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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

# DEEP WATER DYNAMIC CABLE SOLUTIONS - PUBLIC SUMMARY REPORT

PN000659-005-WP6: Public Summary Report



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## DOCUMENT HISTORY

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|          |            |               |                        |               |                      |

## PREFACE

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This report summarises the findings from the DC12: Deep Water Dynamic Cable Solutions project, which is part of the Offshore Renewable Energy (ORE) Catapult's Floating Offshore Wind Centre of Excellence (FOW CoE). The FOW CoE is a collaborative programme with industry, academic and stakeholder partners.

The vision of the FOW CoE is to establish an internationally recognised centre of excellence in FOW. This CoE will work towards reducing the Levelised Cost of Energy (LCoE) from floating wind to a commercially manageable rate, cutting back development time for FOW farms, developing opportunities for the local supply chain, and driving innovation in manufacturing, installation and Operations and Maintenance (O&M) methodologies in FOW.

More details on the FOW CoE can be found at <https://ore.catapult.org.uk/what-we-do/innovation/fowcoe/>.

An overview of the DC12: Deep Water Dynamic Cable Solutions work packages is provided below:

- Work Package 1 (WP1): Project Management, Integration and Scoping
- Work Package 2 (WP2): Deep Water Global Market Size
- Work Package 3 (WP3): Case Study Deep Water Cable Designs
- Work Package 4 (WP4): Supply Chain Opportunities and Development Needs
- Work Package 5 (WP5): Cost Comparison
- **Work Package 6 (WP6): Public Summary Report**

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## NOMENCLATURE

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|       |                                 |
|-------|---------------------------------|
| AEP   | Annual Energy Production        |
| CAPEX | Capital Expenditure             |
| CoE   | Centre of Excellence            |
| CSA   | Cross Section Area              |
| DECEX | Decommissioning Expenditure     |
| DEVEX | Development Expenditure         |
| ERM   | Emergency Release Mechanism     |
| FOW   | Floating Offshore Wind          |
| FOWF  | Floating Offshore Wind Farm     |
| FOWT  | Floating Offshore Wind Turbine  |
| GHG   | Green House Gas                 |
| GIS   | Geographic Information System   |
| GW    | Giga-Watt                       |
| HOP   | Hang-Off Point                  |
| HSE   | Health, Safety and Environment  |
| km    | Kilometre                       |
| kN    | Kilonewton                      |
| kV    | Kilovolt                        |
| m     | Metre                           |
| MW    | Mega-Watt                       |
| OEM   | Original Equipment Manufacturer |

|      |                                    |
|------|------------------------------------|
| O&G  | Oil & Gas                          |
| O&M  | Operation & Maintenance            |
| OPEX | Operational Expenditure            |
| OREC | Offshore Renewable Energy Catapult |
| LCoE | Levelised Cost of Energy           |
| ROV  | Remotely Operated Vehicle          |
| SJB  | Subsea Junction Box                |
| STU  | Subsea Termination Unit            |
| TDP  | Touch Down Point                   |
| T2P  | Tow-to-Port                        |
| TRL  | Technology Readiness Level         |
| W2W  | Walk-to-Work                       |

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# 1 INTRODUCTION

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Floating offshore wind (FOW) projects in UK waters are expected to expand significantly in scale and complexity between 2020 and 2035, evolving from small demonstration projects to large-scale commercial ventures. This trend aligns with the broader growth in offshore wind development in the UK—where the goal is to achieve "net zero" by 2050 (and 2045 in Scotland)—and globally.

While the cable configurations and supply chain capabilities for shallow water projects in the UK are well established, deep water floating wind presents a newer, less understood challenge, particularly in terms of inter-array cable requirements. This technology is being explored for sites identified as deep water locations in the Atlantic, the Mediterranean Sea, the US East and West coasts, and parts of Asia. "Deep water" in the context of this project refers to depths ranging from 300 m to 2,000 m, compared to the 60 m to 150 m depths typical of shallow floating wind deployments in UK waters. The UK supply chain has the potential to export deep water cable and mooring solutions to these markets, building on its strong foundation in fixed wind and oil and gas (O&G) engineering.

The FOW CoE DC12 project is a comprehensive study exploring the opportunities in deep water floating wind. It assesses market size, design feasibility, supply chain capability, and the levelised cost of energy (LCoE) associated with deploying working configurations in this relatively uncharted territory.

The project's initial phase focused on identifying the "size of the prize" by mapping out potential deep water sites with strong wind resources located near population centres.

An assessment of optimal cable configurations was then conducted for a limited set of representative deep water depths, considering the varying conditions in these environments. Insights from this assessment were then extrapolated to determine the requirements for a 1 GW commercial-scale wind farm, which served as a benchmark for analysing the supply chain's capacity to meet deep water demands. This analysis also highlighted development needs and gaps in the current market for dynamic cables.

Finally, a cost analysis study was performed, building on the topologies used in DC06: Dynamic Cable Topology Comparison [1]. The study was expanded to examine the implications and impacts of deep water cable configurations on the overall LCoE for each scenario.

## 1.1 Objectives

- Identify the global deep water floating wind market size;
- Analyse and define a range of feasible deep water cable systems;
- Understand the opportunity and development needs of the UK supply chain;
- Define the cost implications and optimal systems in different deep water depths.

## 1.2 Considerations

This report considers:

- Near-term market outlook for 2025-2030, which serves as the assessment timeframe.

- All cables to be 132 kV. This is due to the expected electrical losses observed with 66 kV cables over the lengths required for feasible deep water configurations.
- A power density assumption of 3 MW/ km<sup>2</sup>.
- 130 km as the High Voltage Alternating Current (HVAC) export limit for site selection.
- Commercial-scale array topologies with a capacity of 1 GW.
- The cost associated with all phases of the project lifecycle, including purchase costs, installation, planned maintenance, unplanned failures, power core losses, and tow-to-port (T2P) costs.

## 2 DEEP WATER GLOBAL MARKET SIZE

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The first objective was to assess the resource potential for deep water floating wind, expanding the focus beyond traditional shallow to mid-depth waters (60-300 m, as defined in this study). The initial goal was to identify areas with strong, consistent wind resources while considering proximity to energy demand centres (population of 600,000+), local infrastructure capacity, regulatory frameworks, and potential constraints.

### 2.1 Critical Water Depths

To frame the analysis, the following depth categories were defined for the study:

- 60 m: Currently the limit for fixed wind turbines.
- 60 m to 150 m: Shallow floating wind.
- 150 m to 300 m: Mid-depth floating wind.
- 300 m to 500 m: Deep floating wind.
- 500 m to 1000 m: Very deep floating wind.
- 1000 m to 2000 m: Extremely deep floating wind.
- 2000 m+: Ultra deep floating wind.

### 2.2 Literature Review

The assessment began with a literature review to gather key insights into the FOW market, drawing on previous studies to inform the criteria for evaluating market size in deeper waters.

As a benchmark, the PR12: International Market Projections study by ORE Catapult (OREC) and OWC [2] was used. This study identified 22 markets with the short-term potential for FOW development. These markets were analysed using weighted criteria, considering technical and policy drivers, the commercial investment landscape, and market facilitators. These factors were scored to evaluate the “readiness” of that market for offshore wind and the speed of market development’ [2]. The markets with the highest weighted scores are predominantly those with FOW demonstrators, clear policy drivers and strong wind power solicitations – as well as existing large power markets, where electricity generation and sales represent viable and commercially proven routes to market [2]. This is shown in Figure 2-1.

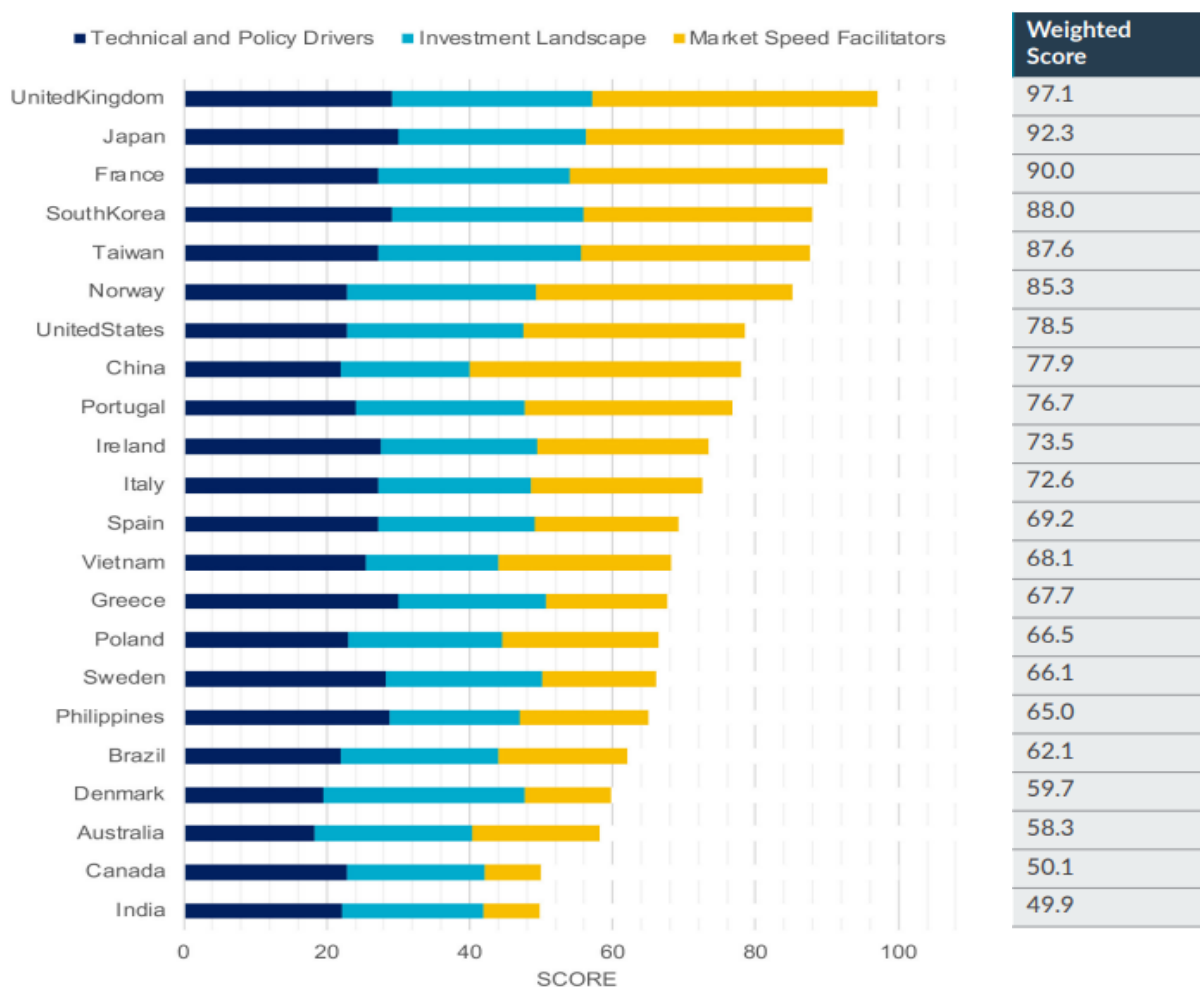


Figure 2-1: Weighted scores of floating offshore wind near-term markets [2].

The 22 near-term markets assessed in the PR12 report have an unconstrained (gross) technical resource capacity of 24,000 GW. This emphasises a vast development opportunity for potential exploitation and is backed by powerful global policy drivers aiming to reduce greenhouse gas (GHG) emissions and amplify the route to net zero – an overview of some of the key global policies from this study are outlined in Figure 2-2.

| Region/country | Policy target                              |
|----------------|--------------------------------------------|
| European Union | 65-85 GW by 2030                           |
| China          | 5 GW by 2020 (10 GW construction capacity) |
| United States  | 22 GW by 2030                              |
| India          | 5 GW by 2022 and 30 GW by 2030             |
| Chinese Taipei | 5.5 GW by 2025 and 10 GW by 2030           |
| Korea          | 12 GW by 2030                              |

Figure 2-2: Key global policy targets [13].

## 2.3 Geographic Information Study

The framework for DC12 expanded on that used for PR12 utilising the same geographic information system (GIS) mapping tools to deliver a detailed global market assessment with the addition of further criteria to ensure relevant deep water markets were captured. The initial screening criteria are depicted in Figure 2-3.

| Market Speed Drivers         | Assessment Criteria                                |
|------------------------------|----------------------------------------------------|
| Technical and Policy Drivers | Technical potential for floating offshore wind     |
|                              | Power demand                                       |
|                              | Policy targets for offshore wind                   |
|                              | Competitiveness of floating in energy mix          |
| Investment Environment       | Ease of Doing Business Score                       |
|                              | ESMAP RISE score                                   |
|                              | Offshore wind players present in market            |
| Market Facilitators          | Offshore wind capacity already installed           |
|                              | Floating pilot projects installed                  |
|                              | Defined regulations and procedures                 |
|                              | Seabed leasing processes for floating wind started |

 Medium Impact on speed of commercial floating wind market development  
 High impact on speed of commercial floating wind market development

Figure 2-3: Deep water FOW market drivers [2].

The 22 territories identified in Figure 2-1 were evaluated for their suitability for deep water FOW development, assessing areas of deep water zones for the near-term markets in relation to km<sup>2</sup> of continuous area that meets the bathymetric range (300 - 2000 m).

