Cornwall FLOW Accelerator

OPTIMISED CABLE CONNECTION OPTIONS FOR FLOATING OFFSHORE WIND

Document Title		OPTIMISED CABLE CONNECTION OPTIONS FOR FLOATING OFFSHORE WIND	
Document Reference		PN000463 CFAR-OC-028-30092022	
Date of Issue		20220930	
Author		Bradley McKay	
Contributor		Cameron Wilson	
Revision History	**Date**	**Reviewed / Approved by**	**Authorised by**
First Draft			
Second Draft			
First Issue	20220930	Paul McKeever	Simon Cheeseman
Rev 1			
Rev 2			
Rev 3			
Rev 4			

HM Government

European Union
European Regional
Development Fund

CORNWALL FLOW ACCELERATOR PROJECT INNOVATION IN LOW CARBON DESIGN AND MANUFACTURABILITY

OPTIMISED CABLE CONNECTION OPTIONS FOR FLOATING OFFSHORE WIND

REPORT

Electrical infrastructure and grid connections

Photo Source: Wind Power < Solutions - LS Cable & System (lscns.com)

ACKNOWLEDGEMENT

The study was jointly supported by the Celtic Sea Cluster (CSC) under the Cornwall FLOW Accelerator Project, led by Celtic Sea Power (CSP), supported by University of Exeter (UoE), University of Plymouth (UoP), Offshore Renewable Energy (ORE) Catapult, and delivered by ORE Catapult.

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.

Author: Bradley McKay – Research Engineer Electrical (FOW Accelerator) MRE

Contribution: Cameron Wilson – Strategy Analyst - Road-mapping Specialist

Paul McKeever – Head of Electrical Research

Published Date: 30/09/2022

The author and Contributors would like to thank a number of individuals, organisations and stakeholders for their support through Steering Committee and Expert Group meetings.

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DOCUMENT HISTORY

Revision	Date	Authors	Reviewer	Approver	Authoriser	Revision History
Draft 1	28/06/2022	Bradley McKay	Simon Cheeseman			Version Rev-1.3
Draft 2	29/08/2022	Paul McKeever				Version Rev-1.5
Draft 3	05/09/2022	Bradley McKay	Paul McKeever			Version Rev-1.6
Final	29/09/2022	Bradley McKay	Paul McKeever	Paul McKeever	Simon Cheeseman	Final Rev-1.7

PREFACE

Offshore Renewable Energy Catapult is leading work package 4 of the Cornwall FLOW Accelerator project and has commissioned this report as part of the Celtic Sea floating offshore wind (FOW) initiative. This report examines how to optimize cable connection options for FOW, and considers the challenges for the integration to the electrical grid infrastructure. The new target set by the Energy Security Strategy 2022 for offshore wind (OSW)[1] in the UK is to achieve deployment of 50 GW of offshore wind by 2030, where 5 GW could come from FOW in deeper seas. In addition, within the energy mix is the ambition set by The Crown Estate[2] to have 4 GW of FOW by 2035 in the Celtic Sea.

The objective of the Cornwall FLOW Accelerator project on behalf of the Celtic Sea Cluster (CSC) is to establish a recognised pipeline of FOW projects, prepare the regional supply chain, and provide expertise, which will collectively help accelerate the deployment of floating wind in the Celtic Sea and maximise the economic benefit to the region.

This report focuses primarily on wet mate high-voltage (HV) power connectors and recognises that existing cable array designs tend to be arranged in a ring or connected in parallel to provide redundancy at wind farms. One of the most common cable solutions for floating structures are lazy wave, consisting of two double-armour cable sections and an intermediate section with buoyancy elements. By using wet mate connectors this could support FOW as a rapid means of disconnecting/connecting inter array cables. This option reduces dynamic loading, reducing critical time the device is out of service, and cost effective to support a shore maintenance regime.

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[1] British energy security strategy - GOV.UK (www.gov.uk)

[2] 2022 - The Crown Estate announces areas of search to support growth of floating wind in the Celtic Sea | 2022 - The Crown Estate announces areas of search to support growth of floating wind in the Celtic Sea

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NOMENCLATURE

ATM	Atmospheres
BEIS	Department for Business, Energy and Industrial Strategy
B-F	Bottom fixed
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CfD	Contracts for Difference
CSA	Cross-Sectional Area
FOW	Floating offshore wind
FOWT	Floating offshore wind turbine
FWT	Floating wind turbine
GHG	Greenhouse gas
GVA	Gross value added
GW	Giga-Watt
H&S	Health & safety
H2	Hydrogen
HND	Holistic Network Design
HV	High voltage
HVAC	High voltage alternating current
HVDC	High voltage direct current
IDC	Industrial decarbonisation challenge
IWES	Integrated whole energy system model
km	kilometre
LCOE	Levelised cost of energy
LCOH	Levelised cost of hydrogen
LDV	Light duty vehicle
MOSS	Multi-Purpose Substation
MRE	Marine renewable energy
MSW	Mean sea water
MtCO2	Metric Tons of Carbon Dioxide
NGESO	National Grid Electricity System Operator
O&G	Oil and gas
O&M	Operation and maintenance
ORE	Offshore renewable energy
OSW	Offshore wind
OTNR	Offshore Transmission Network Review
OWIC	Offshore Wind Industry Council
R&D	Research and development
RE	Renewable energy
ROV	Remotely Operated Vehicle
RoW	Rest of World

StIC	Solving the Integration Challenge
TCE	The Crown Estate
TRL	Technology readiness level
TW	Tera-Watt
TWh	Tera-Watt hour
XLPE	Cross-Linked Polyethylene

EXECUTIVE SUMMARY

The ‘Offshore Transmission Network Review’ (OTNR), investigated the existing offshore transmission regime to address the barriers it presents to further significant deployment of offshore wind, with a view to achieving net zero ambitions. With increasingly ambitious targets for offshore wind, constructing individual point to point connections for each offshore wind farm may not provide the most efficient approach and could become a major barrier to delivery given the considerable environmental and local impacts, particularly from the associated onshore infrastructure required to connect to the national transmission network. The electrical infrastructure and grid connections throughout the UK have been reviewed and identified the limitations of the existing grid network. As we deploy more offshore renewable energy (ORE), a new transmission strategy is required to ensure a more coordinated approach for the future as an enabler to meet the ‘Prime Minister’s - Ten Point Plan for a Green Industrial Revolution’ to de-carbonisation[3].

As part of the electrical infrastructure analysis, focus will relate to what would be new and require development in the future to meet the ambitions of 50 GW by 2030, for OSW (including 5 GW for FOW). Therefore, integrating this level of OSW into our energy mix, requires careful consideration to variability and intermittency, and makes the aim to deliver 95% low carbon electricity by 2030, using a combination of electricity and hydrogen even more important. Establishing a green hydrogen economy that would supply circa 130 Tera-Watt hour (TWh) per annum, would require circa 40 Giga-Watt (GW) of OSW energy to balance the equation.

This report focuses on the electrical challenges, particularly the cable connection interfaces of wet mate cables and FOW turbine interface options as part of a wider analysis to support the OTNR strategy. The report includes a cost benefit analysis, and considers the practicalities of wet mate vs dry mate connectors, for example, whilst integrating embodied carbon considerations. Also considered are the performance features of wet mate connections from previous and new research conducted by ORE Catapult, to address amongst other things, voltage, current, frequency, and power limitations to electrical infrastructure solutions relevant to future FOW installations.

KEY FINDINGS

The report has identified several key findings. These are listed below along with the rationale behind them:

1. Wet mate connectors can improve cable array solutions

To date, connectors have been used in FOW to either connect static export cables to dynamic inter-array cables, or within FOW towers in most instances using T-connectors. Daisy chain cable configurations are not uncommon within wind farms, but the drawback of this design is that in the event of a fault, it causes the loss of the entire string of turbines. Therefore, by using HV power wet mate connectors, this offers reduced installation time potential and can prevent the loss of an entire

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[3] The ten point plan for a green industrial revolution - GOV.UK (www.gov.uk)

string. Furthermore, the use of T-type connectors as a single spur to each turbine could reduce the number of dynamic cables needed throughout an installation.

2. **Wave Hub has provided some useful learning for future FOW cable system solutions and remains a useful asset**

The Wave Hub project in the Celtic Sea, when installed in 2010, used subsea hub technology/experience from O&G. It was designed as a wave energy converter demonstrator site (16 km off the north coast of Cornwall, in circa 57 m of seawater). Wave Hub used dry mate connectors, connected via an export cable operating at 33 kV. Based on the dry mate technology, and by adopting the lessons learnt from Wave Hub this could allow FOW to shape cable systems now using wet mate technology [4]. This is where an option like the multi-purpose offshore substation (MOSS) will be best suited to adopt wet mate connectors (now ranging up to 66 kV). In deeper water, subsea substations are under consideration to connect the arrays by static cables instead of dynamic cables in more onerous metocean environments where the FOW sites have been identified.

3. **The development of a viable HV wet mate power connector will provide an important technology option for future FOW advancement**

A HV wet mate power connector allows for subsea connection, in most instances using a remotely operated underwater vehicle (ROV). The subsea method of connection is faster, more cost effective and more efficient as the cable does not need to be recovered to above the sea surface compared to dry mate alternatives. This significantly reduces costly vessel time . In contrast, the cost of wet mate connectors are more expensive compared to their dry mate counterpart for the same specifications. Maximum HV wet mate power connector voltage and current ratings tend to be lower than dry mate connectors at present. The reason behind the difference is due to the technical challenge of preventing water and contaminant ingress from seawater so maintaining cleanliness and good insulation. Hence, the industry is still debating the pros and cons of wet mate versus dry mate connectors.

4. **The deployment of FOW is dependent on several 'inter-related' factors such as electrical transmission technology, advancement of key innovations, government support, and the nurturing and sustainment of engineering skills and capability**

Wind farms are increasing in size, and FOW is moving to harsher environments, much further offshore, and considerations are building around high voltage alternating current (HVAC) versus high voltage direct current (HVDC) for the future of transmission to overcome potential losses from long distance AC transmission. In current design and technology, OSW substations are located on the surface, either fixed or floating. In HVAC, it may be possible to employ subsea substations using O&G technology for transformers and switchgear removing some reliance on dynamic cables and the benefits of implementing static cables underwater instead – reduces loading and fatigue. Equipment cooling requirements are manageable as the subsea substations are surrounded by seawater, however the higher costs and associated challenges are currently making subsea substations less attractive than the conventional fixed or floating technologies. There are countless opportunities for innovative solutions

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[4] JDR AWARDED WAVE HUB PROJECT - JDR Cables, providing the vital connection

in the FOW sector, this is where Catapult can increase awareness of the opportunities that exist, nurture and sustain the engineering capability to deliver and maintain these innovative solutions.

1 INTRODUCTION

1.1 Background

The net zero targets for renewable electricity will drive an increase in FOW as one of the main sources of energy. The future will require a fully decarbonised system with the majority of energy consumption provided by renewable power. Fully electrifying certain sectors will be extremely expensive and technically challenging. This will require vital upgrades to the electrical infrastructure, and primary focus when expanding ORE connections to gain momentum for future projects. As current energy capacity is limited to 132 kV in the system for many national connections. An upgrade of the system to achieve our 50 GW of OSW goals are in place to reduce our GHG emissions.

Future offshore substations with upgrade capabilities may provide a solution, this would factor in increased cross-sectional area (CSA) to the new subsea cable required. Including wet mate connection solutions to FOW (further details can be found in Early opportunities models: Connection of electricity storage or a demand user to an offshore transmission system in Appendix 2). The expense of laying subsea cable costs £700,000 – 800,000 per km, therefore, Government investment of the subsea cable infrastructure will need to be carefully planned to avoid mistakes made to specific locations of these cables. In addition, the subsea cable will need to have expansion capability in place to manage ORE growth.

The Celtic Sea was overlooked in the OTNR as the original focus was on greater seabed depths for fixed OSW, compared to other regions that were selected. The importance of including FOW has been lobbied by Welsh Government and ignited the Celtic Sea opportunity to achieve The Crown Estate's (TCE) 4 GW ambition to award seabed rights to FOW projects as seen in Figure 1.1, (a) Various test & demonstration projects have preferential bidding rights into TCE leasing areas late in 2023[5]. ORE Catapult suggest that opportunities for the South West and Wales could provide £682M in supply chain growth, and an additional 3,000 jobs to the region. This will put immense pressure on grid connectivity around the Celtic Sea. The key solution is for the National Grid Electricity System Operator (NGESO) to provide the necessary onshore and offshore electrical network infrastructure and be mindful of environmental impact assessments (EIA) due to export cable routes to onshore substations.

To further emphasise the importance of the Celtic Sea and the wind resource available for FOW, found in Figure 1.1, (b) the map of the UK, with focus on the Celtic Sea for this report, shows the mean wind speed, in m/s, at 150 meters (m) above sea level, extending 200 kilometre (km) offshore (ideal maximum region for FOW is beyond 60 km) at 10.3 metres per second (m/s) annual resource[6]. Therefore providing a visual representation of the Celtic Sea to the vital role FOW in this region will play.

