative power up to that rating.

Therefore, to explain this in more detail in an example based scenario, is outlined below for the 1 GW connections. If we consider three OWFs all using 15 MW WTGs, farm 1 at 300 MW (15 MW x 20 WTG's), farm 2 at 225 MW (15 MW x 15 WTG's), and farm 3 at 375 MW (15 MW x 25 WTG's) as shown in Figure 10, and tabulated in Table 2 for simplicity. Having a cumulative power capacity of 0.9 GW (900 MW), and are all 5 by WTGs in a single string for easy cross referencing within the model.

For this OWF at 900 MW example, the wind turbines are rated at 15 MW per turbine with a minimum operating voltage, $U_{op,min}$ of 0.95 per unit voltage*, puV*, and a power factor, *pf* of 0.95. As the cables are 3-phase AC, the power correction of each turbine is calculated by the following *Equations 1 to 3*. To work out the apparent power S_n using the rated turbine power P_n *use Equation 1.* To calculate the corrected voltage use the *puV* from *Equation 2*, and to determine the rated current flowing in the cable I_n, for each turbine without any de-rating factors in the wind farm string, use *Equation 3*.

$$S_n = \frac{P_n}{pf} \quad \textit{Equation 1}$$

$$U_{correct} = U_{op,min} \cdot U \quad \textit{Equation 2}$$

$$I_n = \frac{P_n}{\sqrt{3} \cdot U_{correct} \cdot pf} \quad \textit{Equation 3}$$

A few assumptions are made for all calculation, that the collector cables from each turbine are rated at a maximum capacity of 132 kV each. From manufacture specifications and industry practice, which stipulates that a string of wind turbines using 132 kV cables it is limited to 160 MW [14]. In addition, the de-rating factors are incorporated by means of the following criteria, with a maximum cable operating temperature at 90°C. These are, the maximum seabed temperature at 20°C (rating factor equal to 1.0), laying depth in seabed is 1.0 m (rating factor equal to 1.0), seabed thermal resistivity is 1.0 K.m/W (rating factor equal to 1.0). Using this criteria, the final equivalent current carrying capacity (A) and CSA (mm^2) can be determined [15]. So, in this calculation the de-rating factors will not influence the rated current, I_n flowing in the cable for simplicity.

The details listed above are used for the rated current calculation as follows,

$$S_n = \frac{P_n}{pf} = \frac{15MW}{0.95} = 15.8\ MVA$$

$$U_{correct} = U_{op,min} \cdot U = (0.95)(132kV) = 125\ kV$$

$$I_n = \frac{P_n}{\sqrt{3} \cdot U_{correct} \cdot pf} = \frac{15MW}{(1.732 \cdot 125.4kV \cdot 0.95)} = 73\ A \textit{ (Current per turbine)}$$

Therefore, each turbine of rated power 15 MW with a corrected operational voltage and rated current flow of 125 kV and 73 A respectively. This means that each turbine in a daisy chain string contributes up to 73 A of current into the subsequent turbine. Which contributes another 73 A for each turbine until the end of the chain is reached connecting to a subsea junction box, then on to the substation.

Therefore, the following,

- Offshore substation-1: The cumulative current entering OSS (1) from their respective wind farms are calculated in power and current for farm 1 at 225 MW (73 A x 15 WTGs) equals 1,095 A; farm 2 at 300 MW (73 A x 20 WTGs) equals 1,460 A, farm 3 at 375 MW (73 A x 25 WTGs) equals 1,825 A as shown in Table 2.

The next step, is the sizing of a transformer to step up the voltage of the incoming energy and to reduce the current, due to the relationship of current being inversely proportional to voltage. This relationship can then be calculated by using *Equation 4* as follows,

$$\frac{U_p}{U_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s} \qquad \textit{Equation 4}$$

Where *U* is the voltage, *I* is the current, *N* is the number of coil turns in the transformer (*N* is not being used in this report), and subscripts *p* and *s* denote 'primary' and 'secondary' respectively. Part 1 of these calculations assumes an export cable rating of 275 kV; transmitting the electricity from the OSS to the MOS. Therefore the calculation would be as follows, firstly for OSS-1 then onto OSSs-2-4 towards the extrapolation of the 4 GW,

OSS-1 @ 900 MW: Part 1 (OWF to OSS) to determine the secondary current I_s (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{225\ MW} = \left(\frac{I_s}{I_p}\right)_{225\ MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{1095}\right) \rightarrow I_{s,225\ MW} = 526\ A$$

$$\left(\frac{U_p}{U_s}\right)_{300\ MW} = \left(\frac{I_s}{I_p}\right)_{300\ MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{1460}\right) \rightarrow I_{s,300\ MW} = 701\ A$$

$$\left(\frac{U_p}{U_s}\right)_{375\ MW} = \left(\frac{I_s}{I_p}\right)_{375\ MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{1825}\right) \rightarrow I_{s,375\ MW} = 876\ A$$