Table 2-1: Deep water areas of near-term FOW markets.

| Near-Term Markets | Deep Water (300-2000m) Areas (km <sup>2</sup> ) |
|-------------------|-------------------------------------------------|
| United Kingdom    | 640,578                                         |
| Japan             | 994,768                                         |
| France            | 72,287                                          |
| South Korea       | 90,769                                          |
| Taiwan            | 106,839                                         |
| Norway            | 3,243,194                                       |
| United States     | 714,923                                         |
| China             | 98,835                                          |
| Portugal          | 58,667                                          |
| Ireland           | 308,479                                         |
| Italy             | 321,946                                         |
| Spain             | 249,590                                         |
| Vietnam           | 193,950                                         |
| Greece            | 242,301                                         |
| Sweden            | 3,403                                           |
| Philippines       | 377,858                                         |
| Brazil            | 337,984                                         |
| Denmark           | 1,572                                           |
| Australia         | 1,634,984                                       |
| Canada            | 5,153,539                                       |
| India             | 362,096                                         |

## 2.4 Results

Further layers were then added in to expand on the study and make it specific to deep water FOW:

- Continuous area (km<sup>2</sup>) of 300 – 2000 m water depths
- Average wind speed in deepwater areas greater than 7.2 m/s.

It was concluded that 21 of the markets met the criteria and highlighted a resource potential of 31,023 GW, as depicted in Table 2-2.

Table 2-2: Deep water resource potential of near-term FOW markets.

| Near-Term Markets | Deep Water FOW Resource Potential (GW) |
|-------------------|----------------------------------------|
| United Kingdom    | 1588.0                                 |
| Japan             | 2658.9                                 |
| France            | 128.7                                  |
| South Korea       | 204.0                                  |
| Taiwan            | 270.2                                  |
| Norway            | 6374.2                                 |
| United States     | 1029.2                                 |
| China             | 238.3                                  |
| Portugal          | 161.2                                  |
| Ireland           | 508.6                                  |
| Italy             | 313.4                                  |
| Spain             | 335.8                                  |
| Vietnam           | 399.0                                  |
| Greece            | 500.5                                  |
| Sweden            | 10.2                                   |
| Philippines       | 155.4                                  |
| Brazil            | 582.0                                  |
| Denmark           | 4.7                                    |
| Australia         | 3081.8                                 |
| Canada            | 12409.6                                |
| India             | 69.1                                   |

The final filter assessed the proximity of each deepwater area to major demand centres (130 km or less from a population centre of 600,000 people or more).

The results depicted that 15 of the near-term market territories have cities with a population greater than or equal to 600,000 and within 130 km of a deep water potential resource. The number of cities in each country that meets that criteria is listed below:

 Deep Water FOW Demand Centers ✓

- Japan: 18 cities
- France: 2 cities
- Taiwan: 11 cities
- Norway: 1 city
- United States of America: 19 cities
- Portugal: 3 cities
- Italy: 8 cities
- Spain: 4 cities
- Vietnam: 3 cities
- Greece: 3 cities
- Sweden: 1 city
- Philippines: 14 cities
- Brazil: 11 cities
- Australia: 4 cities
- India: 32 cities

Meaning that the following territories did not meet the demand centre criteria:

 Deep Water FOW Demand Centers ✗

- United Kingdom
- South Korea
- China
- Ireland
- Poland
- Denmark
- Canada

### 3 DEEP WATER DYNAMIC CABLE DESIGNS

The purpose of the deep water dynamic cable design study was to help identify base case designs for the identified critical water depths:

- 300 m: Deep floating wind.
- 500 m: Very deep floating wind.
- 1000 m: Extremely deep floating wind.
- 2000 m: Ultra deep floating wind.

#### 3.1 An Overview of Dynamic Cable Configurations

A typical inter-array dynamic cable configuration in a FOW farm establishes the connection between wind turbines and the offshore substation. This system encompasses not only the cables themselves but also a variety of ancillary equipment designed to facilitate the connection and safeguard the cables, as depicted in Figure 3-1 [3].

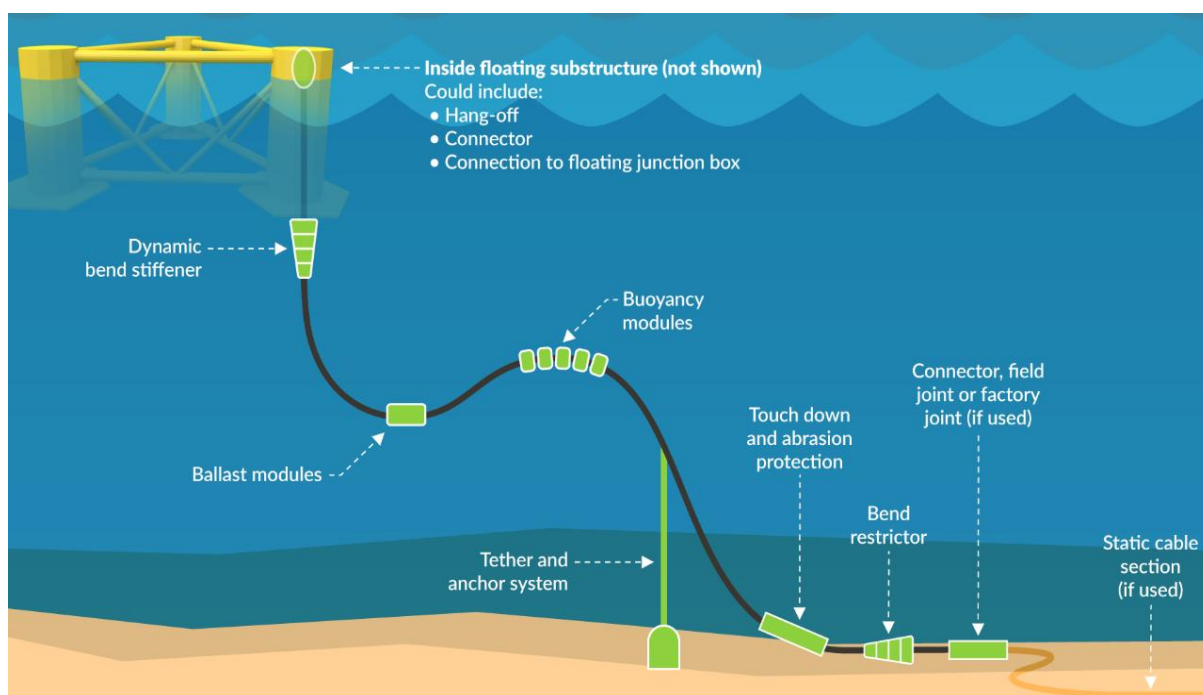


Figure 3-1: Dynamic cable configuration.

Figure 3-1 showcases a standard dynamic cable configuration, yet there is a range of cable configurations available, as portrayed in Figure 3-2, with each system designed to accommodate the specific needs and demands of a given project.

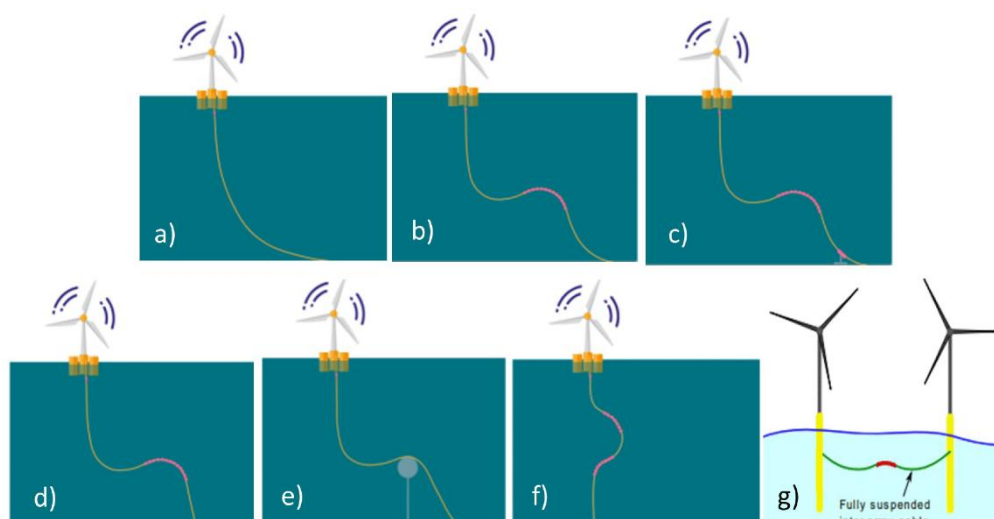


Figure 3-2: Different dynamic cable configurations [3].

As water depth deepens or environmental conditions become more challenging, different design options become increasingly preferable. As the complexity grows, cost becomes a significant factor, rising due to the increased need for supplementary items in the cable system and the extended cable length managed between the floating structure and the seabed. The design is primarily steered by the constraints imposed by allowable tension and curvature. The hang-off point (HOP) and touch-down point (TDP) emerge as particularly sensitive positions in this context. Table 3-1 illustrates the advantages and disadvantages of different cable configurations, offering insights into their suitability for diverse water depths and environmental conditions.

Table 3-1: Advantages and disadvantages of common dynamic cable configurations [3].

| Type            | Description                                                          | Advantages                                                                                                                                                                                         | Disadvantages                                                                                                                                                                                                                                                                                                                              |
|-----------------|----------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| a)<br>Catenary  | Free hanging to the seabed                                           | <ul style="list-style-type: none"> <li>Simplest configuration</li> <li>Lowest cost solution</li> </ul>                                                                                             | <ul style="list-style-type: none"> <li>Floater motion not decoupled</li> <li>No restriction of lateral motion</li> <li>High tension at HOP</li> <li>Bend stiffener at HOP required</li> <li>Unsuitable for significant dynamic motions and deeper water depths</li> </ul>                                                                  |
| b)<br>Lazy Wave | Attached buoyancy modules provide lift at the midwater cable section | <ul style="list-style-type: none"> <li>Simplest configuration</li> <li>Decoupling of floater motions from TDP</li> <li>Proven use for deep water application</li> <li>Low-cost solution</li> </ul> | <ul style="list-style-type: none"> <li>No restriction of lateral motion</li> <li>Prone to marine growth depending on depth</li> <li>Bend stiffener at HOP required</li> <li>Buoyancy modules required</li> <li>Critical where the distance between HOP and TDP is restricted</li> <li>Strong currents may lead to TDP migration</li> </ul> |

| Type                  | Description                                                                                               | Advantages                                                                                                                                                                                                                                                                                                                                                                        | Disadvantages                                                                                                                                                                                                                                                                                                                                                                      |
|-----------------------|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| c)<br>Tethered Wave   | Similar to lazy wave with additional tether restraining TDP                                               | <ul style="list-style-type: none"> <li>Decoupling of floater motions from TDP</li> <li>Reduced freedom of TDP under cross current</li> <li>Higher levels of marine growth possible due to tethered TDP</li> <li>Mid-range cost solution</li> </ul>                                                                                                                                | <ul style="list-style-type: none"> <li>Tether and clamp complicate installation</li> <li>Prone to marine growth depending on depth</li> <li>Bend stiffener at HOP required</li> <li>Buoyancy modules required</li> </ul>                                                                                                                                                           |
| d)<br>Steep Wave      | Similar to lazy wave, but the connection to the seabed junction is made vertically via the bend stiffener | <ul style="list-style-type: none"> <li>Decoupling of floater motions from TDP</li> <li>Limited changes in configuration with higher levels of marine growth</li> <li>Subsea base reduces excursion under current</li> <li>Reduced distance between HOP and TDP</li> </ul>                                                                                                         | <ul style="list-style-type: none"> <li>Bend stiffeners at HOP and TDP required</li> <li>Buoyancy modules required</li> <li>High cost solution given additional termination units</li> </ul>                                                                                                                                                                                        |
| e) Lazy S             | Similar to lazy wave but with subsea buoy (fixed or floating) creating mid-water arch                     | <ul style="list-style-type: none"> <li>Decoupling of floater motions from TDP</li> <li>Limited changes in configuration due to marine growth</li> <li>Subsea buoy reducing excursion under cross current</li> <li>Sag bend (arch open to the top) carefully controlled (good for offset control)</li> <li>Suitable for multiple cables approaching the hub (e.g., OSS)</li> </ul> | <ul style="list-style-type: none"> <li>Bend stiffener at HOP required</li> <li>Buoyant mid-water arch, clamps and maybe tether required</li> <li>Fixed sag bend location</li> <li>High-cost solution; may not be economical for a single cable</li> <li>Minimum separation distance on buoy may become critical (danger of cable clashing and current rating reduction)</li> </ul> |
| f)<br>Chinese Lantern | U-shaped slack keeping tether vertically aligned with HOP                                                 | <ul style="list-style-type: none"> <li>Decoupling of floater motions from TDP</li> <li>Subsea base reduces excursions under cross currents and prevents migration of TDP</li> <li>Reduced distance between HOP and TDP</li> <li>Accommodates significant upward motions (heave)</li> </ul>                                                                                        | <ul style="list-style-type: none"> <li>Bend stiffener at HOP and TDP required</li> <li>Buoyancy modules required</li> <li>Limited regarding water depth</li> <li>Unsuitable for dynamic motions with large offsets</li> </ul>                                                                                                                                                      |
| g) W-Shaped           | Suspended between floaters without touching the seabed and aided by buoyancy modules                      | <ul style="list-style-type: none"> <li>Short cable length for deep water depths</li> <li>Avoidance of TDP and trenching</li> <li>Low-cost solution</li> </ul>                                                                                                                                                                                                                     | <ul style="list-style-type: none"> <li>Buoyancy modules required</li> <li>Bend stiffener at HOPs required</li> <li>Prone to marine growth and cross currents</li> <li>Motions of connected floaters need to be accurately assessed</li> <li>Feasibility not fully proven</li> </ul>                                                                                                |

This understanding of current dynamic cable designs and their potential advantages and disadvantages for use in deep water FOW allowed the dynamic cable analysis to be framed.