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[5] New study reveals floating offshore wind benefits for the South West - Regen

[6] Global Wind Atlas

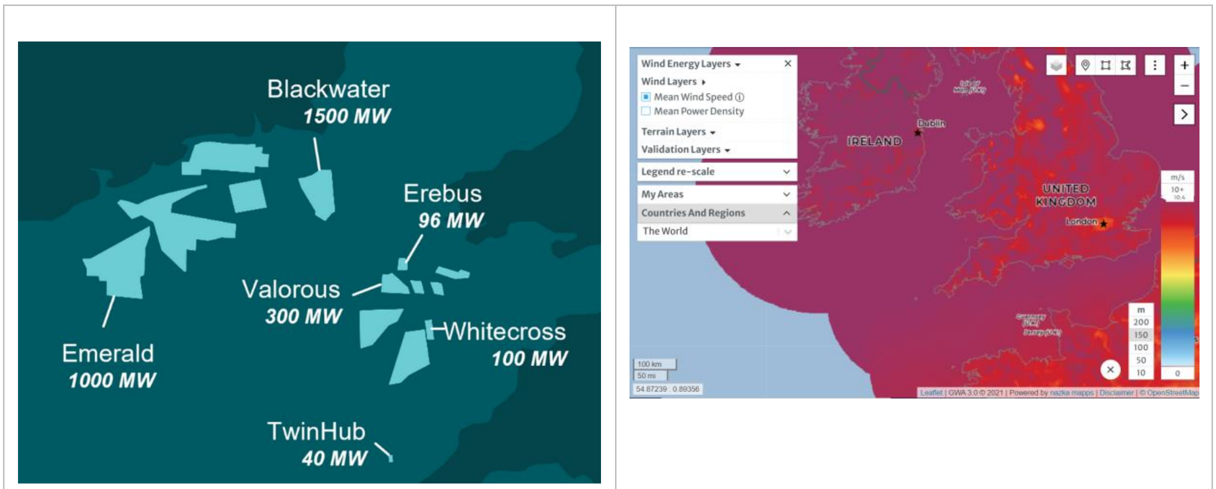

Figure 1.1, (a) Map for FOW in the Celtic Sea that are currently announced; Celtic Sea Power (PDZ/MOSS) demonstration substation; Total (French energy major) has partnered with Simply Blue (Irish marine developer) to progress two sites: Erebus (100 MW) and Valorous (300 MW); Shell has partnered with Simply Blue Emerald (1 GW); Iberdrola (Spanish major) DP energy to progress two Irish projects[7]. (b) Map of the mean wind speed showing the Celtic Sea region at 150 m height, shows the mean wind speed, in m/s, at 150 meters (m) above sea level, extending 200 kilometre (km) offshore (ideal maximum region for FOW is beyond 60 km) at 10.3 metres per second (m/s) annual resource[8].

It is important that the electrical infrastructure and expansion capabilities are addressed in the first instance and vitally important to reaching these goals. Western Power Distribution operates the distribution network on the North Cornwall coast, with closest bulk substations[9] at Yelland, Watchet, and Barnstable; and the transmission network, operated by NGESO – with major substations on the North coast located at Hinkley C and Alverdiscott[10].

When considering projects across the western seaboard from the Celtic Sea into the Irish Sea, energy integration via multi-purpose interconnectors (MPI) are real positive ventures to leverage infrastructures and capabilities. MPI are subsea electricity cables that connect GB to neighbouring markets and also connect offshore generation to shore and are new, innovative asset type. By introducing MPIs as a licensable activity, they could provide certainty to investors and developers, enabling them to make decisions regarding future MPI projects[11]. Comparing conventional existing point-to-point interconnectors and separate radial connections for OW, MPIs combine these activities at lower cost, with less infrastructure. By using MPIs there is a reduced impact on the environment and local communities as OW expands.

From current consultation by the OTNR and NGESO the holistic network design (HND) the Government is attempting to address the electrical challenges, through the OTNR (TCE) NGESO Coordinated project: Pathway to 2030 holistic network design high level plan[12].

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[7] New study reveals floating offshore wind benefits for the South West - Regen
[8] Global Wind Atlas
[9] National Grid - Network capacity map
[10] New study reveals floating offshore wind benefits for the South West - Regen
[11] Energy Security Bill factsheet: Multi-purpose interconnectors - GOV.UK (www.gov.uk)
[12] Offshore Coordination Project - latest news and staying informed | National Grid ESO

The proposals in summary quoted by the NGESO are as follows (further details can be found in Appendix 1)[13],

- "The Pathway to 2030 Holistic Network Design (HND) is a major step for Great Britain in delivering cheap, clean energy from offshore wind.
- It sets out a single, integrated design that supports the large-scale delivery of electricity generated from offshore wind, taking power to where it's needed across Great Britain.
- The HND facilitates the connection of 23 GW wind, helping to deliver the Government's ambition for 50 GW connected offshore wind by 2030.
- This is a first step towards more centralised, strategic network planning that is critical for delivering affordable, clean and secure power, as we journey towards our net zero future."

Lastly, developers are looking to connect Alverdiscott (in Torridge), North Devon as a significant South West investment as multiple FOW farms could be connected in the region.

1.2 Objectives of the research

OSW energy projects are located in high energy environments, especially FOW installations with challenges like O&M that becomes difficult to administer and weather dependant. Therefore an efficient cable connection system is vital to keep the OSW installation operational as a reliable ORE resource. Failures are inevitable, due to the dynamic environment, but proper planning and the correct cable connection options being used will add to solution and cause minimal delays.

This research will address:

- Analysis of subsea cables to the cost crossover point at which FOW turbines become part of the optimal system to ORE, and changes to the system design and operation such as to identify dry mate versus wet mate electrical connection.

- Differentiate the relevant outline of High Voltage Alternating Current (HVAC) from FOW turbines (and arrays), versus converted High Voltage Direct Current (HVDC) with converter stations.

- Determine the limitations and benefits that incorporate voltage, current, frequency, ad power limitations to electrical infrastructures.

- Investigate economic modelling for the Pembrokeshire Demonstration Zone (PDZ), by considering industry cost reduction profiles to calculate Levelised Cost of Electricity (LCOE) related to longevity of subsea cables and connections to arrays (if autonomous repairs outweigh manned deployment for O&M).

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[13] Offshore Coordination Project - latest news and staying informed | National Grid ESO

1.3 Overview and comparison between HVAC versus HVDC

There is a debate going on within the electrical infrastructure and grid sector of the benefits of HVAC from floating offshore wind turbines (FOWT) (arrays), versus converted HVDC transmission options (further details are found in ORE Catapult's study for designs and layouts in Appendix 3).

Most of the transmission lines in existence onshore today are HVAC, however, HVDC transmission offers advantages over HVAC, primarily due to technology progression. The key areas are line losses - less from HVDC cables compared to HVAC cables. HVDC are 2 – 5 times the capacity of an HVAC line at similar voltage, and HVDC has the capability to control the flow of power precisely[14].

New HVDC innovation and the benefits to HVDC transmission are now being considered for FOW, as HVDC is used to transmit electricity over longer distances to FOW farms >50 kilometres (circa 50 – 80 km) offshore or between HVAC power systems of different frequencies, as seen in Figure 1.2[15], showing the clear transition and/or expenditure crossovers, and break even distances between the two HVs.

By using subsea (submarine) cables, as the economic benefits are more attractive compared to conventional HVAC transmission lines, with HVDC converters capable of converting up to 2 GW and voltage ratings >800 kV beneficial. Within a HVDC system (mostly bi-directional) structure could be the HVAC from the FOW array as power, then converted from HVAC to HVDC (by rectification) and then from HVDC to HVAC (by inversion) closer to shore for transmission.

HVDC converter stations use thyristor valves, typically a 12-pulse converter (a solid-state semiconductor device that acts exclusively as a bistable switch) to perform the HVAC to HVDC conversion and vice versa. HVAC uses a three-phase network system, 120° out-of-phase with each other (creating the 3-phases). Compared to a bipolar HVDC cable that uses only two insulated sets of conductors rather than three, like in HVAC – that carries the reactive component of current. Has a skin-effect and induce currents in the cable sheath and armour; resulting in losses in the whole HVAC system. In comparison, the HVDC cable requires only two conductors (one positive and the other negative) and very little losses in comparison.

Therefore the cost estimation for HVDC transmission systems depends on constraints, such as: subsea transmission medium; the power capacity; offshore environmental conditions; O&M constraints; regulatory and safety requirements; filter variety; transformers. According to ABB HVDC technology for offshore wind is maturing. Reasoning behind this statement is that in AC transmission, losses rise with the voltage, the capacitance and the cable length[16]. Beyond the 100 to 150 km 'critical length' that depends on various cable types, there will be no capacity left for active power (P) transmission. Previous methods to increase the transmission capacity is to increase the voltage level, but because reactive power (Q) increases with the square of the voltage (V), the voltage increase reduces the critical length.[17] Therefore the positive outcome for HVDC cables with cross-linked polyethylene (XLPE) insulation (technical readiness of voltages up to ± 320 kV with a capacity of 1,000 MW for a symmetrical

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[14] EEP - Electrical Engineering Portal | Energy and Power For All (electrical-engineering-portal.com)
[15] Electrical Technology | All About Electrical & Electronics Engineering
[16] HVDC technology for offshore wind is maturing | ABB
[17] HVDC technology for offshore wind is maturing | ABB

monopole[18]) are that they are lighter than other cables, making their installation offshore easier and cheaper than HVAC technology. The competitive edge for HVDC under these criteria are better investment prospects and lower operational cost , therefore supporting an increased power rating and increased transmission distance suitable for FOW.

For example, currently in Europe, 40 of the over 90 - OWF greater than 200 MW have roughly a third of them connected to the grid by HVDC transmission[19]. Located in the North Sea an area known as the German Bight there are seven HVDC offshore wind connection systems in operation and another three under construction (operated by the transmission system operator TenneT Offshore).

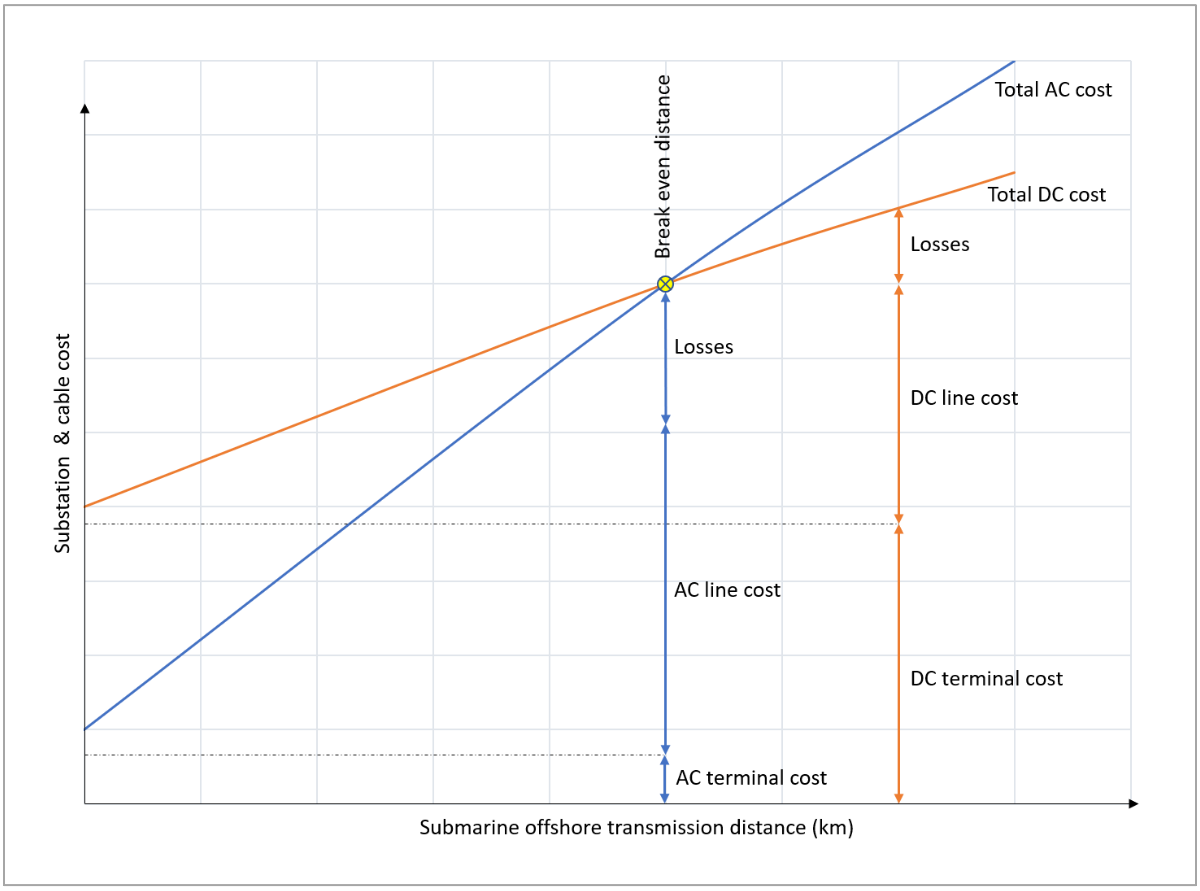

Figure 1.2 HVAC comparison to HVDC offshore subsea cable transmission distances and economical costs, reflecting a break even distance from shore to where HVDC becomes more viable, comparing losses, line and terminal costs associated to the two HVs.

1.4 Offshore wind specific connector requirements

An introduction to subsea wet mate connectors, what they are and how they can be implemented into the OSW industry. They are a type of connector that can be connected within the water environment eliminating any onshore, or on board vessel connection (subsea mating/un-mating connection). Renewable energy (RE) applications are now being considered incorporating fibre-optic applications which used a stab-plate to bring together power wet mate connector and fibre-optic wet mate connectors. Within this report different types of wet mate connectors were looked at and their main

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[18] HVDC XLPE (Cross-linked Polyethylene) - ENTSO-E (entsoe.eu)
[19] HVDC technology for offshore wind is maturing | ABB

advantages, compared to dry mate connectors from relevant manufacturers identified, and seen in Figure 1.3. HV wet mate connectors take on different applications for example, hybrid electrical and fibre-optical connectors, three-phase (three-pin) electrical wet mate power connectors, three-phase (single-pin) electrical wet mate power connectors that are attached to stab-plates for connectivity. Many wet mate connectors operate over a large electrical range, however for this purpose the averages identified were as follows and compared in Figure 1.3. The average figures were 22.9 kV for maximum rated voltage, 742.3 A for maximum rated current, and 1,974.4 m maximum water depth. When considering products >36 kV, Siemens Energy appeared to have high power connection, namely 52 kV and leading the technology at this stage in development.