Part 2 of this calculation assumes an export cable rating of 400 kV transmitting the electricity from the MOS to an onshore substation, therefore the calculation is as follows, OSS-1 @ 900 MW: Part 2 (OSS to MOS) to determine the secondary current I_s (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{225\,MW} = \left(\frac{I_s}{I_p}\right)_{225\,MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{526}\right) \rightarrow I_{s,225\,MW} = 361\,A$$

$$\left(\frac{U_p}{U_s}\right)_{300\,MW} = \left(\frac{I_s}{I_p}\right)_{300\,MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{701}\right) \rightarrow I_{s,300\,MW} = 482\,A$$

$$\left(\frac{U_p}{U_s}\right)_{375\,MW} = \left(\frac{I_s}{I_p}\right)_{375\,MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{876}\right) \rightarrow I_{s,375\,MW} = 602\,A$$

Finally, the total secondary current for a 400 kV export cable back to the onshore grid connection, show clearly in the relationship between voltage and current - indicating that the voltage is increasing and the current is decreasing, as follows,

$$OSS(1)\ I_{s,total} = I_{s,225\,MW} + I_{s,300\,MW} + I_{s,375\,MW} = 361 + 482 + 602 = 1{,}445\,A$$

The export cable from the MOS to the onshore substation rated at 400 kV, therefore requires to carry a current of 1,445 A and 0.9 GW (900 MW) of power. This can of course be shared if more than one export cable is used and/or connected to different regions around the Celtic Sea. However, using lower capacity cables means if a region requires more energy it can only be supplied with the cable power rating installed (with no possibility of expansion and redundancy pathways not possible).

The following calculations will address the remaining three OSSs (2, 3, and 4), tabulated in Table 2, for the total secondary current of 400 kV export cable back to the onshore grid connection for each OSS.

- Offshore substation 2: The cumulative current entering OSS (2) from their respective wind farms are calculated in in power and current for farm 4 at 495 MW (73 A x 33 WTGs) equals 2,409 A, farm 5 at 495 MW (73 A x 33 WTG's) equals 2,409 A, as shown in Table 2.

OSS-2 @ 990 MW: Part 1 (OWF to OSS) to determine the secondary current I_s, (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{495\,MW} = \left(\frac{I_s}{I_p}\right)_{495\,MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{2409}\right) \rightarrow I_{s,495\,MW} = 1{,}156\,A$$

$$\left(\frac{U_p}{U_s}\right)_{495\,MW} = \left(\frac{I_s}{I_p}\right)_{495\,MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{2409}\right) \rightarrow I_{s,495\,MW} = 1{,}156\,A$$

OSS-2 @ 990 MW: Part 2 (OSS to MOS) to determine the secondary current I_s, (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{495\,MW} = \left(\frac{I_s}{I_p}\right)_{495\,MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{1156}\right) \rightarrow I_{s,495\,MW} = 795\,A$$

$$\left(\frac{U_p}{U_s}\right)_{495\,MW} = \left(\frac{I_s}{I_p}\right)_{495\,MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{1156}\right) \rightarrow I_{s,495\,MW} = 795\,A$$

Finally, the total secondary current for a 400 kV export cable back to the onshore grid connection, with the clear indication of the voltage increasing and the current decreasing, is as follows,

$$OSS(2)\ I_{s,total} = I_{s,495\ MW} + I_{s,495\ MW} = 795 + \ 795 = 1{,}590\ A$$

- Offshore substation 3: The cumulative current entering OSS (3) from their respective wind farm are calculated in in power and current for farm 6 at 900 MW (73 A x 60 WTGs) equals 4,380 A, as shown in Table 2.

OSS-3 @ 900 MW: Part 1 (OWF to OSS) to determine the secondary current I_s (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{900\ MW} = \left(\frac{I_s}{I_p}\right)_{900\ MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{4380}\right) \rightarrow I_{s,900\ MW} = 2{,}102\ A$$

OSS-3 @ 900 MW: Part 2 (OSS to MOS) to determine the secondary current I_s (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{900\ MW} = \left(\frac{I_s}{I_p}\right)_{900\ MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{2102}\right) \rightarrow I_{s,900\ MW} = 1{,}445\ A$$

Finally, the total secondary current for a 400 kV export cable back to the onshore grid connection, with the clear indication of the voltage increasing and the current decreasing, is as follows,

$$OSS(3)\ I_{s,total} = I_{s,900\ MW} = 1{,}445\ A$$

- Offshore substation 4: The cumulative current entering OSS (4) from their respective wind farm are calculated in power and current for farm 7 at 990 MW (73 A x 66 WTGs) equals 4,818 A, as shown in Table 2.

OSS-4 @ 990 MW: Part 1 (OWF to OSS) to determine the secondary current I_s (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{990\ MW} = \left(\frac{I_s}{I_p}\right)_{990\ MW} \rightarrow \left(\frac{132}{275}\right) = \left(\frac{I_s}{4818}\right) \rightarrow I_{s,990\ MW} = 2{,}313\ A$$

OSS-4 @ 990 MW: Part 2 (OSS to MOS) to determine the secondary current I_s (Table 2),

$$\left(\frac{U_p}{U_s}\right)_{990\ MW} = \left(\frac{I_s}{I_p}\right)_{990\ MW} \rightarrow \left(\frac{275}{400}\right) = \left(\frac{I_s}{2313}\right) \rightarrow I_{s,990\ MW} = 1{,}590\ A$$

Finally, the total secondary current for a 400 kV export cable back to the onshore grid connection, with the clear indication of the voltage increasing and the current decreasing, is as follows,

$$OSS(4)\ I_{s,total} = I_{s,900\ MW} = 1{,}590\ A$$

The cross-section area (CSA) for 100 to 300 kV are shown in Table 1, for static cable cores, however there is negligible difference when looking at dynamic core design.