## 3.2 Environmental Conditions

### 3.2.1 Site Conditions

UK metocean data was used for site selection and cable analysis due to its accessibility and relevance to typical conditions for ScotWind projects despite the UK's limited focus on deep-water markets. This data provides a useful baseline for general metocean scenarios, though conditions vary significantly by project, especially in deep-water areas. The study used publicly accessible data, noting that project-specific data is often sensitive and restricted.

### 3.2.2 Wind, Wave & Current

The UK Health and Safety Executive Offshore Technology Report 2001/010 [4] was the primary metocean source due to its high-quality 50-year data, aligning with DNV-ST-0119 [5] standards.

**Wind:** The Health Safety and Environment (HSE) report provided contour plots showing 50-year return omnidirectional hourly-mean wind speeds at 10 m above still water. A wind speed of 35 m/s at this elevation, with a 1-hour mean, was selected for mooring analysis, per DNV-ST-0119 [5]. Wind shear modelling was not included in this analysis.

**Wave:** Significant wave heights for the North East of Scotland and the Celtic Sea were estimated between 12 - 14 m, as per Figure 3 of the HSE report [4].

**Current:** The report [4] referenced peak tidal and storm surge combined current velocities at 1 m/s. In the absence of subsurface current profiles, current velocity was modelled down the water column using a power law profile with an exponent of 7, as per OrcaFlex's default. Tidal level variation was not applied.

### 3.2.3 Directionality

Environmental conditions were applied at both 0 degrees and 180 degrees, as previous experience dictates these induce maximum platform displacements and, therefore, cable tensions and curvatures.

### 3.2.4 Marine Growth

For the marine growth sensitivity study, 38 mm of marine growth was applied to the cable up to 50 m deep in the water column. 20 mm of marine growth was applied to the cable between 50 m and 100 m deep in the water column. Below 1000 m in the water column, no marine growth was applied to the cable [6]. There is limited information available on marine growth in deep water, as can be seen in the NORSOK N-003 standard, which only provides data for two levels of marine growth, one for water depths between 2 m to 40 m and the other for water depths below 40 m from sea level [7]. Due to this, the marine growth values used in this investigation were obtained from an analysis of drilling risers in the Gulf of Mexico, which covered a greater water depth. Drilling risers have a much shorter lifespan than floating offshore wind farms (FOWFs), so the marine growth measured is for a 5-year period [6].

## 3.3 Mooring Analysis

The mooring analysis was conducted first to determine the substructure offset; this is the main design factor that influences the dynamic cable system configuration. Each mooring analysis was modelled

using the UMaine VoltturnUS platform with the International Energy Association 15 MW reference wind turbine model provided by Orcina [8] shown in Figure 3-3 below. The motions from the results of the mooring analyses were superimposed into the dynamic cable analysis to give representative motions and excursions. This minimises the computing processing requirements for the dynamic cable analysis.

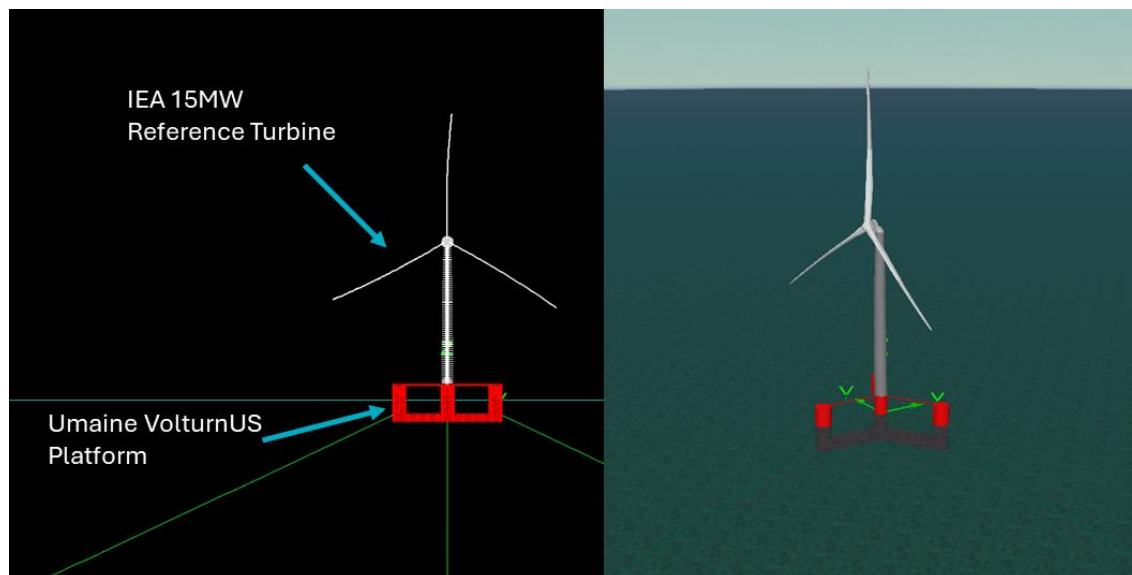


Figure 3-3: IEA 15 MW reference turbine and UMaine VoltturnUS platform [8].

### 3.3.1 Design Constraints

The following constraints were taken into consideration when designing the mooring systems for each water depth:

- **Maximum Line Tensions:** Adherence to the safety factors specified in DNV-ST-0119 is mandatory. Ensuring line tensions remain within these prescribed limits is crucial for system integrity.
- **FOWT Excursions:** Excursions must be maintained within acceptable ranges for each water depth. Based on stakeholder feedback and literature reviews, larger offsets relative to water depth are considered acceptable in shallower waters.
- **Mooring Footprint and Turbine Spacing:** The spatial extent of mooring systems should be managed to avoid interference with adjacent assets. This necessitates a careful balance between system efficacy and spatial efficiency.
- **Pre-tensions:** Due to equipment limitations, such as the absence of winches for line tensioning and the complexities in tensioning the lines with anchor handlers, line pre-tensions should be kept below 150 tonnes.
- **Avoidance of Synthetic Seabed Contact:** Seabed contact of synthetic mooring rope is currently not allowed. There is a chain length at the anchor end, so any slack means the chain touches the seabed and not the synthetic rope.

### 3.3.2 Results

The issue of platform excursions for floating wind turbines remains contentious among cable manufacturers and mooring system designers. There is no clear consensus or standardised guidance on permissible limits. A provisional maximum limit of 30% of the water depth is commonly used.

In the FOW CoE MA02 project ‘Failure Implications of Different Mooring Spreads and Lines’ [9], stakeholder engagement with mooring specialists and developers was conducted to establish expected excursion limits for various water depths. The findings are as follows:

- For water depths under 100 m, a maximum excursion of 30-40% of the depth is preferred.
- For depths between 100 m and 500 m, the preferred limit is 20-30% of the water depth.
- For depths greater than 500 m, preferences vary, with most favouring a 10-20% excursion limit.

Overall, there is a trend toward reducing the excursion percentage as water depth increases.

The insights from the mooring analysis (Table 3-2) showed a general trend in the reduction of the platform excursion as a percentage of water depth before an increase at 2000 m, which aligns mostly with these observations.

Table 3-2: Maximum platform excursion limits for each water depth range

| Water Depth | Mooring system | X Offset [m] | Offset as % of Water Depth |
|-------------|----------------|--------------|----------------------------|
| 300 m       | Taut Polyester | 31           | 10 %                       |
| 500 m       | Taut Polyester | 35           | 7 %                        |
| 1000 m      | Taut Polyester | 63           | 6 %                        |
| 2000 m      | Taut Polyester | 191          | 10 %                       |

The platform excursion values directed the analysis of the dynamic cables, providing essential maximum parameters for water depth-specific dynamic cables. The configuration and extra requirements such as the ancillary equipment associated with the dynamic cable were influenced by these values.

### 3.4 Dynamic Cable Analysis

The dynamic cable analysis offered insights into high-level dynamic cable designs for deep water application, identifying the optimal configurations derived from Figure 3-2 as catenary, lazy wave, tethered lazy wave, and suspended wave across four different water depths. These optimal configurations were designed to align with the excursion limits identified in the mooring analysis, ensuring the most suitable working arrangements are selected. Figure 3-4 gives an overview of the cable designs considered in the analysis, these configurations were selected as they performed best in the initial screening results which considered all designs from Figure 3-2.

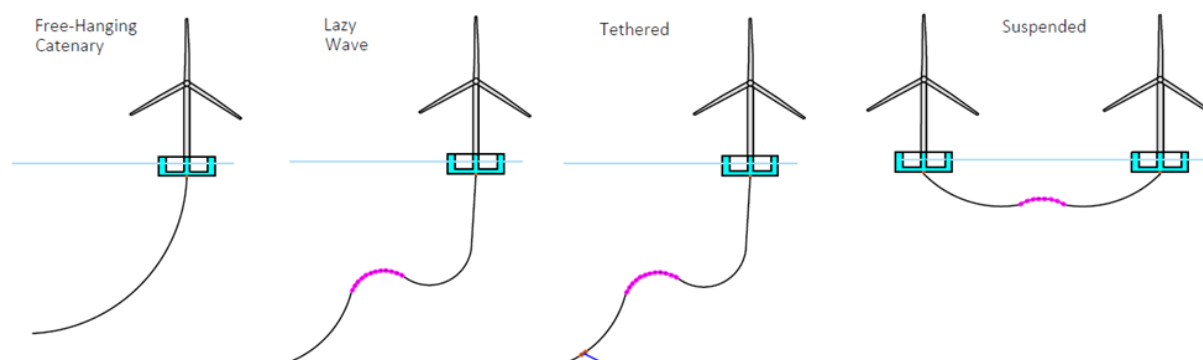


Figure 3-4: The four different cable configurations analysed across the deep water depths [3].

### 3.4.1 Cable Data

A 132 kV copper cable with steel armouring was used for the base case simulations. The cable core was 800 mm<sup>2</sup>. A 132 kV cable was selected for this analysis as it is assumed that this will be the most common cable used in deep water FOW projects. This is due to the core losses that would be seen in 66 kV cables for the required cable lengths at these depths. Table 3-3 contains the cable data used in this report obtained by a cable original equipment manufacturer (OEM).

Table 3-3: Copper cable data

| Voltage [kV] | Core Material | Outer Diameter [m] | Mass per Unit Length in Air [te/m] | Minimum Bend Radius [rad/m] | Maximum Allowable Tension [kN] | Compression Limit [kN] |
|--------------|---------------|--------------------|------------------------------------|-----------------------------|--------------------------------|------------------------|
| 132          | Copper        | 0.236              | 0.10025                            | 0.33                        | 510                            | 51                     |

The axial stiffness, bending stiffness and torsional stiffness were calculated for this cable using the above data provided by the cable OEM using the Umbilical Wizard tool in OrcaFlex. This calculated the data as seen in Table 3-4.

Table 3-4 - Copper cable stiffness data

| Bending Stiffness [kN.m <sup>2</sup> ] | Axial Stiffness [kN] | Torsional Stiffness [kN.m <sup>2</sup> ] |
|----------------------------------------|----------------------|------------------------------------------|
| 39.4328                                | 339800               | 80                                       |

### 3.4.2 Design Constraints

When designing the dynamic cable systems, the following design constraints were considered to achieve the most suitable configurations. The cable OEM that provided the cable specification for the cable used in this investigation also provided supplementary information regarding the maximum allowable tension and the minimum bend radius.

- Maximum Allowable Cable Tension:** The tension along the cable length should not exceed the maximum allowable cable tension of 510 kN, as any tension above this will cause severe damage to the cable and reduce its lifespan.

- **Minimum Bend Radius:** When the minimum bend radius is exceeded, the cable is damaged increasing the chance of failure. The minimum bend radius of the cable is 3 m. The values for the minimum bend radius were converted to a value of curvature for simplicity of analysis using OrcaFlex. The value of maximum curvature for the cable was found to be 0.33 rad/m.
- **Compression:** Compression can damage the cable and reduce its lifetime so the compression experienced by the cable must be minimised. Compression is also more likely to occur when the MBR is exceeded. The current standard practice as provided by the cable OEM is to keep compression within 10 % of the maximum allowable tension limit.
- **Spacing Between FOWTs in the Array:** The turbines in this analysis were spaced 2.2 km apart from each other. This spacing accounts for the rotor diameter of the turbine and has been used previously as the spacing between turbines in FOW CoE reports.
- **FOWT Excursion:** The excursion of the wind turbine and platform used for these analyses was determined by the deep water mooring analysis. The cable configuration designed cannot exceed the maximum mooring offset or breach any other design constraints.
- **Positioning of Buoyancy Modules in Water Column:** The buoyancy modules should be positioned to keep the cable neither too close to the water surface, avoiding wave impact, nor too low, where it risks touching the seabed with added marine growth.

### 3.4.3 Results

#### Overview

The aim of the OrcaFlex analysis was to identify which cable configuration out of the four highlighted in Figure 3-4 performed the best across the pre-defined deep water depths. The best configuration is determined by the performance of the configuration against the design constraints. The configuration with the least tension and compression and the lowest curvature were defined as the optimal solutions. Figure 3-5 highlights some key aspects of the dynamic cable system implemented within the OrcaFlex analysis.