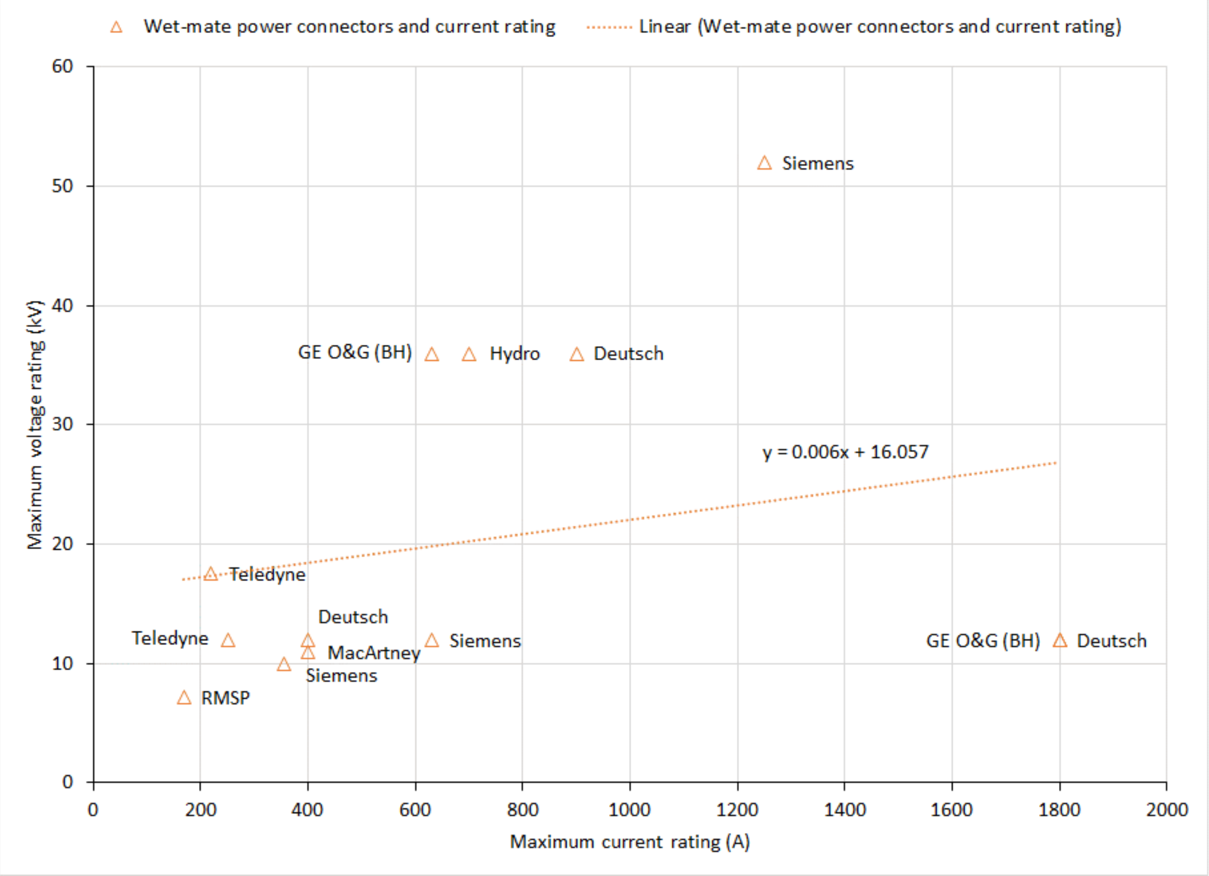

Figure 1.3 Comparison of different types of high voltage wet mate connectors from manufacturers in the offshore subsea environment and comparison of maximum voltage and current ratings.

2 WET MATE CONNECTOR BACKGROUND

2.1 Offshore wind industry

When focusing on the use of wet mate connectors specifically for offshore wind applications, their usage is currently limited. Many earlier, smaller offshore wind developments have inter-array grids which operate at voltages of 33 kV.

However, with 66 kV being the standard operating inter-array voltage for the majority of offshore wind sites currently in operation. Inter-array cables need to be particularly robust to keep them from being damaged by external factors. And offshore windfarms are increasingly growing in size, and moving to deeper water and farther from shore. Manufacturers like Prysmian are pushing the industry forward through their higher-voltage 66 kV cable system developments, that allow developers to reduce capital expenditure by up to 15% compared to lower-voltage systems[20]. To further expedite the use of wet mate connectors on future sites such as those being developed or proposed in the Celtic Sea.

2.2 Introduction and history to subsea connectors

Connector systems used for subsea applications have been developed since the mid-1950's, with the earliest connectors taking the form of a dry mate configuration. These configurations included rubber moulded "interface-fit" connectors and rigid-shelled connectors.

Regarding wed-mate connectors, the first of these were developed in the 1960's and were of pressure balanced oil-filled design. Such a connector design isolated the contacts inside oil sealed chambers which during connection are penetrated by elongated pins with insulated shafts, meaning connection is achieved not in the seawater, but within the connector's oil. By using such a design, disconnection could be achieved at water depths not possible before. To this day, many modern wet mate designs, both electrical and optical, are of a pressure balanced oil-filled configuration. Rubber moulded and rigid-shell connectors can also be used in wet mate designs, although their use is limited to low voltage applications below 1 kV[21].

2.3 Overview of wet mate and dry mate connector installations

When looking at the differences in wet mate and dry mate connectors, their method of installation is what distinguishes them most. Dry mate connectors require connection to be done onboard a vessel in the dry. Cable splicing is required to ensure the connection is sufficiently insulated to be submerged beneath water, with this being a time-consuming process. Additionally, when a dry connection requires disconnecting for purposes such as repair and maintenance, the cable must be retrieved by a skilled diver or remotely operated vehicle (ROV) so that disconnection can be achieved above water. None of this is required with wet mate connectors, where connection and disconnection can all be achieved below sea level. This reduces the time and costs associated with installation and maintenance[22]. Also allows for a different cable architecture, taking away the need for long cable tails with dry mate connectors. The long-untethered cable ends are prone to damage.

2.4 Benefits of wet mate connectors

Compared to working with dry mate connectors, wet mate connectors allow shorter vessel hire periods, greater selection of weather windows in which it is safe to operate, and improved health and safety by removing the potential need to send personnel below sea. With reductions in vessel hire periods and work hour requirements, this will result in subsequent reductions in lifetime O&M costs. In addition to providing the potential for lower lifetime O&M costs, wet mate connectors also enable

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[20] Inter-array Cables Systems | Prysmian Group

[21] Wet Mate Connector Market Study

[22] Final Report Summary - WETMATE (WETMATE – a 33kV Subsea Wet-MateableConnector for Offshore Renewable Energy) | FP7 | CORDIS | European Commission (europa.eu)

shorter cable lengths to be used for projects which can bring about CAPEX savings. Shorter cable lengths can be used as connection points do not require retrieval, as is needed when using dry mate connectors, with the additional cable lengths required being as much as two to three times the sea depth at the site location[23].

3 AVAILABLE CONNECTORS AND SUITABILITY

3.1 Manufacturers of wet mate connectors

As the ORE market grows so does the need for reliable, efficient, and durable connectors installed in some of the most energetic environments, for example, the Celtic Sea. Based on the O&G industry for many decades, many connector manufacturers have tailored their designs to suit different environments. Various voltage requirements will vary depending on the individual projects, however in most instances the required voltage is 33 kV for a single device set to rise as FOW turbines increase beyond the 15 MW scale. Discussions currently underway are to focus on 66 kV wet mate connectors for the future market for export cables. According to Prysmian Group, using their 66 kV inter-array cable system technology that was approved by the Carbon Trust Offshore Wind Accelerator Programme, the benefits are as follows[24],

- "Two times more power can be transported over a single array cable at this higher voltage level, thus reducing the length of cable required, and consequently the cable and installation costs.
- Because fewer cables are entering the offshore substation in question, the number of J-tubes, transformers and switches, as well as the space these items require can be reduced.
- More unit power is provided to reduce the number of turbines and associated array cables."

As OSW activities continue to migrate into deeper more energetic waters. Manufacturers of wet mate connectors are identifying innovative methods to ensure unobstructed electrical flow from FOWT. Streamlined subsea connectors that operate efficiently and profitably for developers will be the key to unlocking the resource to the optimum level. Subsea systems must be modular to allow practical deployment; therefore wet mate connectors are important enablers to enable modular connections.

The specifications that come with wet mate connectors range from hybrid, three-contacts, three-single contacts, transmitting electrical power and optical connections for various applications. Companies currently involved in the RE sector for wet mate connectors are: (1) Deutsch TE Connectivity; (2) General Electric Oil & Gas; (3) Hydro Group; (4) MacArtney; (5) PowerSea; (6) RMS PumpTools; (7) Siemens Tronic; (8) Teledyne ODI discussed further in this report as follows.

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[23] Electrical Components for Marine Renewable Energy Arrays: A Techno-Economic Review (Journal Article) | DOE PAGES (osti.gov)

[24] Inter-array Cable Systems | Prysmian Group

3.1.1 Deutsch TE Connectivity[25] [26] [27] [28] [29] [30]

A manufacturer of connectors for subsea applications that support wet mate connectors for subsea pluggability. Their design lifecycles are counted in decades, that allow their connectors to withstand the temperatures, and pressure of the harsh ocean depths of ORE. As the RE industry moves toward fiber-optic monitoring systems, to control the bandwidth, the large transmission distances, and low noise of optical systems. This flexibility for power connectors, signal connectors, and hybrid electrical/optical connectors enables maximum continuous power from the OSW farms. Deutsch power connectors are designed for wet mate applications and used on subsea boosting, compression and RE applications. There high-power connectors are wet mate able, for flexible designs and layout. The HydraElectric technology is rated at maximum voltage up to 36 kV; and up to 1,600 A maximum rated current, and operates at depths down to 2,000 m as seen in Figure 3.1.

Figure 3.1 Deutsch TE Connectivity 36 KV HydraElectric subsea wet mate power connector.

3.1.2 General Electric Oil & Gas[31] [32]

Baker Hughes now part of General Electric produce reliable power for every application and types of subsea processing activities. Especially in harsh, deep-water or for operation in sensitive areas. General Electric (Baker Hughes) are able to supply fully integrated AC power for multiple, high-power loads. Efficient transmission solution in the multi-megawatt range are 36 kV wet mate connection systems, for subsea processing, seen in Figure 3.2. Qualified up to a maximum 700 A and down to 3,048 m in depth. The current classification for the wet mate system is technical readiness level (TRL) of 4, and included in the mix are wet mate connections at 12 kV and 1,800 A for smaller subsea auxiliary systems.

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[25] Wind Energy Solutions | TE Connectivity
[26] Electrical Wet-Mate Connectors | TE Connectivity
[27] HV Wet-Mate Connectors in Subsea Processing | TE Connectivity
[28] Offshore Power (te.com)
[29] DEUTSCH OFS Series Connectors | TE Connectivity
[30] DDEController (te.com)
[31] GE Oil & Gas launches new subsea connector to enhance reliability of high-voltage operations on the seabed | GE News
[32] Subsea power solutions | Baker Hughes

Figure 3.2 General Electric (Baker Hughes) 36 kV MECON subsea wet mate connector.

3.1.3 Hydro Group[33] [34] [35] [36]

Subsea connectors manufactured by Hydro Group design, are for unique and challenging subsea applications. The three key energy markets Hydro Group work in is, O&G, marine renewable energy, and defence. The 36 kV hydro renewable connector (HRC) with a maximum rated current of 630 A, are connectors that harbour the evolution of their original junction box design reducing installation time to 12 hours, seen in Figure 3.3. The lifecycle is estimated to be 25 years, the maximum water depth is 100 m, and the design function is to connect two subsea 3-phase electrical cables on the seabed, without compromising either circuit.

Figure 3.3 Hydro Group 36 kV HRC wet mate hydro renewable power connector.

3.1.4 MacArtney[37] [38] [39]

As the ORE sector continues to face adverse challenges and scaling-up the RE as in 2011 MacArtney embarked on a wet mate 11 kV, 400 A prototype connector shown in Figure 3.4. The innovation was combined with reliable and tested technologies to the advancements within the ORE industry, and operational to a 100 m depth. By using wet mate connectors this eliminates the need to connect the cables at the surface through wet-mating and de-mating FOWT. The wet mate connector shortens connection time significantly compared to dry mate connectors making it possible to operate in energetic waters with shortened time windows. MacArtney has also opted to pursue the GreenLink (MV & HV) dry mate connector that was spurred on from marine renewable energy (MRE) industries and operators. The methodology was behind continuously increasing demand for dependable

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[33] Marine Renewable Energy (hydrogroup-uk.com)
[34] Hydro Group (hydrogroup-uk.com)
[35] Downloads, Product PDF (hydrogroup-uk.com)
[36] HRC-36kV.pdf (hydrogroup-uk.com)
[37] Power connector - wet mate connectivity solution for underwater technology applications (macartney.com)
[38] Tidal , wave, and current energy, deep water offshore and coastal systems, and hydropower, offshore wind farms and solar energy (macartney.com)
[39] 15_07_15_MacArtney_11kV_7_6MW_wet_mate_connector.pdf (vsense.net)

connectivity solutions. According to MacArtney wind based RE source is producing significant leaps in technology, with FOWT >50 km offshore growing HV connectors significantly. It must be stressed that these GreenLink HV inline terminations are dry mate connections designed to make HV terminations through a mechanical connection making it possible to repeatedly connect and disconnect the cables onboard ships. Often used to connect dynamic cables from OSW farms, and other ORE devices, to HV export electrical cables and subsea units, with ratings of 72.5 kV, and 2,500 A.