In this report copper material was used for the cable cores to shape the scenario based example whilst considering the 4 GW extrapolation. Cross-linked polyethylene cable (XLPE) was also considered as the most widely used cable type as electrical insulation in power cables. Used at medium to high and extra-high voltage power cables with the maximum operating temperature of 90°C. Table 1 [15] was used for HVAC 3-core copper power cables to source the current carrying capacity to the specified CSA and used to create the specifications, found in Table 2.

Table 1: Cable sizes and ratings for Copper (Cu); with cable current carrying capacity for XLPE subsea cable systems [15].

Cross Section (mm^2)	100 - 300 kV XLPE 3-core cables
	Copper (Cu)
	A
300	530
400	590
500	665
630	715
800	775
1000	825

Table 2: Tabulated transmission calculations for sizing a 4 GW extrapolation scenario in the Celtic Sea for multipurpose offshore substations in perspective to voltage and current and size of subsea high-voltage cables.

OW farm MW & farm number	WTG rated power (MW)	Voltage (kV) WTG to OSS	Total number of wind turbines	Rated cable current per turbine	Total current carrying capacity (A) @ OSS	Step-up voltage (kV) OSS	Largest cable CSA (mm^2) from Table 2	Step-up voltage with reduced current (A) OSS	Step-up voltage (kV) OSS	Step-up voltage with reduced current (A) OSS	Total current carrying capacity (A) @ MOS to shore
Transmission OWF to OSS (Total extrapolation capacity 4 GW)						OSS to MOS (cables 275 kV)			MOS to Shore (cables 400 kV)		
Offshore substation 1 @ 1 GW potential capacity (actual loading 900 MW)											
225 (1)	15	132	15	73	1,095	275	300	526	400	361	
300 (2)	15	132	20	73	1,460	275	630	701	400	482	1,445
375 (3)	15	132	25	73	1,825	275	2x300	876	400	602	
Offshore substation 2 @ 1 GW potential capacity (actual loading 990 MW)											
495 (4)	15	132	33	73	2,409	275	2x400	1,156	400	795	1,590
495 (5)	15	132	33	73	2,409	275	2x400	1,156	400	795	
Offshore substation 3 @ 1 GW potential capacity (actual loading 900 MW)											
900 (6)	15	132	60	73	4,380	275	3x630	2,102	400	1,445	1,445
Offshore substation 4 @ 1 GW potential capacity (actual loading 990 MW)											
990 (7)	15	132	66	73	4,818	275	3x800	2,313	400	1,590	1,590

Rated factors used in calculations for XLPE Copper cables are:

Minimum operating voltage 0.95**;** 3-phase AC core with power factor 0.95**;**

De-rating factors (for operating temperature @ 90 °C; maximum seabed temperature 20 °C; laying depth in seabed 1.0 m; seabed thermal resistivity 1.0 K.m/W)

5.3 Schematics to illustrate scenarios based on calculations for multipurpose offshore substations

After working out the relevant total current carrying capacity from OWFs to OSS, to OSS/MOS, and finally to a shore based connection. The following schematics demonstrate the extrapolation to 4 GW's as seen in Figure 10 to 13, and calculations from Table 2. As seen, based on the calculations from section 5.2, and assuming all cables are in HVAC, ranging from 132, 275, and 400 kV. The idea was to build a schematic representation of how current carrying capacity (that is measured in amperes), for four 1 GW maximum capacity OWFs would connect to the shore side substation. The electrical power is produced from the seven OWFs (namely, 1-7) in MW's, as calculated previously from the scenario based example, as follows.

(1) In offshore substation-1 this is based on three rated power OWF's (i.e., farm-1 @ 225 MW, farm-2 @ 300 MW, and farm-3 @ 375 MW) connected to a central OSS/MOS-1 and export cables with an actual load of 900 MW, and maximum capacity of 1 GW (Table 2).

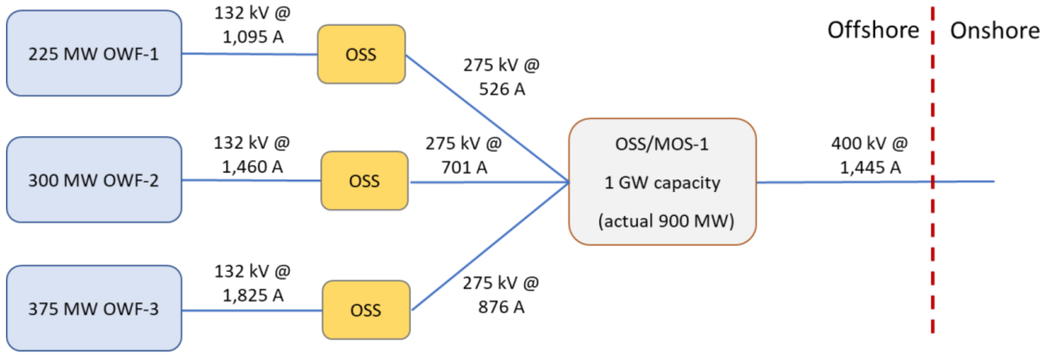

Figure 10: Transmission schematic of three rated offshore wind farms connected to a central MOS and grid implemented export cable.