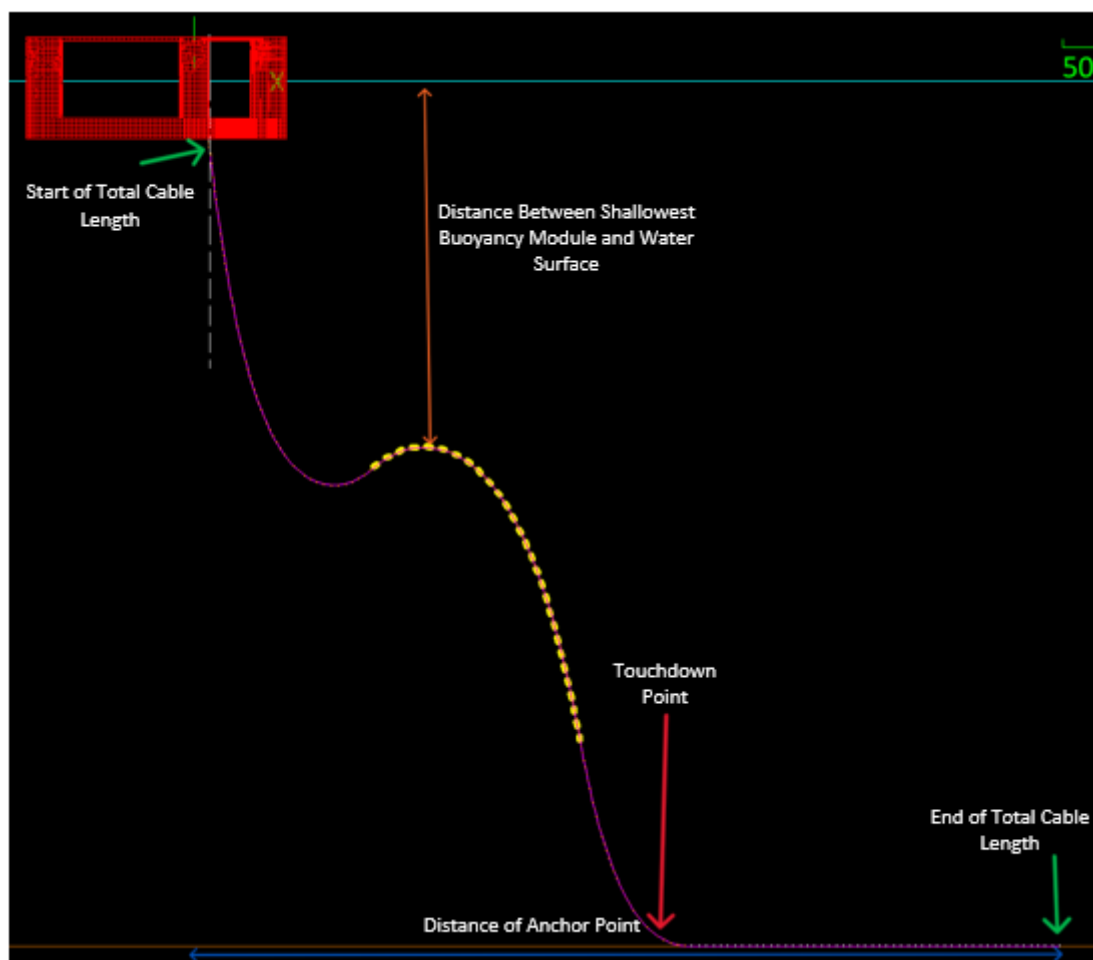


Figure 3-5: Annotated OrcaFlex lazy wave.

### Optimal Configuration for Each Water Depth

Table 3-5 defines the best configuration for each water depth. It shows that a tethered wave is the optimal configuration for 300 m. The lazy wave was the best configuration at 500 m. However, the lazy wave with tether performed similarly. Due to the additional components needed for the tethered wave along with the minimal difference in results, it was decided that the lazy wave was the better configuration. For both 1000 m and 2000 m water depths the suspended wave configuration performed best and was the only configuration to work in 2000 m.

Table 3-5: Optimal configuration for each water depth.

| Depth [m] | Configuration         | Max Tension [kN] | Max Curvature [rad/m] | Compression [kN] |
|-----------|-----------------------|------------------|-----------------------|------------------|
| 300       | Lazy Wave with Tether | 98               | 0.24                  | n/a              |
| 500       | Lazy Wave             | 181              | 0.26                  | -3               |
| 1000      | Suspended Wave        | 290              | 0.02                  | n/a              |
| 2000      | Suspended Wave        | 372              | 0.01                  | n/a              |

## Sensitivity Cases

### Aluminium Core:

The first sensitivity case investigated a change from copper to an aluminium conductor core. Aluminium reduces the weight of the cable as it is a much lighter material than copper. This can be beneficial when trying to reduce the maximum tension experienced by the cable.

Table 3-6: Aluminium cable details

| Voltage [kV] | Core Material | Outer Diameter [m] | Mass per Unit Length in Air [te/m] |
|--------------|---------------|--------------------|------------------------------------|
| 132          | Aluminium     | 0.236              | 0.06954                            |
| 132          | Copper        | 0.236              | 0.10025                            |

The essence of this analysis was to understand the impact an aluminium core had on some of the failed configurations across the various water depths. The findings showed that using an aluminium core had minimal impact on the maximum curvature for lazy and suspended waves but significantly increased curvature in the catenary system, although still within allowable limits. While it reduced tension in the 1000 m catenary system, it remained above the allowable limit. At 2000 m, a workable lazy wave configuration couldn't be achieved due to excessive tension and compression. Although the aluminium core didn't resolve the curvature issue in the 300 m lazy wave, it significantly reduced tension in the 300 m suspended wave, indicating potential advantages for suspended configurations.

### Marine Growth:

The addition of marine growth increased maximum tension and curvature across all cable configurations. For the catenary and suspended wave systems, this led to higher maximum curvature values. The impact varied for lazy wave systems, with some configurations seeing significant changes in maximum curvature and no compression observed in tethered and suspended wave setups.

Marine growth caused failures in four configurations:

- The 2000 m suspended wave exceeded both maximum curvature and tension limits.
- Other suspended wave systems experienced excessive tension, indicating a need for regular marine growth clearance to prevent failure.
- Tethered wave systems at 500 m and 2000 m faced issues with cable overlap and potential abrasion due to shifted touchdown points, requiring optimisation or regular growth clearance.

The 500 m catenary and 1000 m lazy wave systems saw increased tension, approaching their maximum allowable limits, suggesting marine growth management will be required during their lifespan. The 300 m catenary system nearly exceeded curvature limits, indicating a similar need for maintenance. The 500 m lazy wave system was less affected and might not require growth removal.

Overall, marine growth reduced cable drift but highlighted the need for future optimisation studies. The current marine growth model is conservative and may benefit from further refinement.

## 4 DEEP WATER DYNAMIC CABLE SUPPLY CHAIN CAPABILITY AND CAPACITY ASSESSMENT

The deep water supply chain capability assessment leveraged and refined the insights from PR5: Dynamic Cables Supply Chain Capability and Capacity Assessment [10], ensuring their applicability to the specific requirements of deep-water dynamic cables – specifically the use of 132 kV cables and the required ancillaries. Ultimately, the outcomes of this WP depicted the UK and global supply chain’s ability to meet the demands of the deep-water wind energy market. These insights guided the subsequent cost analysis phase, providing a clear understanding of component requirements for the projected global pipeline.

### 4.1 Required Components

To carry out the supply chain assessment, it was necessary to determine the project component requirements to meet the demand for deep water FOW. As a starting point, reference was made to the 12 GW of floating capacity set to enter construction globally between 2025 and 2030 [11] as highlighted in Figure 4-1.

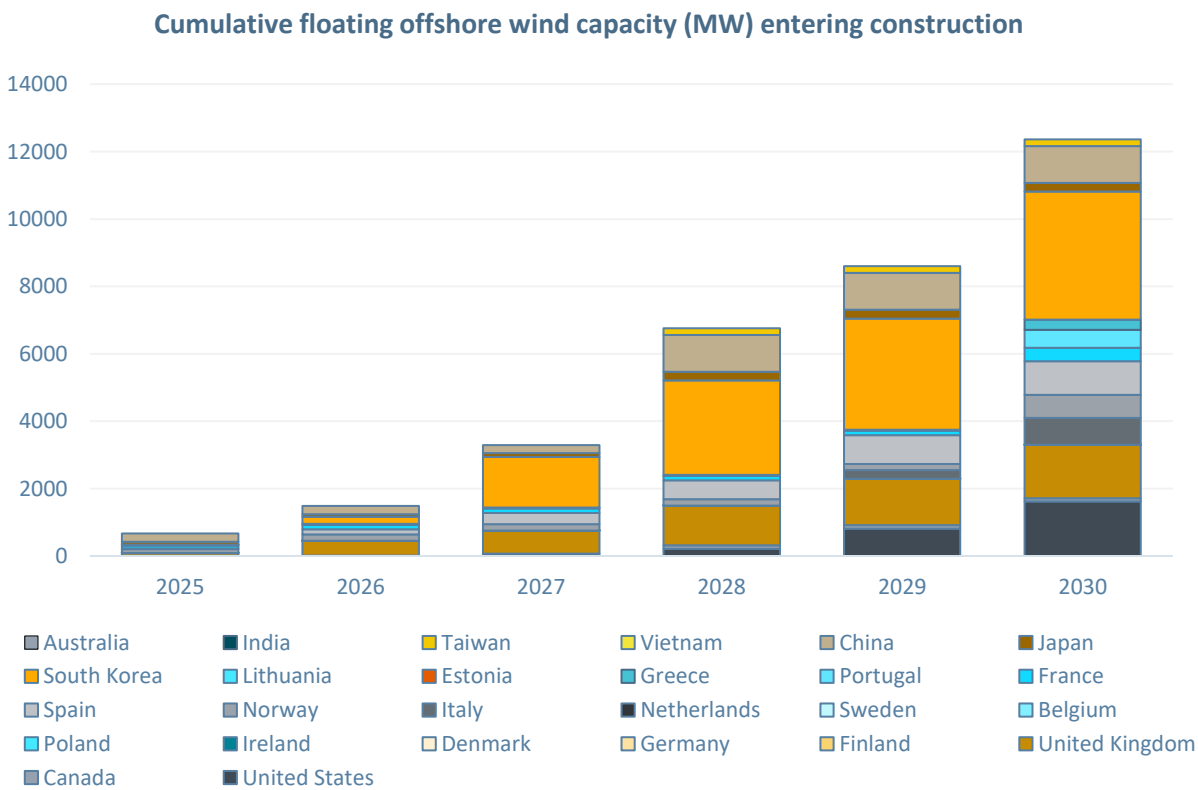


Figure 4-1: Cumulative floating offshore wind entering construction (2025 - 2030) [11].

Utilising the findings from WP2, the markets highlighted in Figure 4-1 have been refined to depict those that meet the near term market criteria and, therefore are deemed eligible deep water demand centres as portrayed in Figure 4-2. The deep water opportunity within the project time frame of 2025 to 2030 depicts that 2,029 MW of floating capacity entering construction is being constructed in depths over 300 m.

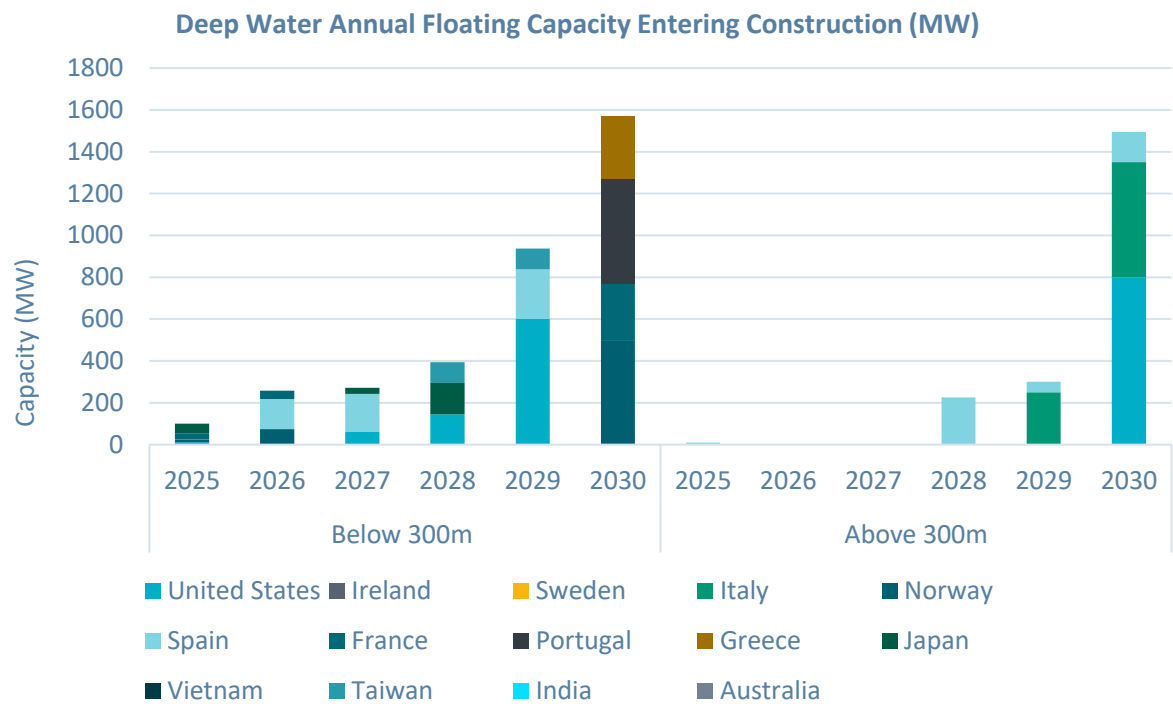


Figure 4-2: Deep water annual floating capacity entering construction (2025 - 2030) [11].