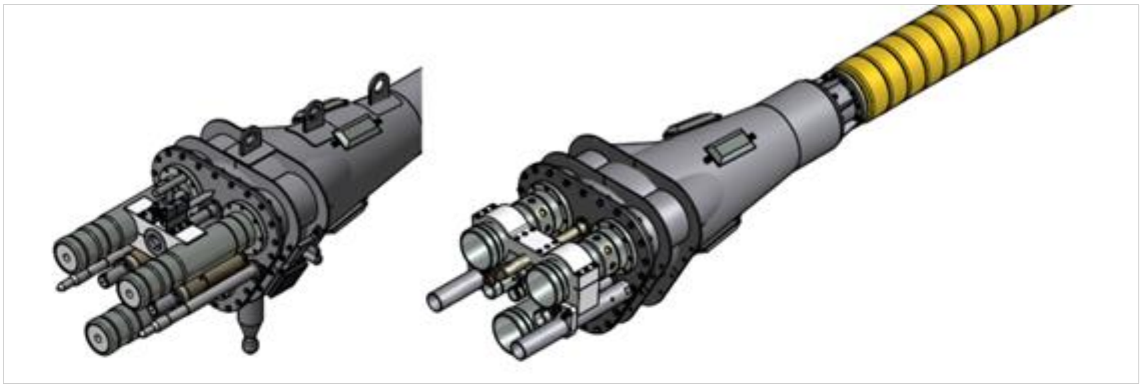

Figure 3.4 MacArtney 11 kV (7.6 MW) SubConn prototype wet mate power connector.

3.1.5 RMS PumpTools[40]

HV wet mate connector by RMS V1 OceanPower™ developed specifically for the RE market, classified as a 3-phase single mandrel connector brings long term reliability and efficiency. The HV connectors are modular inter-changeable male and female, and their plug can be energised in the unmated position. Highly technical dual sealed barriers, and metal to metal sealing and contacts that are gold-plated for connectivity. The 7.2 kV OceanPower V1 connector, and a 168 A maximum rated current, are able to operate to depths of 1,000+ m, seen in Figure 3.5. The key principles of RMS for subsea wet mate connector systems in hostile environments is to establish durability, reliability and longevity from industry preferences.

Figure 3.5 RMS PumpTools 7.2 kV Ocean Power V1 wet mate power connector.

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[40] HV Wet-Mate Connector (rmspumptools.com)

3.1.6 Siemens Tronic[41] [42]

SpecTRON offers the most comprehensive range of subsea HV electrical connector systems, that are world leading wet mate and dry mate connector power distribution. Siemens Tronic has an enviable track record used on a wide range of subsea applications in subsea oil, gas and RE. There has been a significant increase in demand for high power subsea field equipment at TRL 7 (high performance and durable). The latest connector the SpecTRON45 is a 52 kV voltage, and 1,250 A was designed specifically for subsea power distribution, to depths of 3,000 m, and seen in Figure 3.6. These connectors include a metal compensation system (providing long-term stability of the insulation system) and quick connect technology.

Figure 3.6 Siemens Tronic 52 kV SpecTRON wet mate power connector.

3.1.7 Teledyne ODI[43] [44]

Teledyne have a range of underwater electrical wet mate connectors with the ability to be mated and de-mated at full ocean pressure. The products are based on Nautilus technology to accommodate various voltage ratings, depth, and high pressure. The subsea 17.5 kV power electrical connection system is a three-phase system rated to a maximum of 220 A and at depths of 3,048 m, shown in

Figure 3.7. Production trends are moving towards deeper water and much longer step out distances to suit RE, driving higher power, and higher distribution capabilities in the subsea environment. The Nautilus wet mate connectors are built with insulation and redundant sealing systems for reliable performance, to withstand the long-term harsh environments.

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[41] Connectors | Subsea solutions - Oil & Gas - Siemens | Siemens Energy Global (siemens-energy.com)

[42] Siemens Energy · Technical document · DIN A4 portrait – Template (siemens-energy.com)

[43] Underwater Electrical Wet Mate Connectors - Teledyne Marine

[44] ODI_SubseaPower SelGuide697089.pdf (teledynemarine.com)

Figure 3.7 Above: Teledyne ODI 12-17.5 kV Nautilus wet mate power connector Below: Nautilus wet mate connectors showing horizontal mating configuration Left: de-mated Right: mated connections.

3.1.8 Summary of HV wet mate power connectors

At present and to the best knowledge and research for this report, the capability of selected manufactures relating to HV subsea wet mate power connectors for the RE industry was summarised in Table 3.1. The summary represent the most recent and relevant products that manufacturers have developed for the wet mate connector industry. There are as mentioned, different types of wet mate connectors, namely, mateable (driver and ROV), and stab-plate driven for connections. To have a modular approach power distribution must rely on wet mate HV connectors, as they will operate in an unprotected underwater environment by means of, mated or unmated connectors. It must be stressed that subsea wet mate connector application are used to directly connect two modules or to connect a cable to a module as discussed. Therefore, the key factors that surround wet mate connectors, is that they need to be technically feasible for the application and cost-effective for deployment in future ORE projects. Fundamentally the criteria for HV wet mate connectors must be specified, by voltage (in kilo-volt) and current (in Amperes) rating; operational frequencies (in Hertz), deep water pressures from various depths (in meters); and temperature ratings. Standard power for subsea systems is usually in three-phase and low-frequency for transmission of AC and between 50 – 60 Hz, however up to 200 Hz are found downstream in high-frequency applications to accommodate variable-speed drives[45]. In most instances the wet mate power connectors withstand pressures of up to 3,000 m, for example, 10 m of MSW equals 2 atmospheres (ATM), so 3,000 m MSW is 310 ATM, substantial pressures for connectors.

Table 3.1 Current selection by manufacturers for power wet mate connectors.

Manufacturer	**Name of connector** (Uo/U)* (kV/kV)*	**Max rated Voltage** (Um)* (kV)	**Max rated Current** (A)	**Max rated Depth** (m)	**Contacts**	**Design Life** (years)	**Operational stage**
Deutsch TE Connectivity	HydraElectric30kV (18/30)	36	900	2,000	1	25	Operational
	HydraElectric10kV+ (6/10)	12	1,800	2,000	1	25	Operational

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[45] legeay-hv-wet-mate-connectors-penetrators.pdf

	HydraElectric10kV (6/10)	12	400	3,000	1	20	Operational
General Electric O&G (Baker Hughes)	MECON WN 36/500	36	700	3,048	3	25	Operational (TRL 4)
	MECON WN 12/1800	12	1,800	3,048	3	25	Operational (TRL 4)
Hydro Group	HRC (18/30)	36	630	100	3	25	Operational
MacArtney	SubConn (7.6 MW)	11	400	100	3	25	Prototype
RMS PumpTools	OceanPower V1 (3.6/6)	7.2	168	2,000	3	25	Operational
Siemens Tronic	SpecTRON 45 (26/45)	52	1,250	3,000	1	25	Operational (TRL 5)
	SpecTRON 10+ (6/10)	12	630	3,000	1	25	Operational (TRL 7)
	SpecTRON 8 (5/8.7)	10	355	3,000	1	25	Operational (TRL 7)
Teledyne ODI	Nautilus WM15-220 (8.7/15)	17.5	220	3,048	3	20	Operational
	Nautilus WM10-250 (6/10)	12	250	3,048	3	10	Operational

***Note:** Subsea power systems are usually three-phase, a connector is specified through three values (ratings), for example (18/30) and 36 kV; therefore the first number, 18 kV, is the phase-to-ground rating; second number, 30 kV, is the phase-to-phase; the final number, 36 kV, is the maximum system voltage.

4 PERFORMANCE AND RELAIBILITY

4.1 Wet mate expected failures

Corrosion can lead to severe failures in subsea power connectors, therefore most connectors are fitted with anti-corrosion anodes. These anodes must be inspected and replaced frequently through O&M cycles advised by the manufacturers.

Under certain conditions polyurethane elastomers undergo degradation, primary causes are heat, light and atmospheric oxygen that can alter the connectors properties or end in a complete failure.

Seal failure and excessive loading can cause premature unlatching of wet mate connectors. This can cause seawater ingress and contacts of different electrical potential to short-out at the localised exposed contact resulting in a permanent failure. Even excessive use and rating beyond the manufacturers specification can lead to damage, through mate/de-mate life cycles.

Therefore, ant-corrosive systems must be inspected on a regular basis, as high temperature and high pressure are less likely to fail as long as each manufactures connector management systems for mating/de-mate life-cycles are adhered too. Wet mate technology is extremely new and there is limited records of failure within the extreme environments in which they will operate, and are hard to come by at this early stage of development (further details can be found in HV power cable integrity problems in Appendix 8).

Finally, connector cycle numbers for mate / de-mate of electrical high-voltage connectors are >100, however, with any connection a continuous repetition of connections will inevitably degrade the contacts and seals in such an extreme environment.

4.2 Power output ratings

Most high voltage power connectors are designed to operate at a maximum rated current, and therefore from the equation below the rated real power for the connector can be determined. In Table 4.1 and Figure 4.1, the maximum power output is expressed by the voltage and current ratings of the power connectors, expressed in Mega-watts (MW). In the equation, P is equal to power (MW), U and I is the maximum voltage and maximum current rating, and the PF is the power factor selected at 0.85 for this report.

$$P = \sqrt{3}\ x\ U\ x\ I\ x\ Cos\theta \quad \text{where,} \quad PF = Cos\theta$$

It must be stressed that wet mate connectors are on an exponential development pathway to align with the industries RE sector. That given, the power ratings range from 2 – 96 MW, and summarised below in Table 4.1 and Figure 4.1 for further details. Manufacturers are now considering 66 kV wet mate power connectors to suit OSW due to the expansion of the ORE sector.

Table 4.1 Representation of the maximum power output in MW for the wet mate HV power connectors.

Manufacturer	**Name of connector** (Uo/U)* (kV/kV)*	**Max rated Voltage** (Um)* (kV)	**Max rated Current** (A)	**Max operating power** (MW)
Deutsch TE Connectivity	HydraElectric30kV (18/30)	36	900	48
	HydraElectric10kV+ (6/10)	12	1,800	7
	HydraElectric10kV (6/10)	12	400	32
General Electric O&G (Baker Hughes)	MECON WN 36/500	36	700	37
	MECON WN 12/1800	12	1,800	32
Hydro Group	HRC (18/30)	36	630	33
MacArtney	SubConn (7.6 MW)	11	400	6

RMS PumpTools	OceanPower V1 (3.6/6)	7.2	168	2
Siemens Tronic	SpecTRON 45 (26/45)	52	1,250	96
	SpecTRON 10+ (6/10)	12	630	11
	SpecTRON 8 (5/8.7)	10	355	5
Teledyne ODI	Nautilus WM15-220 (8.7/15)	17.5	220	6
	Nautilus WM10-250 (6/10)	12	250	4

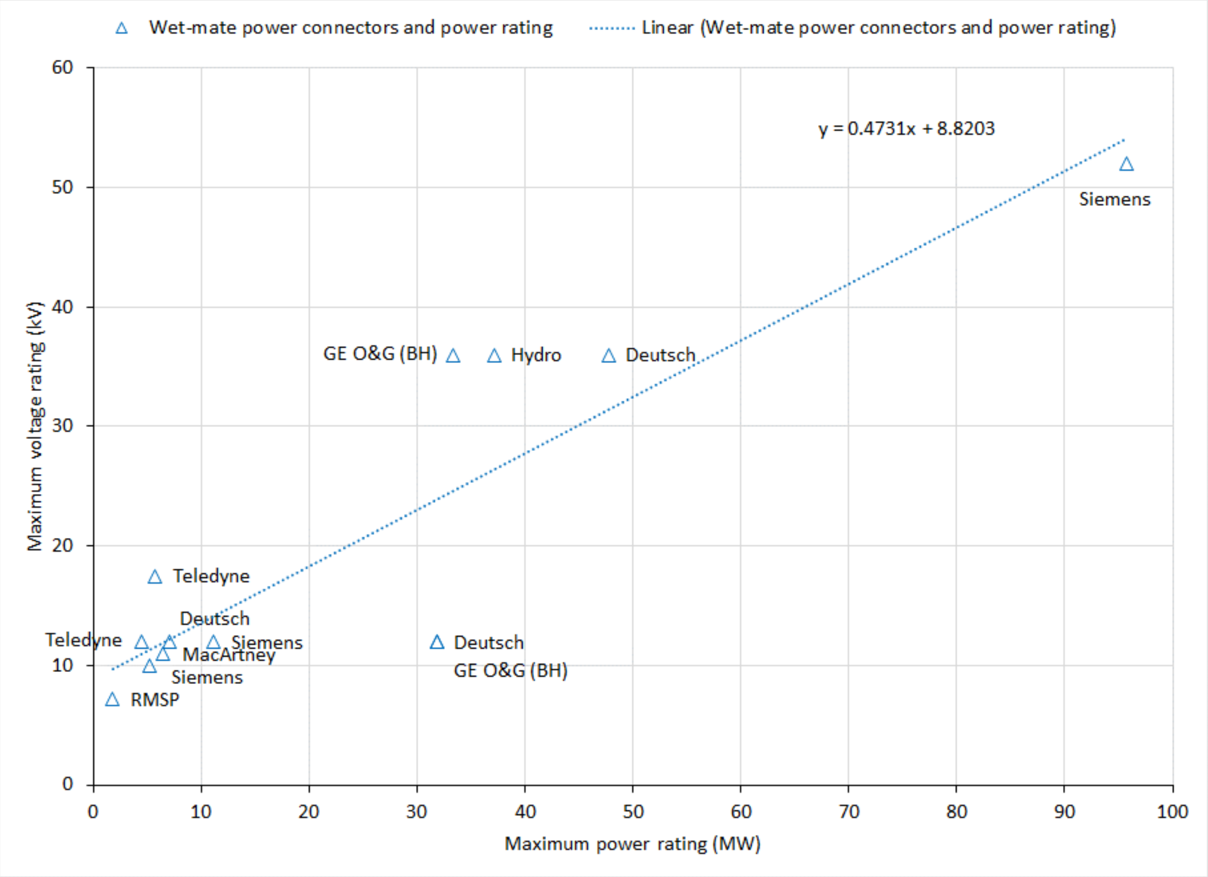

Figure 4.1 Comparison of different types of high voltage wet mate connectors from manufacturers in the offshore subsea environment and comparison of maximum voltage and power ratings.