(2) In offshore substation-2 this is based on two rated power OWFs (i.e., farm-4 @ 495 MW, and farm-5 @ 495 MW) connected to a central OSS/MOS-2 and export cables with an actual load of 990 MW, and maximum capacity of 1 GW (Table 2).

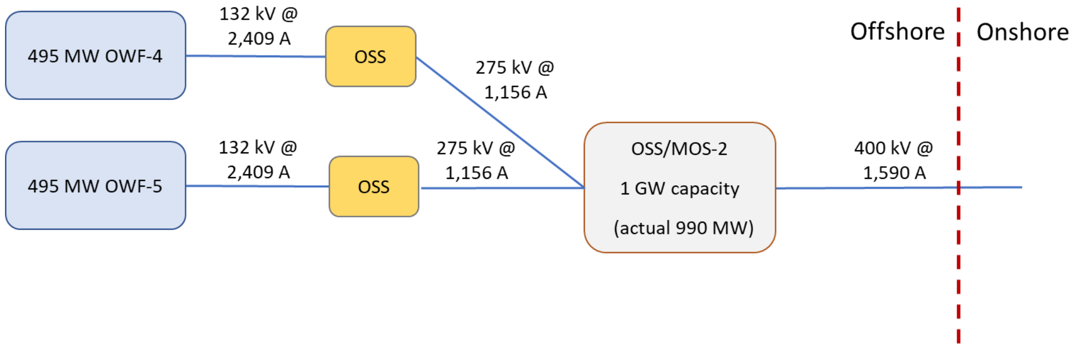

Figure 11: Transmission schematic of two rated offshore wind farms connected to a central MOS and grid implemented export cable.

(3) In offshore substation-3 this is based on one rated power OWF (i.e., farm-6 @ 900 MW) connected to a central OSS/MOS-3 and export cables with an actual load of 900 MW, and maximum capacity of 1 GW (Table 2).

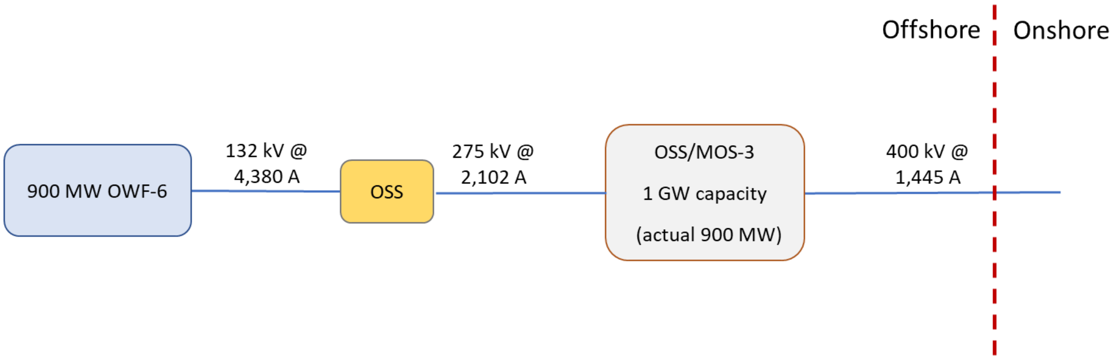

Figure 12: Transmission schematic of one rated offshore wind farm connected to a central MOS and grid implemented export cable.

(4) In offshore substation-4 this is based on one rated power OWF (i.e., farm-7 @ 990 MW) connected to a central OSS/MOS-4 and export cables with an actual load of 990 MW, and maximum capacity of 1 GW (Table 2).

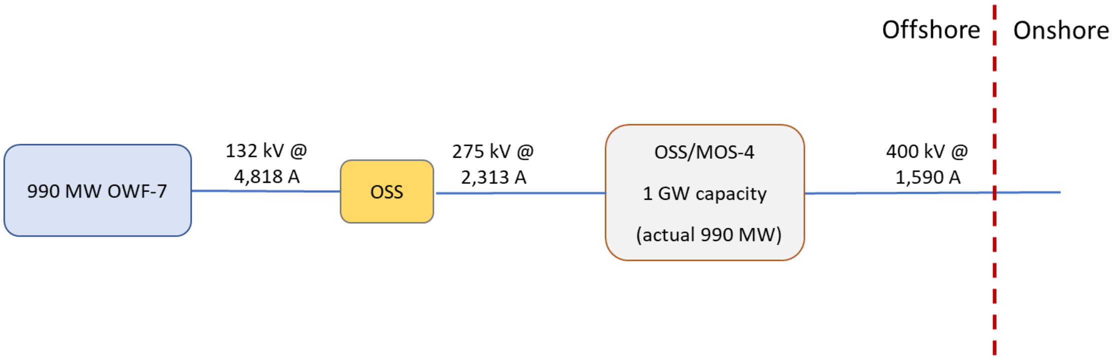

Figure 13: Transmission schematic of one rated offshore wind farms connected to a central MOS and grid implemented export cable.