With approximately 2 GW of deep water floating wind capacity installed by 2030, the component requirements for a 1 GW wind farm were used as a baseline to feed into the calculations. This assessment assumed a 900 MW capacity, 132 kV radial array wind farm design, as highlighted in Figure 4-3. This was used for estimating the lengths of dynamic cables needed and the number of required components. The chosen array served merely as an illustrative example drawn from ORE Catapult’s DC06: Cable Topology Comparison [1] to provide insight into the necessary components for a ~1 GW array. It should be noted that DC06 was assessed using UK bathymetry and therefore the analysis conducted within the project has been used to scale the array for deep water application. DC06 highlighted various topologies that were suitable for FOW. However, the preferred layout for wind farm and cable configurations remains at the discretion of the developer, to date radial designs are the most well established within industry.

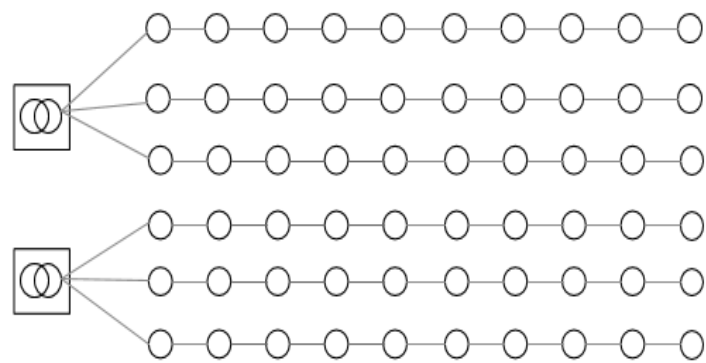


Figure 4-3: 1 GW 132 kV radial wind farm design.

A 500 m lazy wave configuration from the Section 3 analysis was utilised to determine the anticipated required components to achieve the 2 GW of cumulative floating wind capacity for the near-term markets identified in WP2. This was done by scaling the length and number of cable and ancillaries associated with this design for a 2 GW wind farm. Table 4-1 summarises the assumed global project supply chain demand for deep-water FOW by 2030 – outlining the expected quantities to deliver the estimated 2 GW highlighted.

Table 4-1: Indicative expected quantities for 2 GW of cumulative floating wind capacity for near term markets.

|                                      | Unit | Accumulated up to 2030 |
|--------------------------------------|------|------------------------|
| Deployment                           | GW   | 2                      |
| Wind farms                           | No.  | 6                      |
| Turbines (15 MW turbines)            | No.  | 120                    |
| Dynamic cables                       | km   | 352                    |
| Buoyancy modules                     | No.  | 2640                   |
| Dynamic bend stiffeners              | No.  | 228                    |
| Static bend restrictor               | No.  | 12                     |
| Dynamic hang-off termination         | No.  | 228                    |
| Static hang-off termination          | No.  | 12                     |
| Pigtail termination                  | No.  | 228                    |
| Splice box termination               | No.  | 228                    |
| Cable protection sleeve (touch down) | No.  | 240                    |
| Pull-in head                         | No.  | 240                    |
| I tube                               | No.  | 240                    |
| Tethers                              | No.  | 240 (Potential)        |

It should be noted that the calculation of quantities are based on 2 GW being achieved using a 500 m lazy wave configuration, as this is presently more established than other configurations, it also offers a conservative estimate for cable length.

## 4.2 Supply Chain Capability and Capacity

The supply chain assessment offered a comprehensive overview of the capability and capacity needed to provide components for the inter-array dynamic cable system. The information was sourced directly from ORE Catapult's supply chain engagement.

The assessment framework focused on deconstructing the requirements for developing a 1 GW commercial-scale wind farm. Each aspect was analysed separately using predefined criteria consistent with those in PR5: Dynamic Cables Supply Chain Capability and Capacity Assessment [10]. The criteria

covered technical requirements, capabilities, demand fulfilment, potential barriers, drivers, and opportunities for cost reduction focusing on deep water application.

The following sections in 4.2 outline the various components of the complete dynamic cable system that were assessed.

#### 4.2.1 Cables

The list below highlights the key requirements identified through stakeholder engagement on cables, aligned with the criteria outlined in Section 4.2.

- A significant challenge for commercial-scale deep water FOW is the need for further development of 132 kV cables. Currently, neither the UK nor the global supply chain offers commercially available 132 kV wet cables.
- Significant investment is required in cable OEMs' facilities to meet future demand and accommodate upgrades in wind turbine generator size. However, the supply chain has indicated that firm orders are necessary to justify this investment, as past R&D efforts based on future predictions have not always materialised as expected.
- The design of deep-water dynamic cable configurations is particularly challenging due to the many unknowns in the industry and the lack of clear standards or experience to draw from. Each cable design will need to be bespoke and tailored to specific site conditions, including water depths, metocean conditions, and floater configurations.
- Dynamic cables are more expensive to manufacture than static cables, with costs being 50-100% higher due to increased material needs, such as multiple armouring passes.
- The development of floating and subsea substations could significantly reduce the required cable length for deep water floating wind projects.
- Storage, transportation, and installation of cables in deeper waters may be challenging due to a lack of standardisation and best practices.
- There is a limited availability of suitable vessels for cable installation, maintenance, and repair, with significant competition from the O&G sector.
- Marine growth poses a major concern throughout a cable's lifecycle. The added weight from marine growth increases cable tension, and current methods of analysing its impact reveal significant differences between start and end-of-life configurations.
- Effective marine growth management needs to be considered to mitigate these impacts.
- Cable tension, compression, and excessive bending at the interface and touchdown point are significant concerns, potentially leading to fatigue issues over time.
- Type testing of 132 kV cables is another challenge, with limited facilities capable of performing the required tests. Even qualified components must undergo site-specific testing.
- Clarity is needed on future testing guidelines, particularly regarding whether joint electrical and mechanical testing will be required for qualification.
- The supply chain has highlighted that current insurance costs are extremely high throughout the project lifecycle.

### 4.2.2 Connectors

The base case solution does not include connectors; however for deep water application where larger cable lengths are required and as the number of FOW sites increase the ability to streamline connection and disconnection and limit power losses in the event of failure becomes a key consideration. Therefore, an alternative array layout such as the star design depicted in Figure 4-4 which highlights the use of subsea connectors has been included to ensure connectors have been covered.

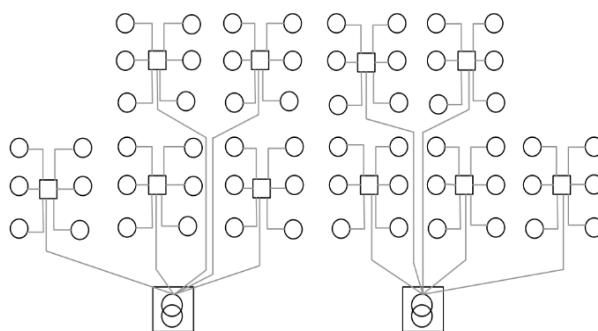


Figure 4-4: Alternative 1 GW wind farm array.

The 132 kV star design utilises subsea hubs, with a spread of 10 Dry Mate 7-way subsea junction boxes (SJB's) or 10 Wet Mate 7-way SJB's. Other arrays such as the fishbone design and branching design taken from DC06 also use various subsea collector hubs.

The list below highlights the key requirements identified through stakeholder engagement on connectors, aligned with the criteria outlined in Section 4.2.

- A key focus for future development is increasing the rated voltage of connectors, with an emphasis on cost reduction and the development of wet mate connectors. Currently, there are no commercially viable 66 kV wet connectors available, and while both UK and global suppliers are working towards developing connectors up to 72 kV, this still falls short of the 132 kV requirement.
- Wet mate connectors must be capable of handling multiple connection and disconnection cycles for periodic tow-to-port maintenance, typically ranging from 10 to 100 cycles. However, qualifying these connectors to withstand high-power capacity, corrosion, mechanical fatigue, electrical/thermal cycling, and marine growth remains a significant challenge.
- The low availability and long lead times for wet mate connectors are known barriers for marine renewable projects, impacting project timelines and costs.
- Spliced joints are currently the lowest capital cost solution and are well-proven, but they require significant vessel time, making them less efficient for large-scale operations.
- Further qualifications of disconnection system designs are needed to improve efficiency during return-to-port turbine maintenance, ensuring quicker and more reliable operations.
- As connector sizes increase with the uplift in voltage, concerns arise regarding the storage, transportation, and installation of these larger components in deeper waters, particularly given the limited availability of suitable vessels.
- Clarity on future requirements from developers, such as the prioritization of 132 kV connectors, SJBs, and Quick Connects, would greatly assist in directing research and development efforts.

- Cost reduction remains a critical area of focus, with the goal of making high-voltage, wet mate connectors more commercially viable and accessible for future marine renewable projects.

#### 4.2.3 Interfaces, Protection Systems and Modules

The list below highlights the key requirements identified through stakeholder engagement on interfaces, protection systems and modules, aligned with the criteria outlined in Section 4.2.

- A standard list of ancillary components could be developed for each FOW project, provided standard cables and interfaces are established. Flexibility should be maintained to accommodate site-specific conditions, with a selection of components from a range of 'standard' options.
- Available cable accessories are versatile and suitable for both deep and shallow waters, with the supply chain capable of scaling up operations. However, concerns exist regarding potential lead times, especially as large FOW projects require bulk purchases that exceed the quantities typically needed in the O&G sector.
- Key priorities for future development include reducing cable failure rates under dynamic loading, shortening installation times, and lowering costs. Additionally, reducing fabrication and assembly time remains a critical focus.
- Buoyancy modules may require redesign to minimise volume and handling complexity, improving HSE aspects while also reducing costs.
- Improvements are needed in bend stiffener connections, as current industry standards may not always provide secure fastening.
- The methodology for connections, such as the potential adoption of quick connects, remains unclear, posing challenges for standardisation efforts.
- The UK lacks prominent OEMs specialising in cable terminations.
- The potential for competition between the O&G and FOW sectors could impact business opportunities, especially as each FOW project requires bespoke cable designs due to varying site conditions, platform configurations, and system setups.
- The installation of dynamic cables in deeper waters necessitates more ancillary components than static cables, leading to higher installation costs. Moreover, the configuration of these cables varies based on environmental factors such as water depth, with a lack of insight into the efficiency of these designs remaining a barrier.
- Concerns exist that efforts to standardise components and processes could hinder future innovation within the industry.

#### 4.2.4 Condition Monitoring

The list below highlights the key requirements identified through stakeholder engagement on condition monitoring, aligned with the criteria outlined in Section 4.2.

- Fibre Bragg Grating sensors and Distributed Acoustic Sensors provide continuous, real-time data on strain, tension, and compression, which is crucial for dynamic cables under constant movement and varying loads.

- Distributed Strain Sensing offers detailed strain profiles, aiding in the detection of bending and curvature to ensure the structural integrity of cables.
- Line Impedance Resonance Analysis adds an additional monitoring layer by detecting electrical impedance changes, which can indicate mechanical stress and potential failure points.
- There is a lack of publicly available cable data for monitoring companies to set normal operating parameters. Improved information sharing on expected cable parameters and faults is needed.
- Monitoring companies are seeking opportunities to partner with operators on demonstrator projects to showcase and validate their technology.
- For monitoring systems to have a real impact on the industry, they need to be included in developer specifications. Otherwise, they risk being dismissed as an unnecessary added cost at the purchasing stage.
- Strain gauges could be embedded in dynamic cable bend protection equipment, either as data loggers or for real-time monitoring.
- Accelerometers and inclinometers positioned along free span areas can provide vibration histories in either data logger or real-time format. Suppliers already have experience in designing and supplying accelerometer data loggers for vibration monitoring.
- Embedding strain gauges in hang-off locations can effectively monitor changes in the overall system's weight due to marine growth or buoyancy loss.

#### 4.2.5 Required Services

The following services highlight the key requirements identified through stakeholder engagement on engineering design, installation and operation and maintenance, aligned with the criteria outlined in Section 4.2.

##### Engineering Design

- Cable system modelling, including Finite Element and full-scale analysis, is typically conducted in-house by the OEM.
- Various engineering analyses and designs can be undertaken by multiple OEMs, with certain design consultancies also engaged for initial system and component design.
- Segregating engineering and design consultancies across system and component design can enhance the validation process, though challenges may arise when integrating separately designed components.
- Design consultancies and OEMs provide site investigation services.
- Testing and qualification are available in the UK, though some components, such as 132 kV wet cables and wet mate connectors, are not yet commercially available.
- Currently, cable designs undergo validation for specific site conditions on a project-by-project basis, alongside type qualification and testing. This process may diminish as the industry matures and confidence in the design and analysis process grows.

- Most relevant standards for dynamic to static cable connectors currently pertain to oil and gas systems, but as floating offshore wind deployment expands, appropriate standards and guidelines will emerge.
- The CIGRE-TB-862 currently offers guidance on recommendations for mechanical testing of submarine cables for dynamic applications.

### Installation

- Operations are typically constrained to specific weather windows based on vessel capabilities and increased water depths.
- Some OEMs are considering offering installation services in the future.
- Current large-scale cable-laying vessels are generally equipped for deep water dynamic inter-array cable installation, though there are a limited number of these vessels available.
- There's no consensus on preferred trenching methods, such as jetting, cutting, or ploughing, nor on pre-trenching versus simultaneous trenching and cable-laying.
- Training and safety are identified as crucial areas for improving cable installation methods and best practices.
- Best practices for installation methods can vary by project, with requirements open to discussion between supply chain partners and operators.
- Assessment of storage capacity for bulk dynamic cable accessories is necessary. While companies like Ocean Wind excel in large cable system installation, they may lack expertise in storing dynamic cable accessories, such as buoyancy modules which grow considerably in size for deep water application.
- Spare stock can be stored during projects if needed.
- Installation is currently the leading factor for cable failure in offshore wind.