5 ELECTRICAL SPECIFICATIONS AND CABLE TYPE

5.1 Optimum connector performance

There are a wide range of factors that need to be address when optimising the performance of a given wet mate connector. Designs need to ensure that adequate filtering is in place to mitigate electromagnetic interference and radio frequency interference. Those of which would cause reductions to the power quality delivered as well as disruptions to the fibre optic communications of the cables at either side of the wet mate connection. In addition to filtering, shielding will be required to protect connector components from high voltages and currents.

Wet mate connector designs will also need to consider the harsh environments in which they operate and be robust enough to resist the effects of wave motion, corrosion, and high water pressure over extended periods of time[46]. To resist the above, material choice is crucial. Typically, wet mate connector bodies will be made of materials such as Titanium and Inconel (an alloy primarily formed from nickel and chromium) because of their strength and resistance to corrosion and heat. Alternatively, super duplex or 316L stainless steel can also be used as wet mate connector bodies.

Mitigation of partial discharge and treeing is another design factor that needs to be considered. This becomes of even greater importance when considering future wet mate connector. Which are designed to operate at voltages of 66 kV and above, with partial discharge and treeing becoming more prevalent at higher voltages. Partial discharge is the result of localised dielectric breakdown to a wet mates solid or fluid electrical insulation when subject to high voltage stress. This tends to begin at voltages of around 6 kV in spaces or cracks at conductor-dielectric interfaces within a solid insulator, or in bubbles within liquid dielectrics. This leads to progressive deterioration of insulating materials, and ultimately to full electrical breakdown. The effect of partial discharge within solid dielectrics is the formation of numerous branching, partially conducting, discharge channels – this is known as treeing[47]. Treeing is a gradual degradation of a cable’s dielectric material by water, moisture, and/or vapours. The prolonged presence of water and electric field that subsea cables are exposed to can produce tree like structures that cause localised damage and eventual cable failure[48].

6 SITE CONSIDERATIONS AND MECHANICAL PROPERTIES

6.1 Wet mate connector properties

For wet mate connectors to be successfully implemented at numerous locations across the Celtic Sea, site considerations must first be addressed in advance. Regarding the bathymetry of the Celtic Sea. As much of the seabed depth is in the region of 90 – 100 m which does not present issues when using wet mate connectors, with many being designed to operate in water depths of 2 km and deeper.

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[46] EATON - Subsea connectors and cable assemblies

[47] Final Report Summary - WETMATE (WETMATE – a 33kV Subsea Wet-MateableConnector for Offshore Renewable Energy) | FP7 | CORDIS | European Commission (europa.eu)

[48] Wind-Energy-Article-v5a.pdf (wavetidalenergynetwork.co.uk)

When developing FOW over large areas of the Celtic Sea, steps will need to be taken to ensure all parties that have presence in the vicinity can continue their respective operations with minimal disruption. There are numerous high density shipping lanes within the Celtic Sea, some of which run through areas which have been proposed for future FOW development as seen below in Figure 6.1.

From Figure 6.1, it can be seen that proposed sites 1 and 2 run in close proximity to two of the busiest shipping lanes in the Celtic Sea. If any future sites are to be located near such busy shipping lanes, then adequate planning needs to be in place to prevent shipping traffic from interfering with installation and O&M of wet mate connectors and the wider OSW electrical infrastructure. For O&M that is required in the harshest of future Celtic Sea sites, unmanned vehicles will play an increasing role, including ROV. For this purpose, it is likely that wet mate connectors used at these sites will be of an ROV matable design. Again, on the harshness of the conditions at any proposed FOW sites in the Celtic Sea, whatever wet mate design is selected to form inter-array electrical connections; they will need to be designed with the capability of handling the strongest of wave motions alongside suitably designed HVAC dynamic cables.

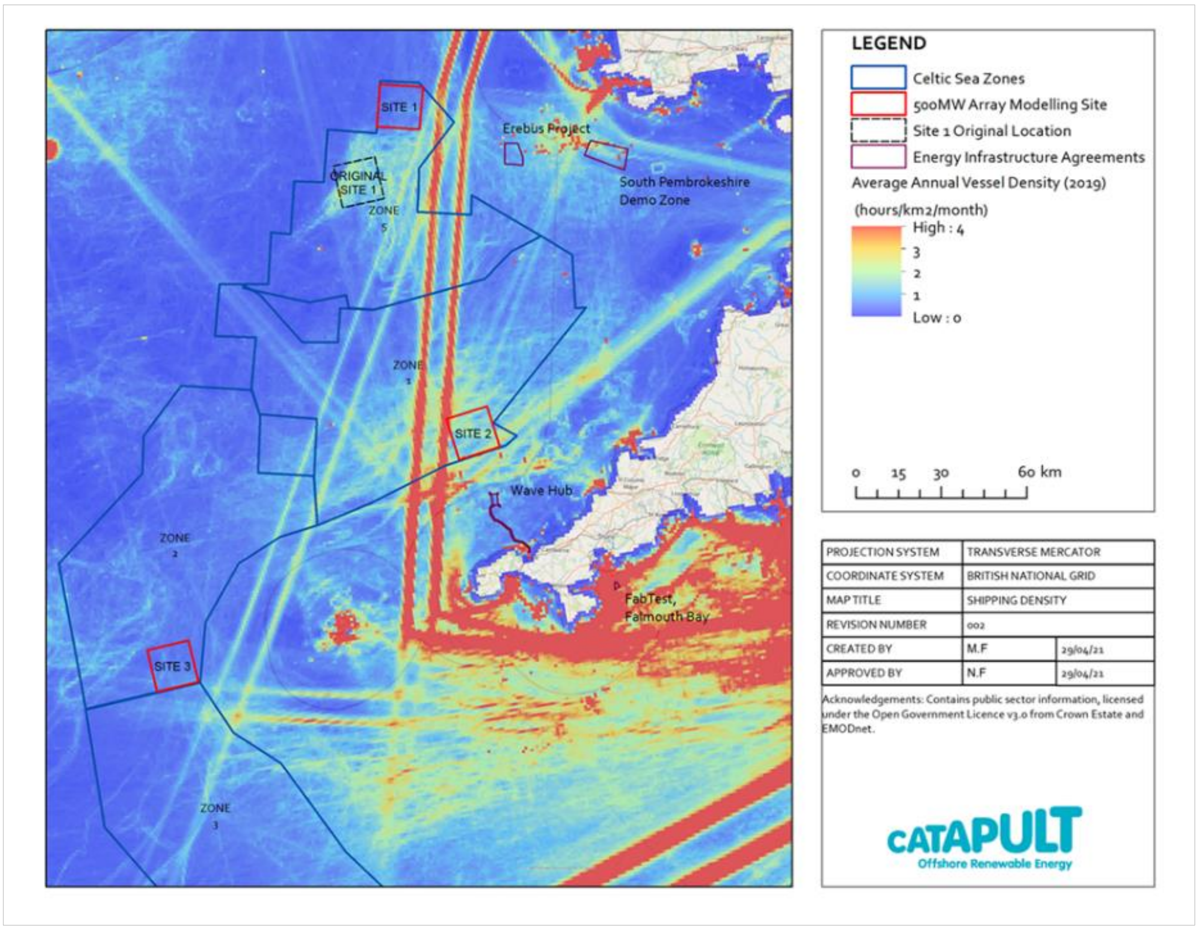

Figure 6.1 Shipping Lane Density and Proposed Celtic Sea Sites[49]

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[49] ORE Catapult Cornwall FLOW Accelerator project 500MW array modelling sites

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

Current wet mate subsea connectors split by maximum cable voltage and maximum current ratings are described in detail in this report as potential technology for the future of OSW. This is captured in Key Finding No.1 and 3 earlier in this report. The wet mate connectors would be used at the seabed, under pressure at extreme depths, to connect lengths of cable and FOW arrays together; the subsea connectors would undergo several mate and de-mate cycles across the 25 to 30-year life cycle as part of anticipated maintenance and unplanned repair operations.

The grid connection for FOW development is a vital component as discussed in the report and captured by Key Finding No. 4; both onshore and offshore substations will require radical change and a new approach to meet future targets (circa 4 GW). As discussed, Western Power Distribution operates the distribution network on the North Cornish coast, with closest bulk substations at Yelland, Watchet, and Barnstable. The transmission network is operated by NGESO[50]. The radical change of thinking is producing ideas like multi-purpose interconnectors (MPI) to best prepare the electrical network for an influx of offshore renewable energy capacity. The downside of MPIs is that NGESO investment would have to seriously upgrade their existing substations throughout the entire region.

ORE Catapult has identified up to 20% of FOW project cost is spent on electrical infrastructure capital expenditure. Previous demonstration projects, like Wave Hub and the newest demonstration project PDZ are showing various options for offshore substation technology to consider in the Celtic Sea. These projects have provided some useful learning and Wave Hub remains a useful asset (as captured in Key Finding No.2). However, as larger FOW projects develop in the Celtic Sea, more extensive electrical infrastructure will be required; switchgear and converter stations (in both HVAC and HVDC), and reactive power compensation for both offshore and onshore substations.

In conclusion, another vital element will be the laying of cables, with subsea being the most challenging. Future projects have the opportunity to utilise some of the leading manufacturers in the region for the construction and installation of onshore substations including Hellermann Tyton, Balfour Beatty, and Morgan Sindall. This is also recognised by Key Finding No.4 which highlights the need to nurture and sustain engineering skills and capability.

7.2 Next Steps

ORE Catapult, the lead partner for electrical infrastructure activity in work package 4, will build on the outcome of this report. With further research in electrical architecture and cable design concepts, there will be two additional high-level reports within work package 4 for the following themes:

1. The future potential role of offshore multipurpose connectors – Title: A strategic offshore transmission network for the Celtic Sea (due early 2023)

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[50] New study reveals floating offshore wind benefits for the South West - Regen

2. The SW transmission network and floating offshore wind in the Celtic Sea – Title: Integrating future floating wind developments into the SW and Wales energy network (due early 2023)

Focus areas will be: wet mate technology; review of models for substation coordination; and NGESO HND alignment under OTNR. Follow on work will consider how HVDC can be integrated into the overall strategic plan for future transmission and how the electrical infrastructure will need to align with the expansion of offshore renewable energy within the Celtic Sea.

According to Ofgem (relating to OTNR activity), reference is made to the EU (offshore wind farms in Danish and German jurisdiction) case study of Krieger's Flak where multi-purpose interconnectors are likely and have an important role to play in supporting the decarbonisation agenda[51]. This aligns with government ambitions (part of Key Finding No.4), and is likely to have positive impacts for consumer cost reduction in the long run, and an electrical system with redundancy capabilities. The development of multi-purpose interconnectors also offers an opportunity for developers to work together in joint ventures from early opportunity models through to project coordination.

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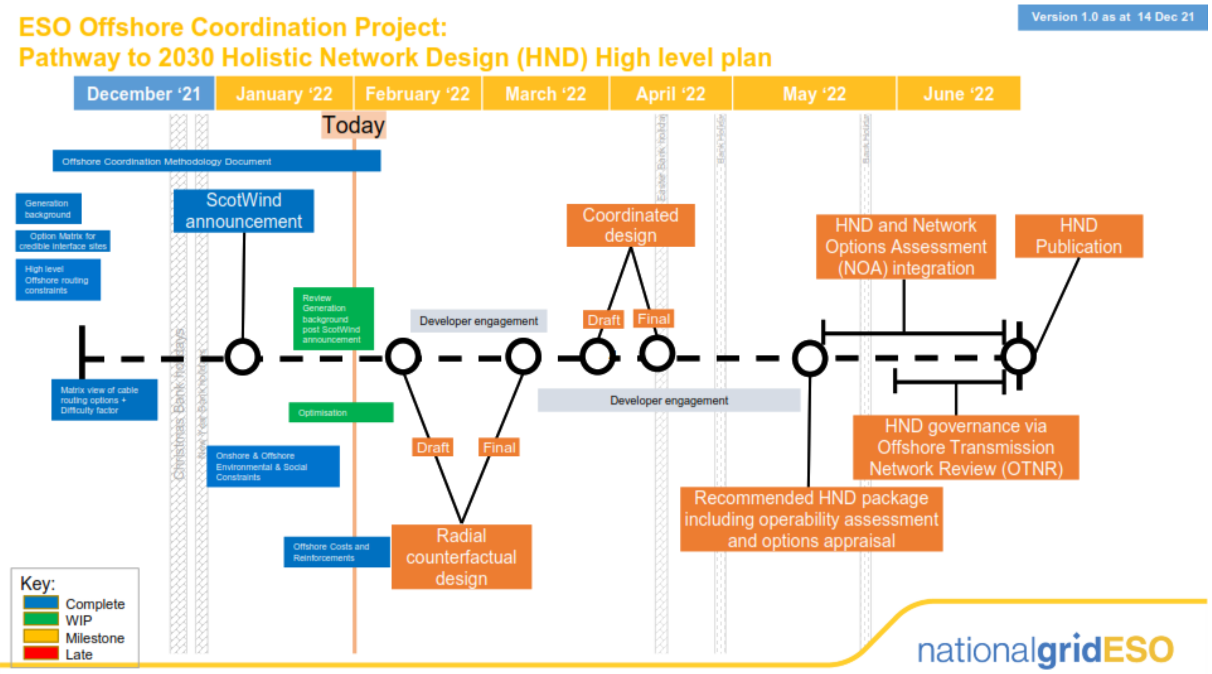
[51] Offshore transmission network review - GOV.UK (www.gov.uk)

APPENDIX 1 OTNR NGESO OFFSHORE COORDINATED PROJECTS: PATHWAY TO 2030 HOLISTIC NETWORK DESIGN

OTNR (TCE) NGESO Coordinated project: Pathway to 2030 holistic network design high level plan[52]

The proposals in summary quoted by the NGESO are as follows[53],

- "The Pathway to 2030 Holistic Network Design (HND) is a major step for Great Britain in delivering cheap, clean energy from offshore wind.
- It sets out a single, integrated design that supports the large-scale delivery of electricity generated from offshore wind, taking power to where it's needed across Great Britain.
- The HND facilitates the connection of 23 GW wind, helping to deliver the Government's ambition for 50 GW connected offshore wind by 2030.
- This is a first step towards more centralised, strategic network planning that is critical for delivering affordable, clean and secure power, as we journey towards our net zero future."