Therefore, in summary by incorporating various OWFs into the four OSS/MOS for the initial extrapolation of 4 GW into the Celtic Sea seen from the schematic layouts provided. There are many challenges in HVAC versus HVDC, such as CSAs to export cables, volage level to select according to the current carrying capacity for OSSs, and maximum distances where FOWs can be deployed offshore. In addition, the total secondary current for a 400 kV export cable back to the onshore grid connection can be seen for OSS (MOS) 1 to 4, with a clear indication of the voltage increasing and the current decreasing throughout the system summarised in Table 3.

Table 3: Summary to OSS (MOS) 1 to 4, final current carrying capacity, OWF's and cable voltage comparisons.

Offshore Substations	OSS/MOS Power Capacity (GW)	XLPE HVAC 3-core export cable (kV)	OWF's per OSS	OWF/OSS Actual power loading (MW)	Total current carrying capacity from OSS/MOS to shore (A)
OSS (MOS) - 1	1	400	3	900	1,445
OSS (MOS) - 2	1	400	2	990	1,590
OSS (MOS) - 3	1	400	1	900	1,445
OSS (MOS) - 4	1	400	1	990	1,590
Total System	4	400	7	3,780	6,070

6 MODELLING FLOATING OFFSHORE SUBSTATIONS

From previous discussions, when considering the design concepts for FOSS, the suggestion is to follow similar concepts adopted by FOWT's. This section will compare semi-submersible, spar, tension leg platform (TLP), and barge as substructure designs. There is a reduced steel weight in the TLP design compared to the other three concepts mentioned. It has been found that semi-submersibles can be deployed in a wide range of water depths. The downside is cost as a semi-submersible substructure can incur very high costs due to their construction because of large amounts of steel needed.

6.1 Floating offshore substation stability

For most floating structures, there are defined terms that must be considered, namely, the centre of gravity (CoG) and the centre of buoyancy (CoB). A FOSS is acted upon by two forces, a vertical downward force of gravity that is equivalent to the weight of the body (W) as seen in Figure 14, acting on the CoG, and an upward vertical buoyancy force (F_B) on the CoB. Therefore, the FOSS is required to be in equilibrium as seen in Figure 14 (left) where the F_B should be equal to the weight of the FOSS ($W = F_B$). In this state the CoG and the CoB should lie on the same vertical centre line (dotted blue). Providing the load of the FOSS remains stable, CoG is fixed.

If the FOSS undergoes an angular displacement, seen in Figure 14 (right), the resultant volume displaced is larger towards the right side. Therefore, the CoB shifts towards the right from CoB to CoB' dash (forming a couple trying to rotate the platform). Creating the new metacentre (M), which is the point of intersection of the vertical centre line (dotted blue), through the new CoB' dash vertical line (dotted red) and a new F_B is formed. Forming the metacentric height (GM) is an approximation of the stability to a floating structure (best at a small angle from 0 – 15 degrees of heel). The GM is the distance (in metres) by which the metacentre lies above the CoG of a floating body. It must be noted that there are environmental factors beyond this report that will not be considered for simplicity, and a more conservative approach has been taken. For small angles, GM can also be considered fixed, while CoB moves with FOSSs.

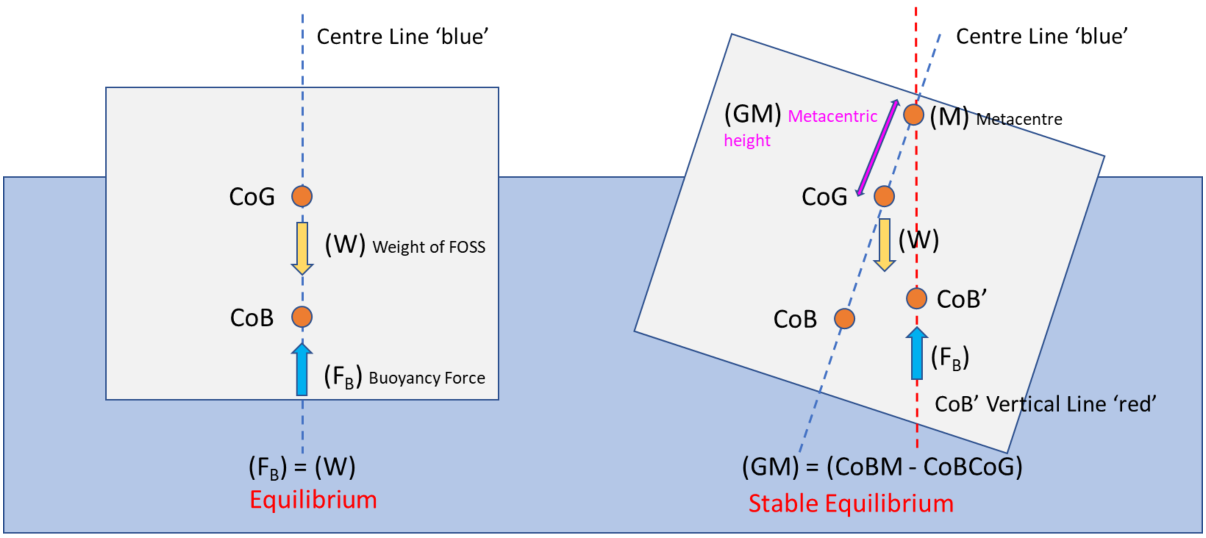

Figure 14: Metacentric height (GM) stability to a FOSS. (Left) FOSS in equilibrium; (Right) GM above CoG results in stable equilibrium of FOSS.