### Operation and Maintenance

- Offshore cable maintenance involves system upkeep, documentation, spare parts management, preventive measures, and response to outages. Deep water FOW projects face greater challenges due to harsher conditions, higher pressures, and marine growth, requiring more frequent and rigorous maintenance.
- Dynamic cables in deeper waters need more frequent inspections for buoyancy, tether integrity, and marine growth impact, due to constant movement and additional stress.
- Testing is critical for new installations and repairs, with heightened requirements in deep water due to extreme conditions. Key tests include Time Domain Reflectometry, Tan Delta, withstand tests, Partial Discharge (PD), and Optical Time Domain Reflectometry. Testing needs to be rigorous and frequent in deep waters.
- Managing spare cable in deep water is complex and costly due to depth and environmental conditions. Marine growth accelerates cable degradation, increasing maintenance requirements.

- Repairing deep water cables involves handling new dynamic cable ends, using specialised equipment, and preparing repair vessels. Core repairs may require spare core sections and support vessels with sufficient deck space.
- Replacing spare cables includes cutting the damaged section, preparing and connecting the spare, and conducting thorough testing before lowering the cable back into the water with repair vessels and ROVs.
- Best practices from offshore wind and O&G sectors can enhance FOW O&M efficiency, covering umbilicals, dynamic risers, and static cables.
- The growing number of FOW sites will increase demand for asset integrity and maintenance services, posing future challenges for the FOW, offshore wind, and O&G sectors.

## 5 DEEP WATER DYNAMIC CABLE COST ANALYSIS

### 5.1 Base Case Criteria

The design parameters outlined below are derived from DC06 [1] and have been expanded to illustrate the impact of the optimised deep water dynamic cable configurations highlighted in Section 3 compared to a 100 m shallow water benchmark. These selected parameters are part of a reference FOW site used across various projects within the Dynamic Cable Strategic Programme. The 132 kV site features 60 turbines, each rated at 15 MW, providing a consistent base case for the techno-economic analysis. For comparison, the project is assumed to have a 30-year operational lifespan.

Table 5-1: Wind farm site conditions.

| Parameter                          | Conditions                                                                              | Notes                                                                                                                                                                                                                  |
|------------------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wind farm size                     | 1 GW approximately                                                                      | To create an even number of turbines per string the 132 kV farm will be a total of 900 MW (60 turbines).                                                                                                               |
| Farm voltage                       | 132 kV                                                                                  | CSA calculations and topology design for 132 kV only.                                                                                                                                                                  |
| Turbine rating                     | 15 MW                                                                                   | Electrical considerations use turbine capacity rating.                                                                                                                                                                 |
| Floater type                       | Steel semi-submersible                                                                  | Expected to be dominant in global projects.                                                                                                                                                                            |
| Water depth                        | 100 m (benchmark)<br>300 m<br>500 m<br>1000 m<br>2000 m                                 | Benchmark mid-range of UK bathymetry.<br><br>300 – 2000 m is classified as deep water in the context of DC12.                                                                                                          |
| Seabed                             | Sand or soft clay soil                                                                  | Little impact on cable design comparisons at the level of this study. Seafloor cable protection systems are not included in the study as they will have negligible variations across designs.                          |
| Substation type                    | 2.4 km from the nearest turbine, floating substations are assumed for deep water sites. | To create a fair comparison to the fixed substation in the shallow water benchmark, floating substations have been assumed for the deep water sites. Limited sensitivities on substation positioning will be assessed. |
| Distance between floating turbines | 2.2 km                                                                                  | To be consistent with previous PR5 study [12]; IEA 15 MW turbine rotor OD of 240 m.                                                                                                                                    |

## 5.2 Topology and Connector Scenarios

Each 132 kV topology and connector scenario is assigned an index number, which is referred to throughout the study as the topology scenario number. These align with the 132 kV topologies used in DC06 [1].

- **Radial Design** - turbines are daisy-chained to a single feeder cable, a traditional, low-cost, and widely used topology. This topology design is suitable for all cable configurations highlighted in Figure 3-4. This topology is considered with the following listed substructure connectors, each identified with a topology scenario number (T):
  - T1 - Conventional (future case),
  - T2 - Disconnectable I-tube,
  - T3 - Quick connection at the substructure.
- **Radial Return Design** - A radial return design includes an additional cable from the last turbine on the string to the substation. This topology is also suitable for all cable configurations highlighted in Figure 3-4. However, at depths exceeding 1000 m, where the design involves suspended cables, careful consideration is needed to assess the feasibility of a dynamic cable length reaching the seabed to accommodate the static return length. Within the scope of this work, this has been deemed achievable. This topology is considered with the following substructure connectors, each identified with a topology scenario number (T):
  - T4 - Conventional (future case),
  - T5 - Disconnectable I-tube,
  - T6 - Quick connection at the substructure.
- **Ring 20% Redundancy Design** - The turbine count per string and cable CSA can be adjusted for redundancy. Connecting adjacent strings with a short cable between the last two turbines is more cost-effective than radial return but has lower current-carrying capacity. Without the need for a long redundancy return cable this is perhaps a more practical solution in deeper waters, again this topology is suitable for all cable configurations highlighted in Figure 3-4. This topology is considered with the following various substructure connectors, each identified with a topology scenario number (T):
  - T7 - Conventional (future case),
  - T8 - Disconnectable I-tube,
  - T9 - Quick connection at the substructure.
- **Ring 67% Redundancy Design** - For the 67% redundancy more strings are added, with the same concept applied as the Ring 20% scenario. This topology is considered with the various substructure connectors, each identified with a topology scenario number (T):
  - T10 - Conventional (future case),
  - T11 - Disconnectable I-tube,
  - T12 - Quick connection at the substructure.

- **Fishbone Design** - Fishbone designs reduce the number and size of dynamic cables per string by using three-way subsea connections between turbines and static cables via a subsea hub. These connections can be wet or dry. This study assumes all subsea hub-connected topologies use a conventional future-case substructure connection. At depths exceeding 1000 m, where the design involves suspended cables, this topology is deemed unachievable due to its reliance on subsea hubs. This topology is considered with wet and dry mate subsea hub designs and conventional future case substructure connection, each identified with a topology scenario number (T):
  - T13- Wet mate subsea hub,
  - T14 - Dry mate subsea hub.
- **Fishbone Radial Design** - The fishbone radial design provides the same benefits as the fishbone design, with an additional turbine connecting into each subsea hub. The same assumption has been made for this configuration for depths exceeding 1000 m. This topology is considered with wet and dry mate subsea hub designs and conventional future case substructure connection, each identified with a topology scenario number (T):
  - T15- Wet mate subsea hub,
  - T16 - Dry mate subsea hub.
- Star Design** - The star design connects multiple turbines to a central subsea junction box, with wet or dry cable connections. Longer cable lengths are required for distant star-formed strings. This study assumes all subsea hub-connected topologies use a conventional future-case substructure connection. Similarly to the fishbone designs, at depths exceeding 1000 m, where the design involves suspended cables, this topology is deemed unachievable due to its reliance on subsea junction boxes. This topology is considered with wet and dry mate subsea hub designs and conventional future case substructure connection, each identified with a topology scenario number (T):
  - T17- Wet mate subsea hub,
  - T18 - Dry mate subsea hub.
- **Branching (Turbine) Design** - Branching is similar to the radial design, but the string is split into two at the first turbine. This reduces the total length of cable on the last string to the substation while also offering some level of redundancy. This topology design is suitable for all cable configurations highlighted in Figure 3-4. This topology is considered with the various substructure connectors, each identified with a topology scenario number (T):
  - T19- Conventional (future case),
  - T20 - Disconnectable I-tube,
  - T21 - Quick connection at the substructure.
- **Branching (Hub) Design** - Instead of branching the cables at a turbine, they branch at a subsea hub, which uses a static feeder cable and two dynamic cables for the split string. This design has been assessed similarly to the radial return topology – with the assumption that it is also suitable for all cable configurations highlighted in Figure 3-4. However, at depths exceeding 1000 m, careful consideration is needed to assess the feasibility of a dynamic cable length reaching the seabed to accommodate a single subsea hub at the start of the string. Within the scope of this work, this has been deemed achievable. This topology is considered with wet and dry mate subsea hub designs

and conventional future case substructure connection, each identified with a topology scenario number (T):

- T22- Wet mate subsea hub,
- T23 - Dry mate subsea hub.

5.3 Connector Designs

5.3.1 Substructure Connections

Figure 5-1 displays the main substructure connections.

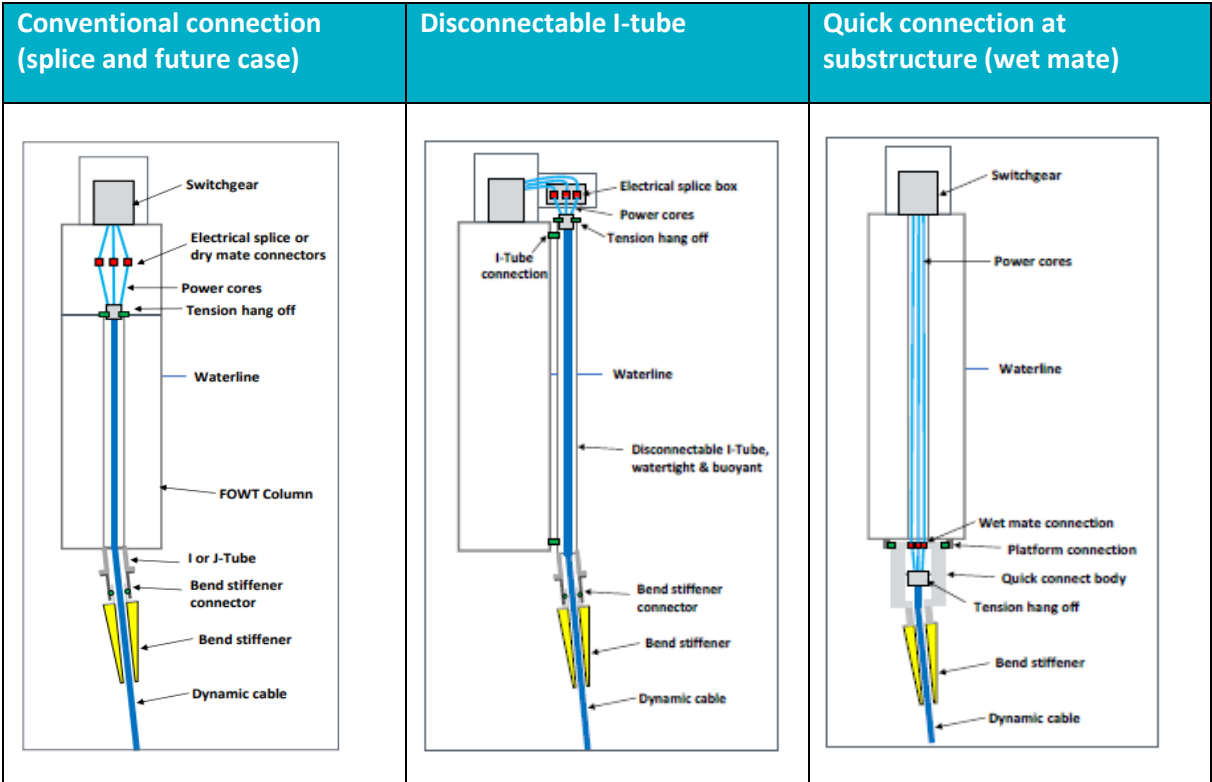


Figure 5-1: Various connection subsystems connecting FOW turbine and dynamic cable [1].

• Conventional Design (Spliced)

The bend stiffener connects to the substructure via a latching mechanism, which can be triggered without ROV intervention, though ROV confirmation may be needed. The cable is then pulled above the waterline, where a technician manually terminates the armour wire at the hang-off flange. In deep water applications, where longer, heavier, and stiffer cables are involved, the pull-in and hang-off process must accommodate these increased demands. This phase also requires a 20-meter overpull, along with walk to work (W2W) operations, which contribute to higher costs, increased weather dependencies, and heightened schedule and personnel risks. These challenges are further amplified in deep-water environments, where accessing larger wind resources is often accompanied by more severe weather conditions, impacting both installation windows and operational safety. Additional considerations include ensuring that equipment and procedures are robust enough to handle the mechanical stresses and potential fatigue associated with deeper deployments.

• Conventional Design (Future Case)

The cable pulling and bend stiffener connection method are the same as in the conventional spliced design. However, the electrical connection uses dry mate connectors and pre-terminated cable ends, which is expected to halve the connection time compared to the spliced design. This eliminates the need for manual splicing at the turbine, reducing W2W crossings, man hours, and

associated risks which is a key factor when considering that larger wind resources are often accompanied by smaller weather windows. The future-case design also incorporates pre-lay and wet storage of cables, this needs to be carefully considered for deep water installation where cable retrieval and pull-in occurs at greater depths and can impact connection time.

- **Disconnectable I-tube**

The cable connection can be designed to detach from the FOWT structure, facilitating easier disconnection. A watertight housing is needed to protect the cable during wet storage. Although this increases capital costs, it can reduce vessel standby time. Manual splicing or a pretermination future case conventional design is still required for the connection to the switchgear. The detachable connections can theoretically speed up the disconnection and connection process and reduce vessel requirements during operation. This study assesses the benefits of using the disconnectable I-tube with the use of a pretermination future case design.