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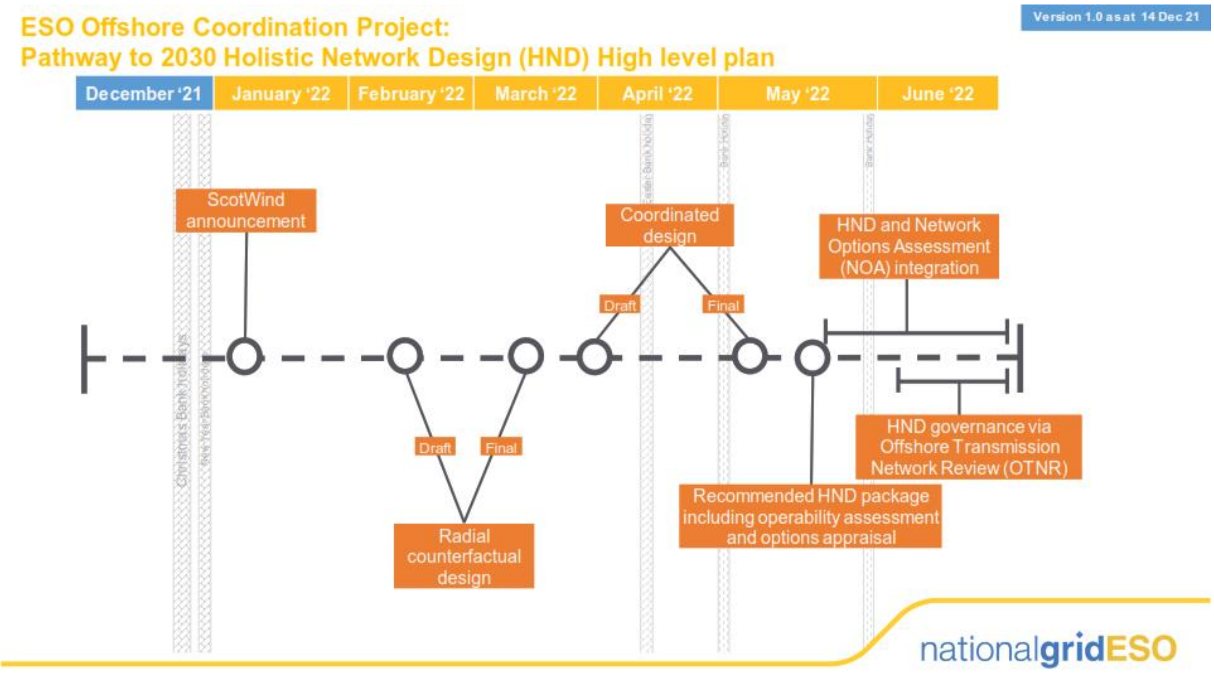
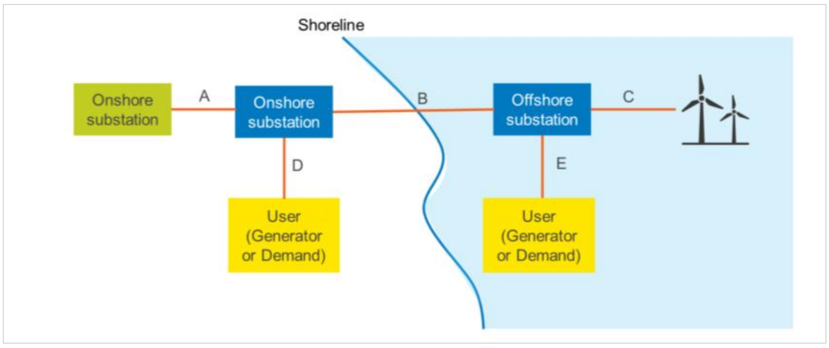
[52] Offshore Transmission Network Review-webinar-presentation-Jan-2022
[53] Offshore Coordination Project - latest news and staying informed | National Grid ESO

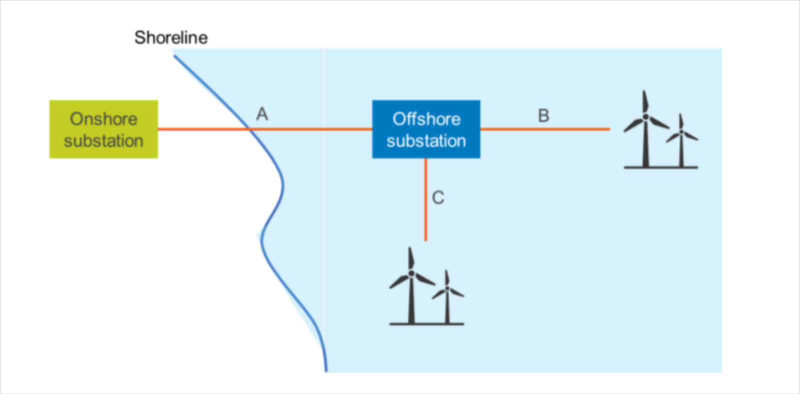

Version 1.0 as at 14 Dec 21
ESO Offshore Coordination Project:
Pathway to 2030 Holistic Network Design (HND) High level plan
December '21
January '22
February '22
March '22
April '22
May '22
June '22
Christmas Bank holidays
New Year Bank holiday
Easter Bank holiday
Bank Holiday
Bank Holiday
ScotWind announcement
Draft
Final
Radial counterfactual design
Draft
Final
Coordinated design
Recommended HND package including operability assessment and options appraisal
HND and Network Options Assessment (NOA) integration
HND governance via Offshore Transmission Network Review (OTNR)
nationalgridESO

APPENDIX 2 NGESO OFFSHORE COORDINATION: EARLY OPPORTUNITIES UPDATE

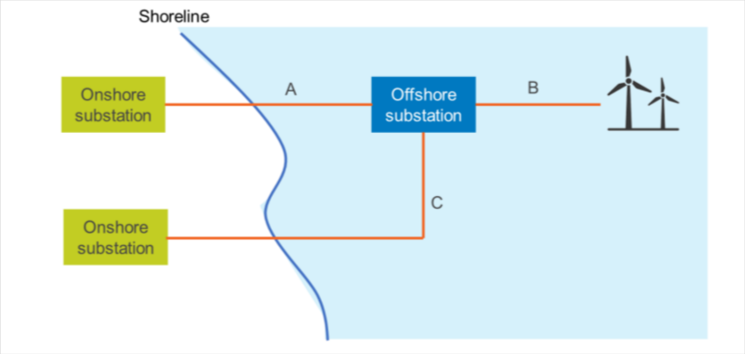
Early opportunities models: Connection of electricity storage or a demand user to an offshore transmission system[54]



Shared offshore transmission system



Connection to a Transmission Owner (TO) owned bootstrap



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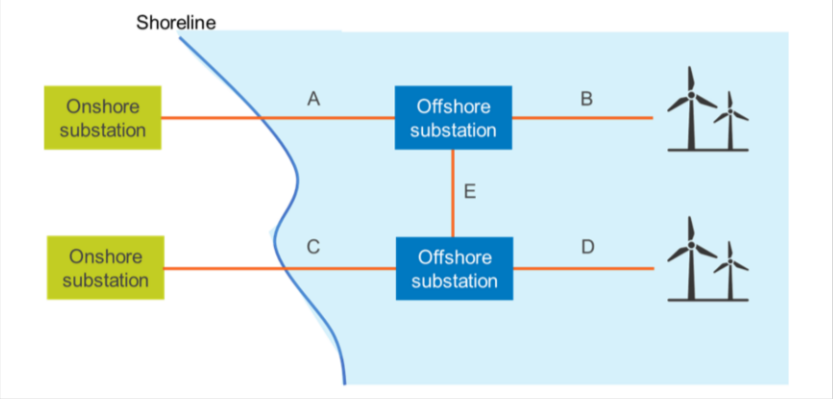
[54] National Grid ESO, Offshore Coordination: Early Opportunities Update May 2022

Quasi bootstrap



Multi-purpose interconnector (IC)-led model and Offshore Transmission Owner (OFTO)-led model

Diagram 1 – one market

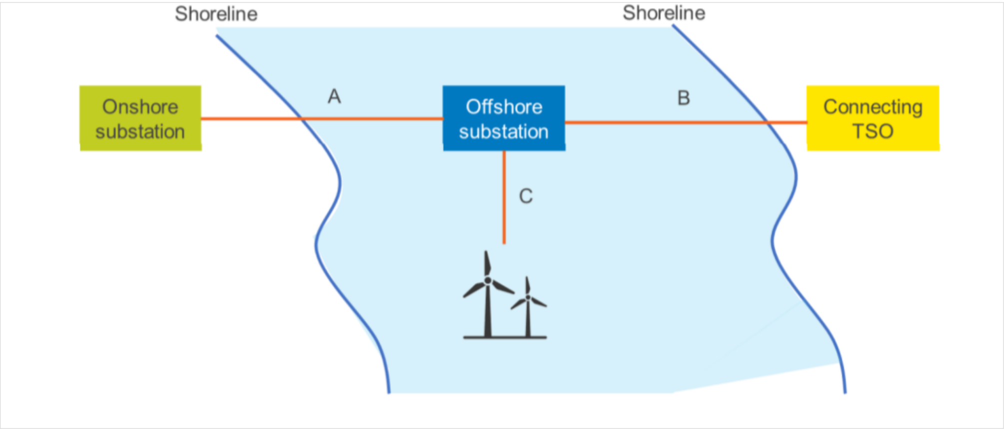
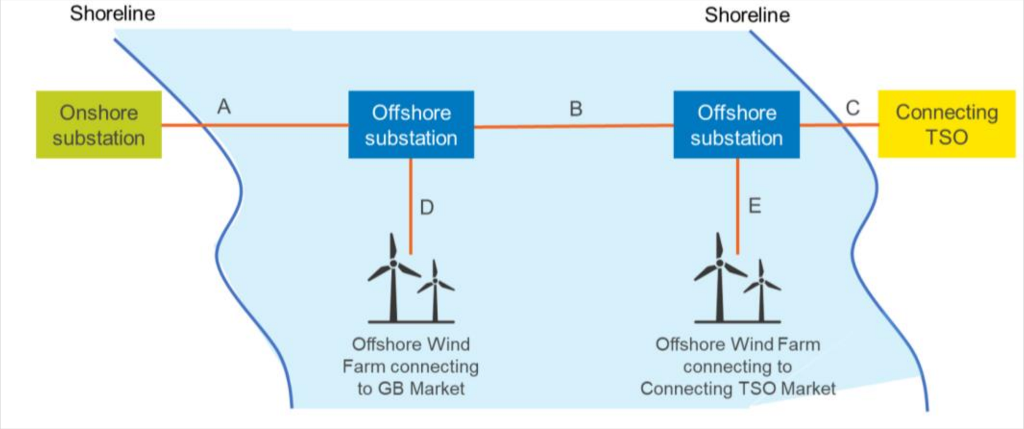
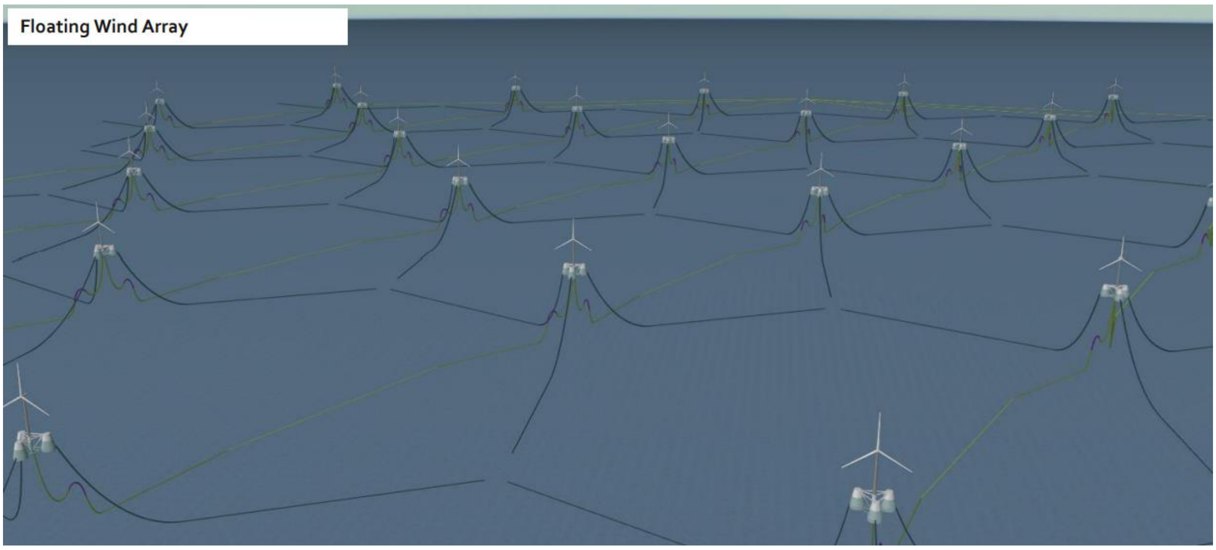