For example, if a spar platform undergoes a small displacement in either pitch or roll movement and M is above the CoG, a restoring couple is formed by the F_B and the weight of the body which tends to turn the platform to its original position (said to be in a stable equilibrium). In comparison, when M is below the CoG, an overturning couple is formed by the F_B and the weight of the platform, resulting in overturning (said to be in unstable equilibrium).

In 2021, ORE Catapult conducted research and published a paper into the technoeconomic analysis of both fixed and floating offshore substations [17]. From the findings the two most preferred floating structures, each having a range for GM, and topside mass values are as follows. The floating platforms were spar and semi-submersible with GM ranging from 2 – 4 metres and the mass ranging from 2,300 – 3,200 tonnes. The GM for a typical spar must be equal to or greater than 1 m [18], with the GM increasing as the draft to the platform increases. For a typical semi-submersible the GM as suggested by the Health & Safety Executive (HSE) must be at least 1 m [19], however in comparison, according to the National Maritime Institute a 2 m GM is recommended [20] to avoid steady tilt or occasional long period roll motion.

Therefore, to explain this concept further the plot representation found in Figure 15, explains what the conclusions were on which type is more stable. The plot in Figure 15 compared the substation mass (in tonnes) to the metacentric height (in meters) for substructure spar and semi-submersible designs. So, the conclusions were that for a larger metacentric height this would imply a greater initial stability against overturning. By comparing spar and semi-submersible platforms, spar platform at a higher metacentric height of 4 m is more stable at 2,300 tonnes, compared to semi-submersible one at a lower metacentric height of 3.6 m at 2,300 tonnes (less stability). There is a cross-over when semi-submersible platform becomes more stable at 3.1 m metacentric height with 3,000 tonnes. Therefore, semi-submersible is more stable at a higher metacentric height of 2.9 m with 3,200 tonnes compared to spar one at a lower metacentric height of 2.4 m at 3,200 tonnes. Finally, the metacentric height is a key parameter to measure the static stability of a floating body, as it is defined as the distance between the CoG of a platform and its metacentre. In this case, semi-submersible is more stable, when heavier platforms are deployed, compared to spar that is more stable with lighter platforms.

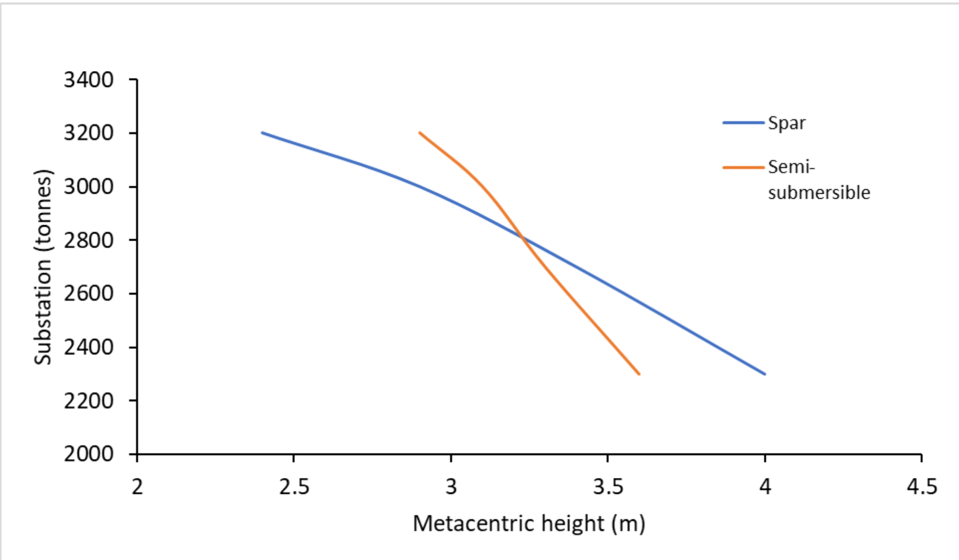

Figure 15: Representation of the comparison between substation mass (tonnes) and metacentric height (m) comparing spar and semi-submersible platforms.

7 TECHNICAL BOTTLENECK AND PROMISING TECHNOLOGIES

7.1 Future ambition for the Celtic Sea

With the PDZ project underway and the vision to develop a 1.2 GW multipurpose offshore substation in the Celtic Sea by 2030, and the extrapolation to the initial 4 GW ambitions [6], the projects in the Celtic Sea in the future should take into account the results and lessons learnt from the demonstration MOS. To collaborate with developers and government to interconnect with each other to drive down costs and performance to reach more areas of the community, multipurpose offshore substations should be considered and investigated further to connect several energy producing wind farms and additional alternate ORE resources, e.g., wave and tidal, to reach The Crown Estates aspirations of 4 GW by 2035. As the wind industry seeks sites and equipment for deeper water to suit floating offshore wind turbines, along with the B-F MOS successful demonstration, the MOS design could be replicated to expedite the deployment of FOW in the Celtic Sea.

7.2 Subsea substations

Offshore substations are predominantly fixed structures with electrical equipment on the platform above the water surface. This is economical and ideal for shallow water with the depth up to 60 m, however as offshore wind is expected to locate further from shore in deeper water at a depth of over 100 m, a subsea substation could be more viable for collection of energy produced by offshore wind farms. The benefits of subsea substations are cost reduction of up to 30%, lower CO_2 emissions, and improved energy efficiency.