- **Quick Connection at the Substructure**

Connection and disconnection are done using a winch wire to pull the device in or out. While this can save on vessel and installation time, a fully wet-mateable substructure connection system tends to be large, costly, and requires extensive qualification for reliable long-term performance. Despite these requirements, the connection and disconnection procedures are quick and reversible, potentially reducing the time and vessels needed for cable mating or de-mating from the FOWT. This connection approach holds substantial potential benefits for deep-water installations, where quick-connect solutions can facilitate pre- and post-installation operations by allowing the cable to be temporarily stored in the water column in its final configuration. Although the CAPEX for these systems can be high, they promise OPEX savings by simplifying repairs and replacements through faster disconnection. Additionally, many of these systems are designed with Emergency Release Mechanisms (ERM) to mitigate costly repairs in case of failure, an essential consideration in deep-water environments where operational risks are elevated due to harsher conditions and the logistical challenges of intervention.

### 5.3.2 Subsea Hubs

The below list describes the subsea hub design types used within this study (Figure 5-2):

- **Wet Mate Connection at Subsea Hub**

A wet mate subsea hub on the seabed uses short ( $\approx 3$  meters) single-phase cables, or jumpers, connected to a single-pin wet mate connector. The cable is terminated with a subsea termination unit (STU) and protected by a bend restrictor. Alternatively, a 3-phase stab connection head can simplify installation. The hub allows for quick disconnection in case of cable failure, reducing the impact on turbines and recovery time. A 'smart' hub with switchgear, sensors, and protection equipment offers advanced monitoring, reducing fault-finding time. The main limitation for wet mate subsea hubs in deeper water is that suspended cable systems have been deemed the most optimal solution for water depths in excess of 1000 m, making them surplus to requirement at these depths.

- **Dry Mate Connection at Subsea Hub**

For a dry-connection subsea hub on the sea floor, cables are typically twice the water depth to allow for an in-air connection to a 3-pin dry mate connector or spliced joint. This requirement makes dry mate connection subsea particularly costly for deep-water applications, where doubling the cable length for connection purposes poses significant economic challenges. The

installation process becomes more complex and expensive as additional cable length and careful management of each cable end are required. Unlike wet mate connectors, dry mate connectors take longer to install due to the necessity of vessel-based splicing or jointing, adding further limitations for deep-water projects. These constraints are compounded by the reduced availability of weather windows in deeper waters, where larger wind resources are typically found, making timely and efficient installation more difficult.

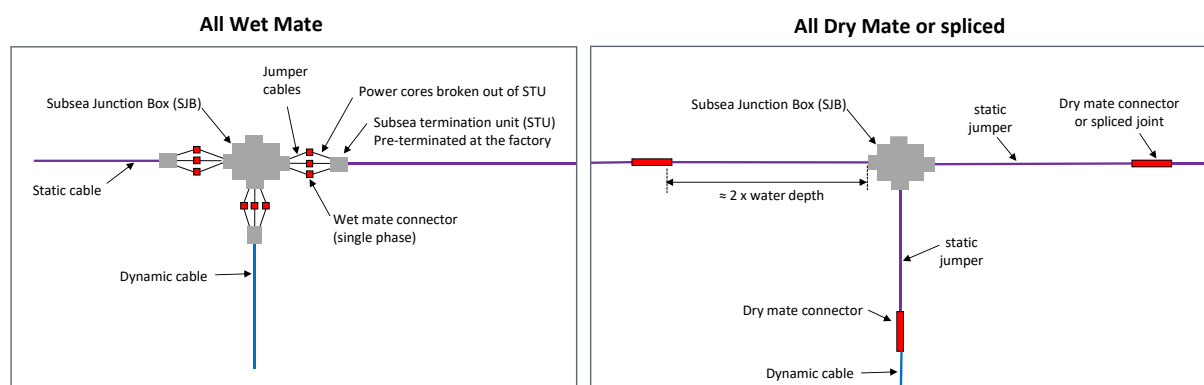


Figure 5-2: Subsea connection options.

## 5.4 Approach

The approach outlined within this report portrays the key considerations within the cost analysis for DC12. Additionally, the aim of this section is to highlight how the deep water configurations from DC12 were used to expand on the work conducted as part of DC06 [1], which was the benchmark for this study.

Through a review of existing research and stakeholder engagement, a foundation for the methodology was established in the DC06. This included the identification of the key variables for comparison, such as supply costs, vessel procurement, installation costs, and O&M expenses. The collected data has been analysed through the ORE Catapult internal LCoE calculation tool, which is summarised into the DC12 Excel model available for the FOW CoE partners as part of this deliverable. The results were then interpreted to highlight key cost and value outcomes for a 900 MW FOWF. This analysis underscores the increased costs associated with installing a wind farm in deeper waters compared to the base case analysed in DC06 of 100 m.

The supply chain and FOW CoE partners outlined key considerations for the DC06 techno-economic analysis [1]. These assumptions were reviewed and validated by the CoE and subsequently applied in the DC12 cost analysis. This approach allowed for a more focused comparative analysis in the current report, which has been summarised below.

### 5.4.1 Development and Decommissioning Expenditure

DEVEX covers costs during the development stage, including feasibility studies, design, testing, and commissioning. DECEX included costs for decommissioning, such as cable retrieval, material disposal, and site restoration. Although DEVEX and DECEX are not part of the main analysis, they were estimated to enable LCoE comparisons for each scenario. ORE Catapult's internal cost model estimates DEVEX and DECEX, which were used in the DC12 techno-economic analysis. These factors remain unchanged from DC06 since they are not a key focus of this study and are included primarily to inform the overall LCoE. While deeper waters may increase these costs, they represent more of an unknown for FOW. Deeper waters could potentially lead to longer development timelines, enhanced design processes,

and additional testing and qualification of 132 kV cables. However, for the purposes of this study, these factors have been kept consistent.

#### 5.4.2 Capital Expenditure

A significant portion of the CAPEX costs used in the DC12 cost comparison were drawn directly from DC06. In the main body of this report, these costs are discussed but not elaborated on in depth.

This study focused on the CAPEX of deep water dynamic cable systems, which significantly impacts the LCoE of a FOWF and varies based on cable configuration, water depth, topology, and technologies. CAPEX includes costs for cable supply, installation equipment, labour, and related expenses, all of which differ in deeper waters. Each CAPEX cost element is detailed in DC06 [1]. Costs for supply and installation were evaluated for each of the 23 topologies and related water depth cases. CAPEX encompasses all pre-operation costs, after DEVEX, typically forming a significant portion of overall expenses.

#### Supply and Installation

This study evaluates several factors impacting CAPEX for supply and installation, noting that these costs generally rise with greater installation depths. Cable lengths and components are based on a fixed number of turbines and distances, including extra length for dry mate subsea hubs. For cables longer than 3 km, the transition to static cables helps manage costs. Site-specific testing was estimated at £2.5 million and consistent across scenarios, while costs for seabed interfacing, cable protection, clump weights, and substation designs were not included but may be explored in future studies. Installation costs were found to be influenced by the cable lay vessel, buoyancy modules, and the number of connectors and cables per vessel trip. The choice between carousels and reels for different cable sizes also affects installation costs.

The DC12 cost analysis highlights how water depth and array types influence component requirements, revealing the added equipment and longer cable lengths needed for deeper water installations, which in turn increases supply costs. Installation is also impacted, as pre-laying longer cables with more ancillary equipment extends vessel time, potentially requiring larger vessels. Deeper waters prolong cable hookup due to retrieval from greater depths, and vessel mobilisation and demobilisation are slower as transpooling and handling larger, more complex equipment takes more time. The installation complexity - although closer to the surface - increases further when dealing with suspended wave systems. These considerations have been factored into the installation assumptions by adjusting the DC06 shallow water benchmark, with validation from relevant stakeholders.

Several aspects of the supply costs remain consistent from DC06 to DC12. These supply costs were broken down into different sub-segments of the deep water dynamic cable system. The first segment included topside components needed at the substructure, such as cable interfaces, hang-off points, pull-in assemblies, I/J tubes, and bend stiffener connectors—all accounted for in the DC12 cost analysis. These cost estimates are based on assumptions derived from supply chain interactions and prior ORE Catapult expertise.

Subsea connection supply costs were taken directly from DC06 [1] for consideration in this DC12 cost comparison; this includes the wet mate quick connection at the substructure and various multi-way subsea hubs.

The breakdown of the FOWT connection supply cost is also included, incorporating the connection subsystems. This covers conventional connection (spliced and future cases), disconnectable I-tubes and quick connect designs.

DC12 is focussed on 132 kV cables due to the significant electrical losses seen at 66 kV for the cable lengths required for deep water installation. For the topologies assessed in DC12 the cable designs range in CSA from 150 mm<sup>2</sup> up to 1200 mm<sup>2</sup> which vary across the 132 kV static and dynamic cables.

### CAPEX Findings

Keeping CAPEX low is an important factor in reducing the LCoE. Certain array topologies are seen as a desirable solution if they offer the benefit of redundancy; however, the additional cable lengths can lead to a substantially higher CAPEX when compared to the baseline T1, as seen for the radial design with 100% return in Figure 5-3 (T4–T6). Also, the fishbone design T14 was estimated to have a high overall CAPEX.

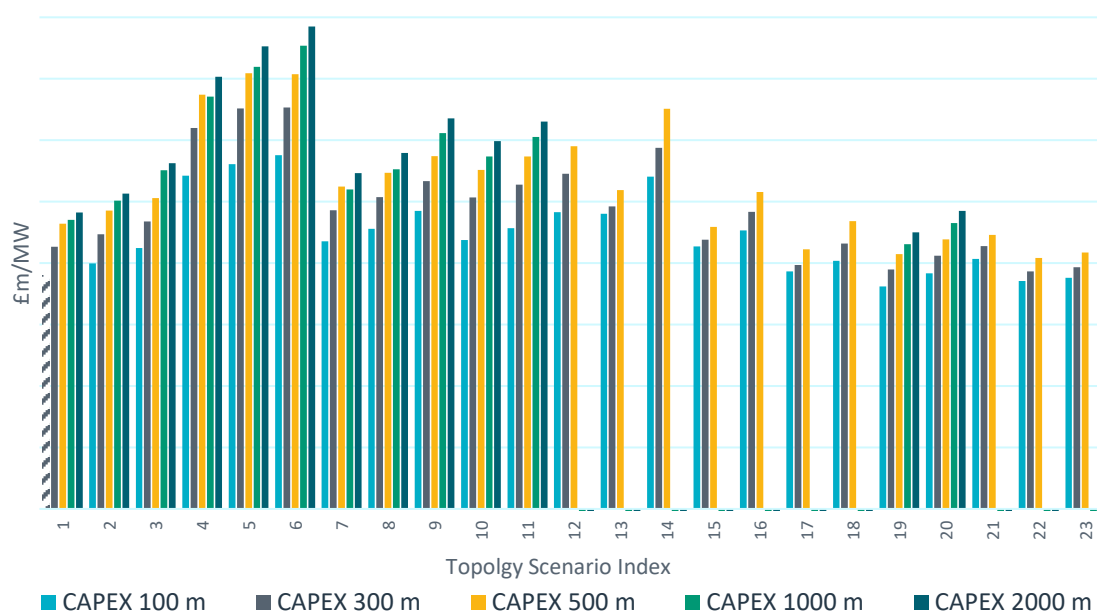


Figure 5-3: Total CAPEX costs for the assessed topologies across all water depths.  
Radial (T1->T3), Radial Return (T4->T6), 20% Ring (T7->T9), 67% Ring (T10->T12), Fishbone (T13->T14), Fishbone Radial (T15->T16), Star (T17->T18), Branching (T19->T21), Branching Hub (T21->T23)

Figure 5-3 offers insight into CAPEX variation as water depth increases from the shallow 100 m benchmark to 2000 m, showcasing the results for all topology scenarios.

The below topology scenarios provided some of the lowest CAPEX costs for the 100 m shallow water benchmark:

- T19-20: 132 kV, branching (turbine) design:** The CAPEX for the traditional future case and disconnectable I-tube have a low cost at 100 m. The topology is observed to have a low CAPEX compared to the other designs. This will be due to the single feeder cable connecting two strings and the relatively low CSA required, also, it will be influenced by the reduced installation requirements of these novel designs.
- T2: 132 kV, radial design:** The total CAPEX for the disconnectable I-tube connection is also low. This is due to the disconnectable I-tube accommodating the cable entry of both cables, reducing the number of connectors required.

Figure 5-3 shows an average CAPEX increase of 1.15% from 100 m to 300 m, with the largest impact observed in the radial return topologies (T4–T6), peaking at a 2.24% increase for T5. This is primarily due to the significant increase in cable lengths across the FOWF compared to other designs. The findings also showcase that T5 remains the highest CAPEX topology at 300 m, still marginally greater than T14 and that T19 remains the lowest CAPEX option only increasing by 0.74%, when compared to T5 which increased by 1.22%.

A similar trend can be seen for the step up to 500 m water depth where again the increased cable lengths for the radial return topologies boast the highest CAPEX increases from the 100 m benchmark at 3.24% for T6, a significant step up from the average increase of 1.99% across all the topologies. Additionally, T19 remains the lowest estimated CAPEX option.

As water depth increases to 1000 m, while the same trends persist, the scenario shifts as optimal designs become suspended, rendering several topologies obsolete due to the impracticality of seabed connection. T6 again shows the highest CAPEX, with a 4.38% increase from the 100 m benchmark, while T19 remains the lowest CAPEX option.

The 1000 m and 2000 m results shown in Figure 5-3 are quite similar due to the comparable suspended cable configurations. T14 consistently has the highest CAPEX, while T35 remains the lowest.