Diagram 2 – two markets

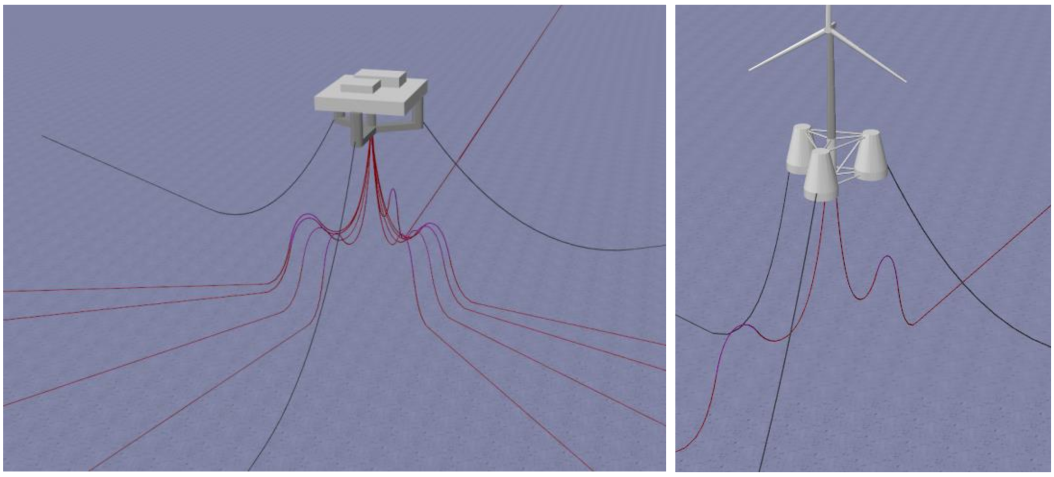


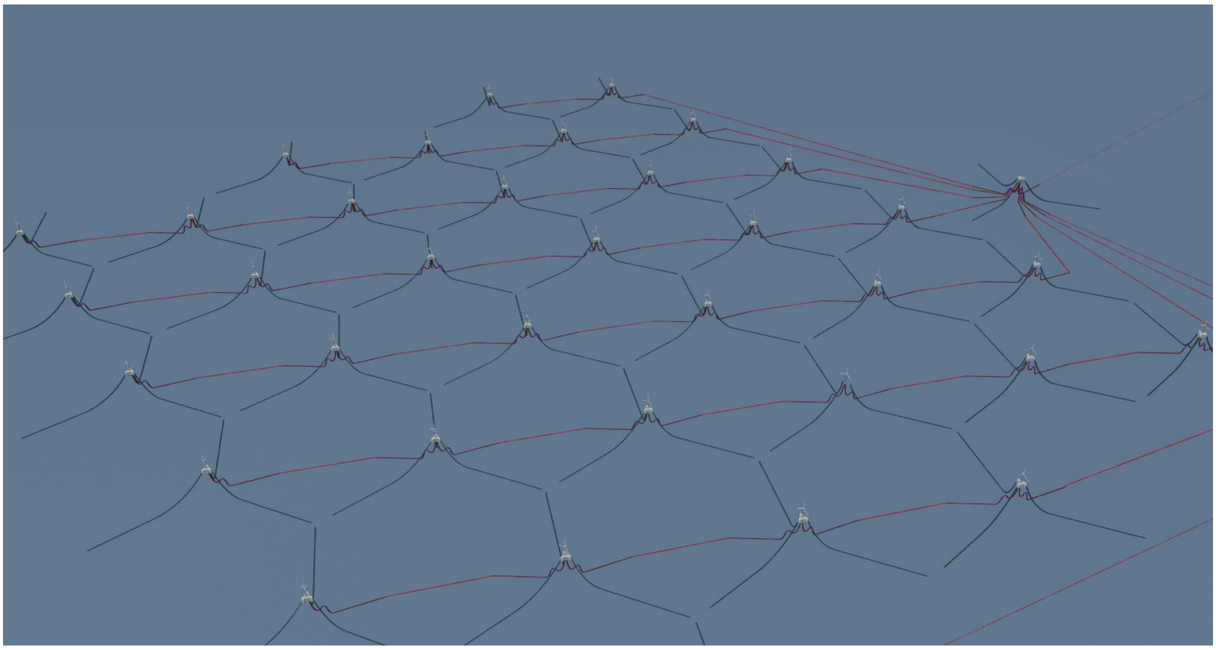
APPENDIX 3 ORE CATAPULT DESIGN THE BIG PITURE: FLOATING WIND POWER CABLES

- 2000-2020: Oil & Gas dynamic power cables ≈**50** cables
- 2021: 0.1GW floating wind; **23** dynamic inter-array cables (≈5MW turbines)
- 2021-2035: 15GW floating for **ScotWind**; **1000** dynamic cables (≈15MW turbines)
- 2050: 50GW projected by ORE Catapult; **3000** dynamic cables (≈20MW turbines)



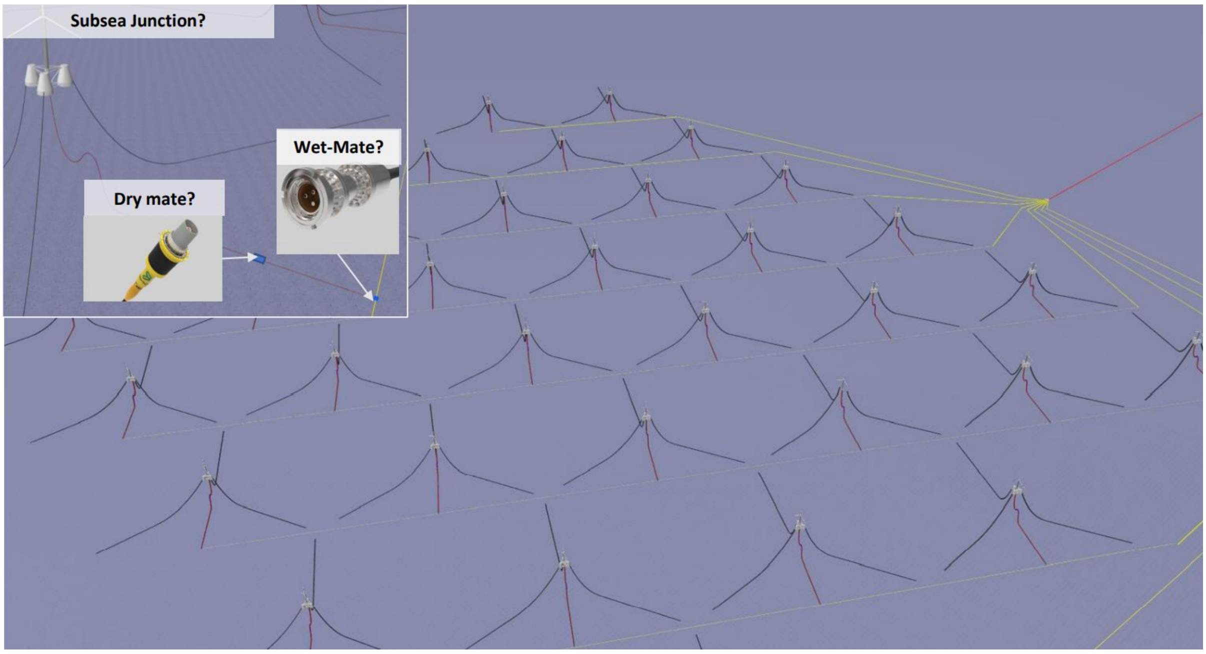
APPENDIX 4 ORE CATAPULT 500 MW FLOATING WIND ARRAY: DAISY CHAIN CONFIGURATION



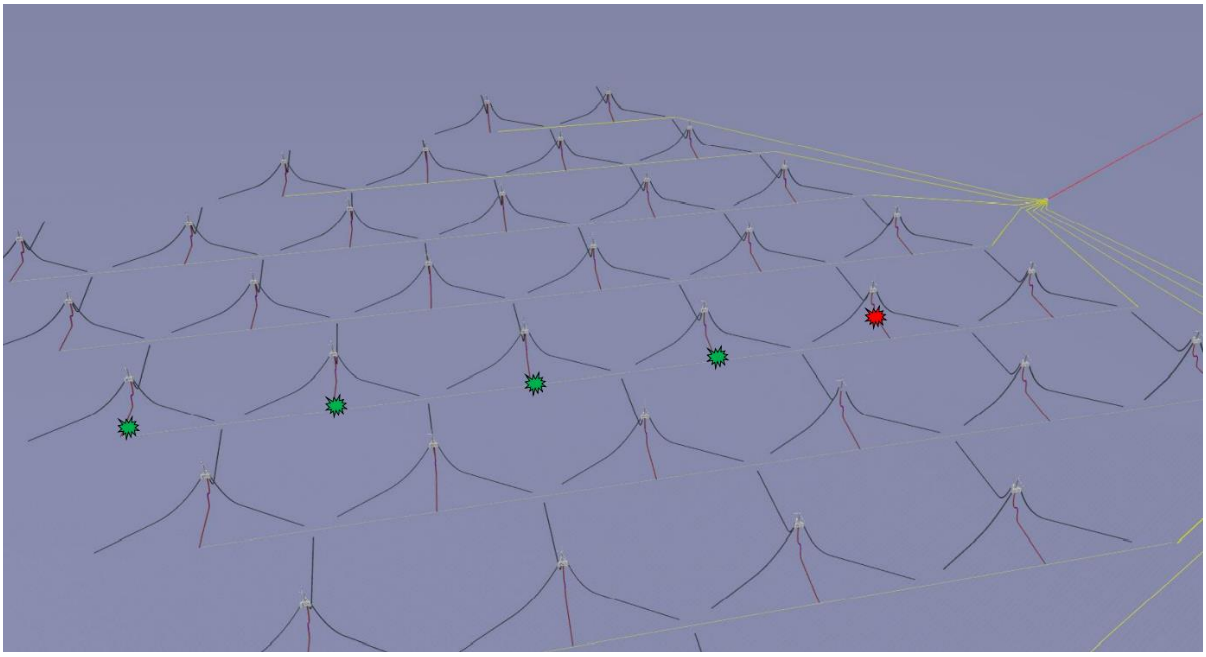


APPENDIX 5 ORE CATAPULT DESIGNS SUBSEA CONNECTOR CONFIGURATION

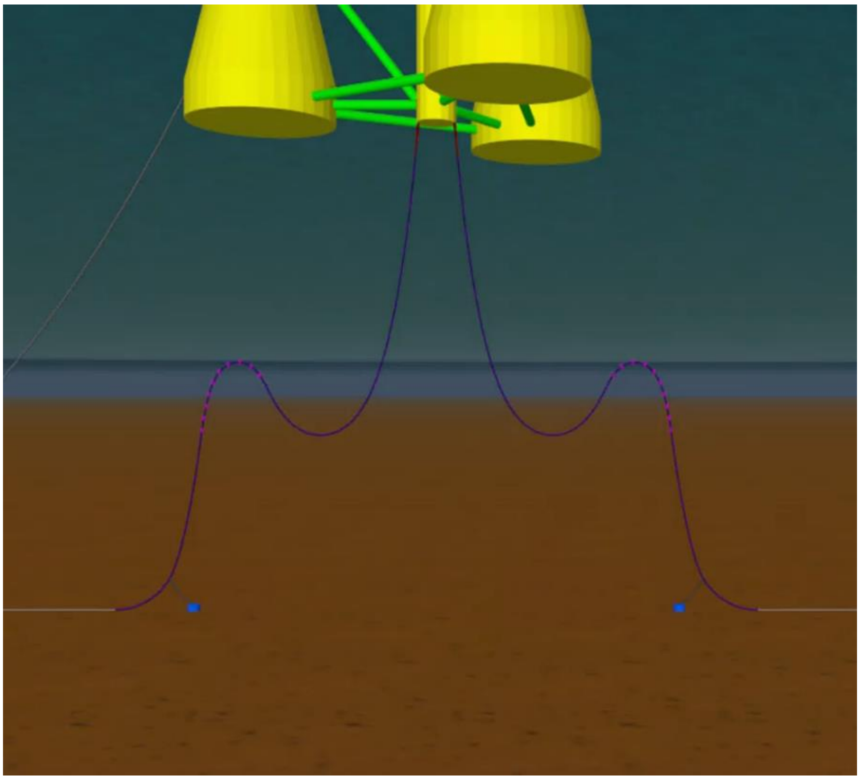
Subsea connector configuration (HV power wet mate connector & dry mate connectors)

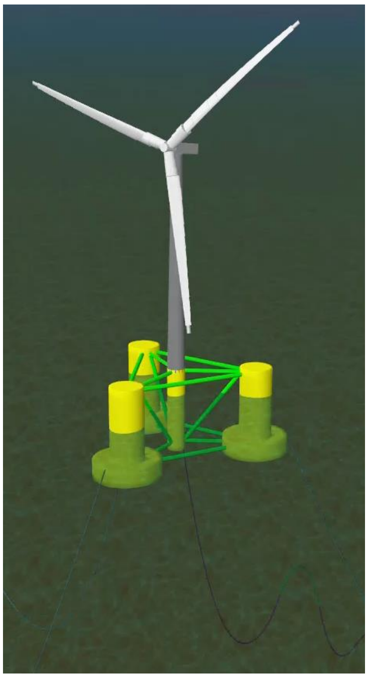


Field reliability considerations: array layout (use of subsea connectors can give enhanced field resilience to cable failure)