These structures house similar connections and transformer equipment as the substation located on the sea bed and could potentially be the future of FOW. This technology could be an effective move to connect large windfarms to the MOS, for example, from wind farm to subsea substation, then to MOS, and finally to grid connection onshore.

7.3 Floating offshore substation limitations

As floating offshore wind becomes more prominent in the future, it will require the floating offshore substation to collect and export power but with limitations.

The O&G industry has deployed floating structures in much deeper waters than the one proposed for offshore wind in the near future, therefore, their techniques can be useful lessons learned and a good starting point for floating substation design. The increased dynamic motion caused by extreme weather limits the substation connections which must be adequately stiff enough to ensure that dynamic cable failures are minimised when entering the substation. Larger substation structures with suitable mooring anchors are less affected by the environment than smaller designed structures. Therefore, larger components can be utilised with extra room for future connections on larger floating substations. However, if modules that use fluids such as oil, hydrogen storage or fluid reserve tanks are incorporated, the effects of dynamic motions that cause “sloshing” and displacement of the centre of gravity and buoyancy must be considered in the design simulations.

8 CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

The technical solutions to multipurpose offshore substations are being considered by Celtic Sea Power who are developing the outline design for a multipurpose offshore substation in the Pembroke Demonstration Zone as a shared asset for connecting floating offshore wind projects. This approach will help overcome grid constraint and reduce uncoordinated cable landfalls and is a response to the rapid emergence of floating offshore wind projects in the Celtic Sea. The Pembroke Demonstration Zone project wants to ensure that development activity both within and around the zone continues to strive to attract innovation, inward investment and return for its stakeholders to meet the Government's ambitions.

To link the multipurpose offshore substations and regions of the Celtic Sea, the incorporation of multipurpose interconnectors have been considered. Interconnectors are high-voltage cables which connect the electricity systems from neighbouring countries, in the case of the UK to mainland Europe. These multipurpose interconnectors could enable interconnection and offshore wind to work together as one combined asset across the Celtic Sea. The proposed projects could connect giga-watts of floating offshore wind farms through subsea high-voltage electrical cables. The cables would travel between two different regions or two different countries whilst connecting to floating offshore wind at sea. Harboured by import and export cables that would connect to onshore converter stations on either end to transform high-voltage direct current into high-voltage alternating current to be fed into the transmission network of each region/country. Therefore, multipurpose interconnectors will allow clusters of offshore wind farms to be connected as green energy hubs, rather than connecting individual wind farms to shore one after the other.

The role of conventional offshore substations is that they are links between power generation, transmission, and distribution to electrical grid via a point of connection. The primary function of the substation is to accommodate the high-voltage and medium-voltage inter-array cables as electrical components are required to transfer the power generated by the turbines. This high-voltage electricity is transmitted from the substation via the collector station to the shore through offshore export cables, and connected to the national grid via the onshore substation. Alongside the bottom-fixed offshore substations for the 1 to 2.4 GW Pembroke Demonstration Zone, there is the equivalent deep water floating offshore substation. Another major difference when considering floating offshore substations is the requirement and connection for in-situ dynamic inter-array and output cables.

By introducing multipurpose offshore substation systems instead of the traditional substation, there are additional considerations and advantages as a whole, which are; (1) higher voltage collection cables will be accumulated at wind farm substation where the farm is larger than one string; (2) the transmission to shore may have more than one grid connection point with varying grid connection capacity; (3) alternating and direct current inversion/conversion may be required at different levels depending on the collection system; (4) the multipurpose offshore substation with modular design would allow new systems to be added at a later date, wind farm expansion or used for different decommissioning schedules. There are currently no offshore wind collector designs planned using high-voltage direct current technology. However, depending on the distance between the farm and the multipurpose offshore substation, high-voltage direct current technology may be advantageous for serious consideration. If this is the case, the size of the multipurpose offshore substation could increase significantly to meet the Celtic Sea's ambitions for floating offshore wind.

Offshore substations play a critical role in offshore wind farms, collecting power from individual turbines and stepping up the voltage, reducing the current to support cable cross-sectional areas appropriate for transmission to shore for integration with the grid network. As floating offshore wind farms increase in size and move into deeper waters, advanced substation platform designs will need to support heavier topsides. The question being asked is when will floating offshore substations become technically and economically viable to support deep water floating offshore wind arrays . The complexity to the question ranges from substation size and mass that can vary significantly. Therefore, the answers will depend on many factors that include turbine size, metocean conditions, water depths, and manufacturing costs.

Floating substations are extremely important to the challenges of commercial-scale floating wind farms and must be considered as fundamental electrical structures. The offshore substation will link the inter-array cables from floating offshore wind turbines and the export cables to the onshore substation and grid connection. Government policy helps to steer the floating offshore wind agenda because it can access 80% of offshore renewable energy generation potential that is in the water depth exceeding 60 meters. As floating offshore wind transitions to a commercial scale, the project will require voltage increase or power conversion before connecting to the grid. Therefore, an offshore substation will be required to host the step up transformers and conversion equipment necessary to export high-voltage power back to shore.