APPENDIX 6 ORE CATAPULT DESIGNS DYNAMIC INTER-ARRAY CABLES – SHALLOW WATER CHALLENGES





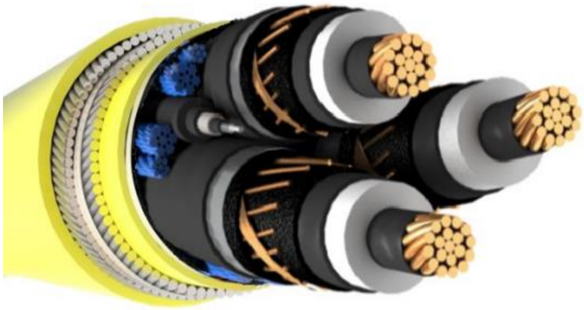
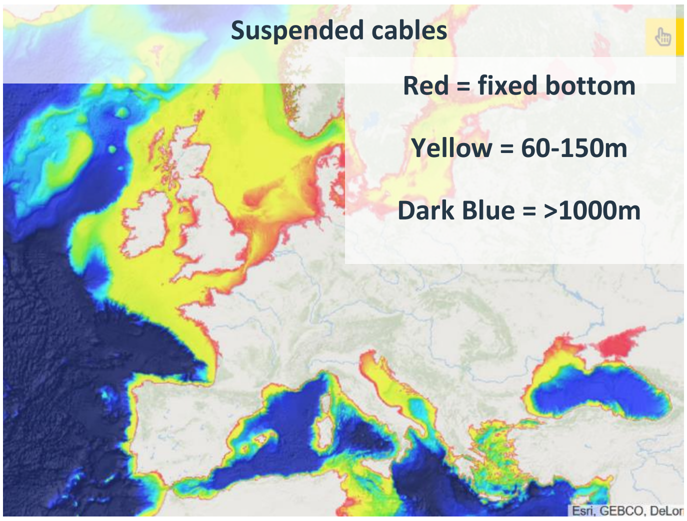


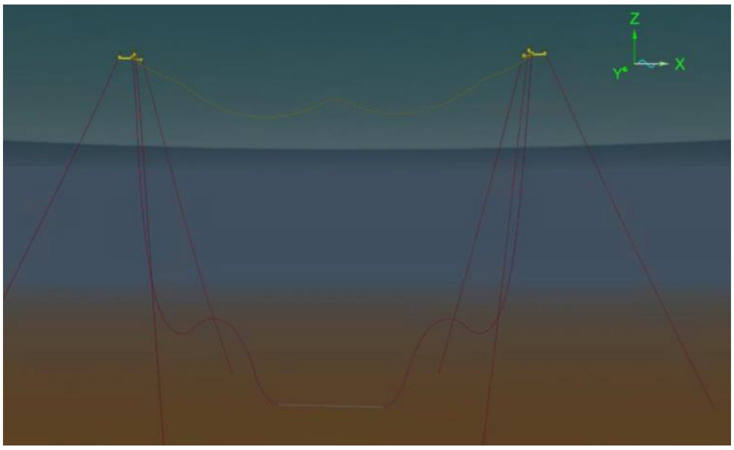
Image courtesy of JDR

APPENDIX 7 ORE CATAPULT DESIGNS DEEP WATER CABLE DESIGN CHALLENGES

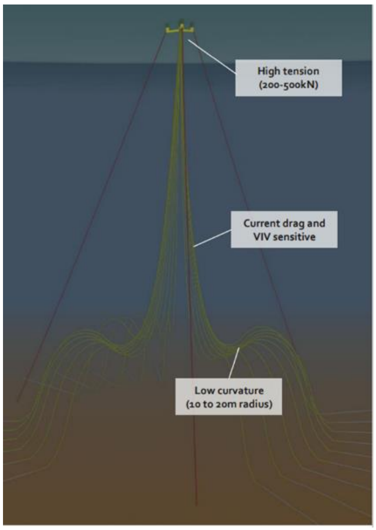


Hellenic light weight cable (Flotant D3.4)

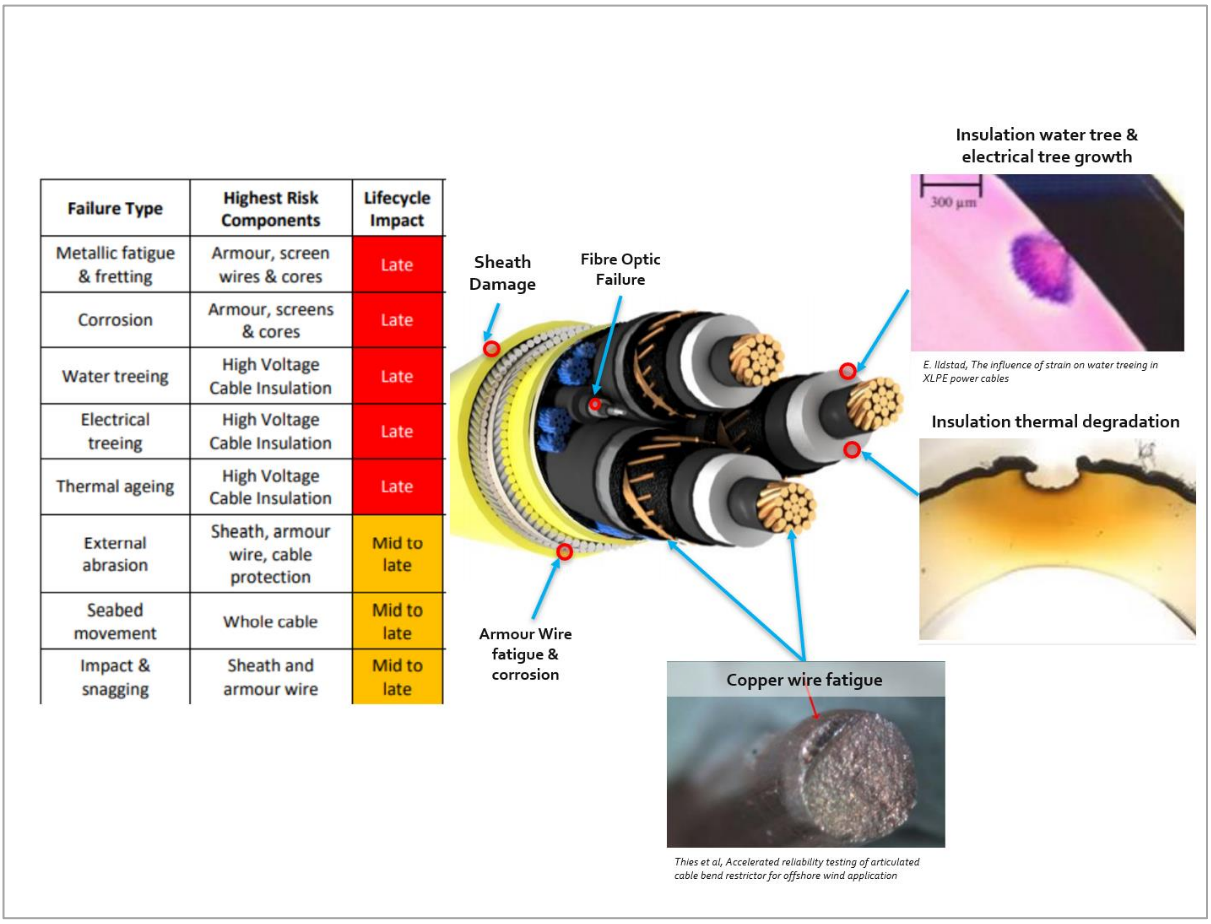
Suspended cables



Conventional deep-water O&G configuration



APPENDIX 8 ORE CATAPULT HIGH VOLTAGE POWER CABLES INTEGRITY PROBLEMS

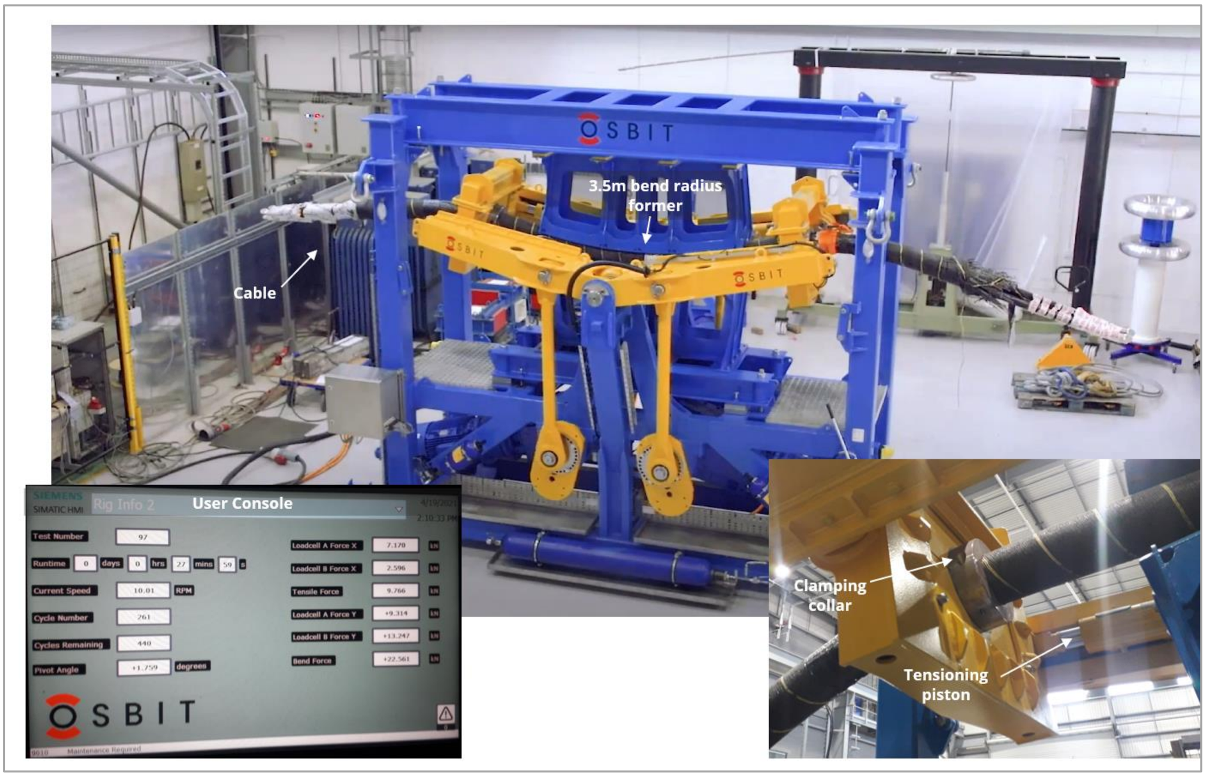


Failure Type	Highest Risk Components	Lifecycle Impact
Metallic fatigue & fretting	Armour, screen wires & cores	Late
Corrosion	Armour, screens & cores	Late
Water treeing	High Voltage Cable Insulation	Late
Electrical treeing	High Voltage Cable Insulation	Late
Thermal ageing	High Voltage Cable Insulation	Late
External abrasion	Sheath, armour wire, cable protection	Mid to late
Seabed movement	Whole cable	Mid to late
Impact & snagging	Sheath and armour wire	Mid to late

E. Ildstad, The influence of strain on water treeing in XLPE power cables

Thies et al, Accelerated reliability testing of articulated cable bend restrictor for offshore wind application

APPENDIX 9 ORE CATAPULT DYNAMIC CABLE TEST RIG



4/19/2021
2:10:33 PM

Test Number: 97
Runtime: 0 days 0 hrs 27 mins 59 s
Current Speed: 10.01 RPM
Cycle Number: 261
Cycles Remaining: 440
Pivot Angle: +1.759 degrees

Loadcell A Force X: 7.170 kN
Loadcell B Force X: 2.596 kN
Tensile Force: 9.766 kN
Loadcell A Force Y: +9.314 kN
Loadcell B Force Y: +13.247 kN
Bend Force: +22.561 kN

0010 Maintenance Required

CATAPULT
Offshore Renewable Energy

GLASGOW

ORE Catapult
Inovo
121 George Street
Glasgow
G1 1RD

+44 (0)333 004 1400

BLYTH

National Renewable
Energy Centre
Offshore House
Albert Street, Blyth
Northumberland
NE24 1LZ

+44 (0)1670 359555

LEVENMOUTH

Fife Renewables Innovation
Centre (FRIC)
Ajax Way
Leven
KY8 3RS

+44 (0)1670 357649

GRIMSBY

O&M Centre of Excellence
ORE Catapult, Port Office
Cleethorpe Road
Grimsby
DN31 3LL

+44 (0)333 004 1400

ABERDEEN

Subsea UK
30 Abercrombie Court
Prospect Road, Westhill
Aberdeenshire
AB32 6FE

07436 389067

CORNWALL

Hayle Marine Renewables
Business Park
North Quay
Hayle, Cornwall
TR27 4DD

+44 (0)1872 322 119

PEMBROKESHIRE

Marine Energy Engineering
Centre of Excellence (MEECE)
Bridge Innovation Centre
Pembrokeshire Science
& Technology Park
Pembroke Dock, Wales
SA72 6UN

+44 (0)333 004 1400

CHINA

11th Floor
Lan Se Zhi Gu No. 15
Ke Ji Avenue,
Hi-Tech Zone
Yantai City
Shandong Province
China

+44 (0)333 004 1400

LOWESTOFT

OrbisEnergy
Wilde Street
Lowestoft
Suffolk
NR32 1XH

01502 563368