Another design influence on both bottom-fixed and floating substructures are the harsh hydrodynamic conditions of waves and currents and the resulting fatigue loads. Higher electrical current demand will be inevitable as floating offshore substations grow larger, increasing the weight and size of cables needed for the design, putting more strain on the substructure. Overall cost and complexity are increasing due to the need for electrical equipment and expensive additional protection to accommodate the required redundancy. There are concerns of having too many dynamic cables connecting to the substation that can inflict damage to each other. To mitigate this, configurations must be located at different heights in the water, so redundancy can be supported by adding mechanical protection when approaching floating offshore substations.

This report has reviewed offshore substations deployed to date and key design considerations to be considered for the future. The multipurpose offshore substation has been introduced and suggested to support foundations structures for typical jacket or monopile bottom-fixed offshore substations. The jacket design is being considered for the three potential bottom-fixed offshore substation platforms in the Pembrokeshire Demonstration Zone ranging from 1 GW, 1.2 GW or 2.4 GW. The structures (known as a floater) supporting floating offshore substations are also compared. High voltage subsea equipment (dynamic cables and connections) will require more substantial R&D with the development of offshore wind and multi-purpose floating structures. All high voltage export cables for bottom-fixed offshore substations are ‘static’ design, but floating offshore substations export and collection cables will need to be dynamic in operation. Displacement and lifetime of greater than 25 years require that the offshore substation be able to withstand extreme storms and have sufficient fatigue tolerance during its life cycle.

The logistics behind such multipurpose offshore substations require collaboration between project stakeholders, owners and partner companies. One possible solution found is for the owner of the offshore substation to essentially “rent” connections to wind farm projects, which would be more economical for both parties than developing their own substations and long-distance cable lengths. Therefore, to scale up and extrapolate the initial 4 GW deployment in the Celtic Sea requires careful planning through cable scale and multi-purpose offshore substation deployment.

To meet the 4 GW target, the Celtic Sea must plan to accommodate the power infrastructure and export additional power to land areas or neighbouring countries. By incorporating various offshore wind farms into four offshore substations (i.e., multipurpose substations) for the initial extrapolation of 4 GW into the Celtic Sea, the export cable from each of the multipurpose substations to the onshore substation were determined at 400 kV. The export currents required for the multipurpose substation were as follows, (OSS-1) 1,445 A, (OSS-2) 1,590 A, (OSS-3) 1,445 A, (OSS-4) 1,590 A with a total load power of 3.8 GW (4 GW capacity) with a total current of 6,070 A for the four substations. The identified current reduction is driven by using step up transformers to increase the voltage to 400 kV due to the relationship of current being inversely proportional to the voltage. However, there are many challenges to consider, namely, options to high-voltage alternating current versus high-voltage direct current, cross-section areas to export cables, selected cables in kilo-volts according to the current carrying capacity for each offshore substation, and extended distances that floating offshore wind are to be deployed.

Modelling for floating offshore substations in this report looked at the preferred floating structures, each having a range of metacentric heights (ranging from 2 – 4 metres) and topside mass (ranging from 2,300 – 3,200 tonnes) for spar and semi-submersible platforms. The metacentric height is a parameter to measure the static stability of a floating body, as it is defined as a distance between the centre of gravity of a platform and its metacentre, when comparing the substation mass (in tonnes) to the metacentric height (in meters) for substructure designs, i.e., spar and semi-submersible. The conclusions were that larger metacentric height would imply greater initial stability against overturning. Comparing spar and semi-submersible platforms, the semi-submersible is more stable when heavier platforms are deployed, whereas the spar platform is more stable with lighter load.

In conclusion, future projects in the Celtic Sea should consider the results and lessons learned from the demonstration of the multipurpose offshore substation. Collaboration between developers and the Government and National Grid is crucial to interconnect and drive down costs while improving performance in more refined areas of the search. The Crown Estate's aspiration of achieving 4 GW by 2035, as shared in this research, should also be considered. It is recommended that further more detailed investigation be conducted into the use of multipurpose offshore substations to connect multiple energy-producing offshore wind farms and other renewable energy sources, such as wave and tidal power.

8.2 Recommendations

It is important to acknowledge that the scenarios presented in this report introduce a degree of uncertainty in the calculations related to floating offshore wind farm designs. However, the technical aspects and models developed in this study can be refined through future research to optimize floating offshore wind farms. Areas for further investigation include redundancy, dynamic inter-array cable management, failure rates, and fatigue. ORE Catapult is planning further research in 2023 that will address these areas, focusing on dynamic inter-array cable management and failure rates, as well as optimizing floating offshore wind farms in the Celtic Sea.

To address future uncertainties and investigate certain areas in more detail, several potential areas for future work have been identified:

- Develop a flexible system that allows for new farms and energy sources to be added or decommissioned based on optimisation research and redundancy.
- Conduct further studies on power quality management, monitoring systems, power optimisation, multipurpose interconnectors, and multipurpose offshore substation placement and layouts.
- Conduct more research and development into floating substations, including the influence of movement on electrical components affected by metocean conditions.
- Conduct more research and development into subsea substations.
- Give further consideration to the impact of topside design and costs when moving from fixed to floating offshore substations and collaborate with industry partners to explore potential for additional topside weight in floating offshore structures.

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