Some additional findings from the CAPEX comparison have been listed below:

- Dry mate subsea hub connections resulted in a high installation duration, causing the costs of vessel hire to rise considerably. In deeper water the requirement for the dynamic cable to be two times the water depth to allow for dry connection topside also majorly impacts the total supply costs.
- The quick connection at the substructure design had the lowest TRL compared to the other designs – demonstrations of this technology type have all been in shallow water (in the context of this scope of work) – meaning further development, testing and qualification will be required to showcase this is a reliable solution for deeper waters, which will be partly responsible for the higher cost. As the technology becomes more established, it will become lower in cost. If these solutions can provide good value for operational sites, it could become less expensive due to product development and industry acceleration.
- The topside disconnectable I-tube design included one disconnectable tube for two cable entries. If installed in the expected future case way with pre-installed terminations, it would, as demonstrated provide a lower CAPEX than the conventional (future case) design due to a shorter installation duration. However, with deeper waters typically being associated with larger wind resources smaller weather windows have to be considered.
- Including a redundancy line in a traditional daisy chain arrangement, like the radial return or ring design, was found to lead to a higher supply cost. This is due to the additional cable required. To increase the level of redundancy, the CSA of the cable across the entire string will need to increase, thus increasing costs. When comparing the shallow water benchmark to the deep water scenarios the stand out consideration is the impact of suspended systems on the viability of redundancy lines running along the seabed.

### 5.4.3 Operational Expenditure

OPEX encompasses routine operation and maintenance (O&M) activities as well as repair situations and unforeseen events during operation that need intervention, such as towing to port (T2P) for

significant component replacements. For cables specifically, OPEX may involve monitoring, maintenance, repairs, replacements, and technician training. This expenditure can greatly impact the LCoE of a FOWF, but it varies widely based on the cable topology and connection types, which are influenced by their associated failure rates.

### Cable Maintenance, Repair and Tow to Port

Scheduled maintenance, which includes both subsea and topside tasks, is consistent across all designs, with most maintenance expected to be topside due to the focus on maintenance-free subsea equipment. The study primarily examines fault finding and repair costs for various connector types and topologies, noting that repair durations and costs vary based on the complexity of the connections and equipment involved. The introduction of 'smart' hubs could reduce pre-repair time by improving fault detection, though this benefit is not fully quantified.

T2P procedures are standardised across all topologies for water depth, vessels and port considerations for comparative purposes, with the distance to port not affecting the analysis. However, the time taken for (dis)connection is considered for each of the topologies. A full T2P operation involves disconnection, the T2P procedure, and reconnection and energising. For major component repairs or replacements, the array must be powered down to disconnect the affected turbine. The process duration varies depending on the connector type, which influences the required vessels. For example, conventional splices have longer connection times due to manual splicing, while quick connectors offer faster, plug-in connections.

As part of T2P in DC06, continuity becomes a consideration. Continuity is the process of reconnecting the cable string after an asset has been removed for a T2P repair or replacement. Without continuity, the system is powered down, and the affected turbine is disconnected, leaving its string inactive. With continuity in place, the remaining cable ends will be connected together.

Regarding OPEX, water depth significantly impacts repair costs. As water depth increases, the expenses for vessel mobilisation and component removal and repair also rise. Additionally, basic repairs in deeper waters take longer due to the increased time needed to access and fix components further from the vessel. DC06 presented hypothetical scenarios for repair to determine an 'average failure impact'. This approach compared topologies objectively to evaluate their performance and has been used in DC12.

DC06 [1] introduced sensitivity cases as an increase in reliability by introducing 50% improvements, 90% improvements, and 95% improvements for substructure connectors and subsea hubs. This same methodology has been utilised in the DC12 cost analysis. These reliability improvement figures were determined as part of a reliability assessment conducted by DNV, which identified high failure rates for connectors due to the uncertainty of risk for new novel designs. Using the valuable insights gained from DNV's assessment, the range of sensitivity cases were selected.

The failure rates from DC06 [1] have signified that the novel connector designs have low reliability; however, this is likely to change as the technology is used and developed, thus leading to better reliability as the technology reaches mass production and full commercialisation and standardisation.

These OPEX considerations have been factored into the repair assumptions by adjusting the DC06 shallow water benchmark to account for the increase according to water depth, with validation from relevant stakeholders.

## OPEX Findings

The results for OPEX show a linear increase in OPEX cost with increase in water depth. T2P is unaffected by water depth, while repair costs have been scaled directly in relation to water depth up until the system becomes suspended. The purpose of DC12 is to assess OPEX across all topology scenarios, from 100 m to 2000 m. The table below shows the percentage increase in OPEX costs from the 100 m shallow water benchmark to 2000 m, for both 0% and 95% improvements in the lowest OPEX cost scenarios, as seen in Table 5-2.

Table 5-2: The OPEX percentage increase for both 0% and 95% improvement scenarios from the 100 m benchmark through to 2000 m.

| Topology Scenario                          | Improvement % | Percentage Increase % |             |              |              |
|--------------------------------------------|---------------|-----------------------|-------------|--------------|--------------|
|                                            |               | 100 – 300 m           | 100 – 500 m | 100 – 1000 m | 100 – 2000 m |
| T1 : Radial (conventional connector)       | 0             | 2.28                  | 4.55        | 6.83         | 6.83         |
|                                            | 95            | 2.28                  | 4.55        | 6.83         | 6.83         |
| T4: Radial Return (conventional connector) | 0             | 2.35                  | 3.26        | 7.05         | 7.05         |
|                                            | 95            | 2.35                  | 3.26        | 7.05         | 7.05         |
| T13: Fishbone (wet mate hub)               | 0             | 2.44                  | 4.87        | -            | -            |
|                                            | 95            | 1.68                  | 3.35        | -            | -            |
| T14: Fishbone (dry mate hub)               | 0             | 3.09                  | 6.18        | -            | -            |
|                                            | 95            | 1.91                  | 3.82        | -            | -            |
| T17: Star (wet mate hub)                   | 0             | 2.27                  | 4.54        | -            | -            |
|                                            | 95            | 2.03                  | 4.06        | -            | -            |

As previously stated, T2P remains unchanged despite increasing water depth, while repair costs scale with deeper waters. The results roughly show a steady 2% increase in total OPEX for the radial design (T1) and the radial return design (T4) at each step up in water depth from 100 m to 1000 m, where the system becomes suspended, and OPEX costs stabilise. This is consistent for both the 0% and 95% improvement scenarios, as connection reliability doesn't vary between them.

For the fishbone designs (T13 & T14) and the star design (T17) the percentage increase from 100 m to 300 m doubles for 100 m to 500 m in both improvement scenarios. These designs also become obsolete at 1000 m when the cable configuration is suspended.

In these topologies, the 95% improvement scenario clearly offers a benefit over the 0% scenario, showing a lower percentage increase in OPEX as water depth rises, resulting in significantly lower total OPEX costs at 95% improvement. Figure 5-4 visually represents these findings by highlighting the total OPEX costs at 500 m, again showcasing T1 (0%) as the baseline.

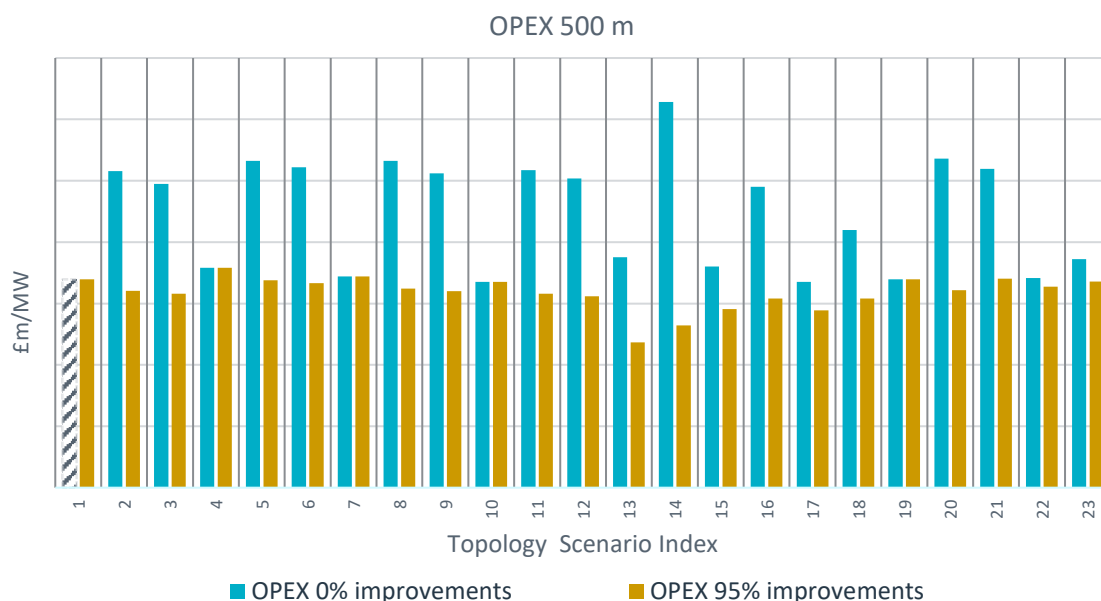


Figure 5-4: The estimated OPEX per year for a range of topologies with 0% and 95% engineering improvement at 500 m. Radial (T1->T3), Radial Return (T4->T6), 20% Ring (T7->T9), 67% Ring (T10->T12), Fishbone (T13->T14), Fishbone Radial (T15->T16), Star (T17->T18), Branching (T19->T21), Branching Hub (T21->T23).

By improving the reliability of the subsea hubs, the fishbone and star designs could lead to substantial reductions in OPEX. Some additional findings from the OPEX comparison have been listed below:

- As expected, where there is a substantial improvement in reliability (95%) for novel connector designs, the overall OPEX begins to shift from traditional connector design to both, disconnectable I-tube design and the quick connection. The main disadvantage to date of these technologies is the reduction of risk.
- Fishbone with wet mate hubs have the lowest overall OPEX with a 95% reliability improvement. As it is assumed static cables have lower failure rates compared to dynamic cables, the fishbone design allows for a modular design allowing for quick repair of components. Even without the connector failure rate sensitivity study, the fishbone design isn't seen as having a substantially high OPEX.
- An infield connection can be made for two cable ends for the splice or a disconnectable I-Tube connector design allowing continuity. By using continuity methods, the LCoE can ultimately be reduced.
- The conventional connection with future pre-terminated cables can provide the best OPEX security in a variety of topology designs, even without providing any continuity during T2P activities.

'Smart' hubs, both dry and wet mate designs, are not yet in deployment, and concepts aren't available to feed into the study. Therefore, there is limited information that can be shared on how exactly these hubs will be designed. Through the advanced utilisation of condition monitoring and the deployment of a subsea switchgear, operators will be able to identify potential issues before they become major problems. This will ultimately reduce the time and cost associated with pre-emptive repair. Condition monitoring will also play a key role in 'standard' hubs, to reduce the time required for fault finding.

5.4.4 Energy Production

Energy production must be considered when comparing the value and cost of each scenario. This includes a comparison of system performance and annual energy production (AEP) of each site.

In regard to the system performance the 132 kV cable designs were identified to have a capacity factor of 62%. This is also considered the AEP of each site and uses an ideal power factor of 0.95.

To determine the AEP, the following calculation was used:

*AEP = Installed Capacity × Capacity Factor × Wind Speed × hours in a year*

AEP Findings

The value of the different designs and connectors can be assessed by comparing the AEP of the different scenarios. The AEP will vary in parallel with the revenue potential, system performance, and overall expenditure of the project. AEP can be observed in Figure 5-5.

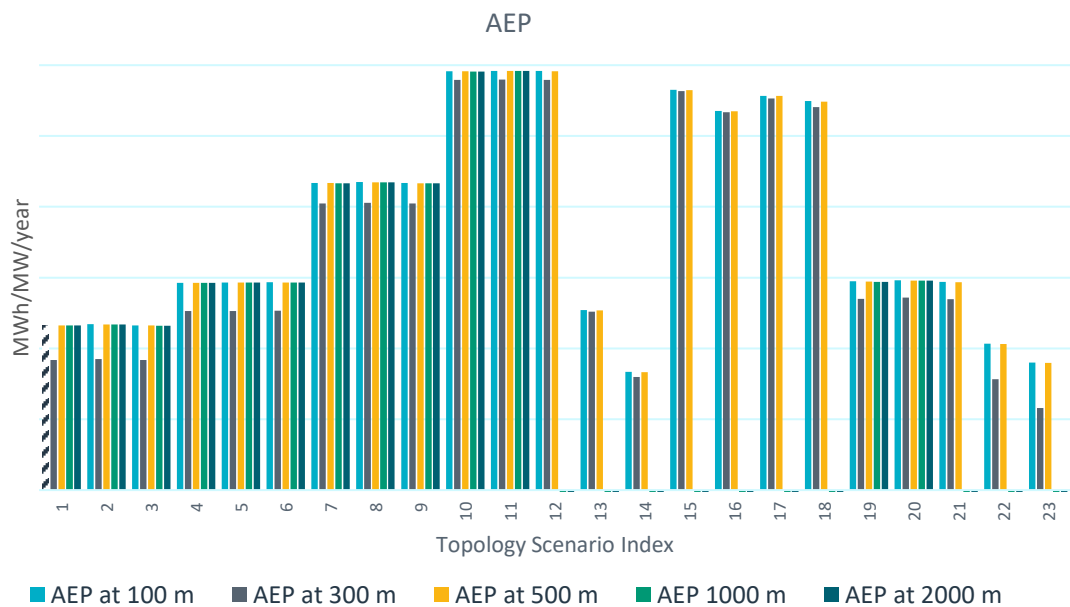


Figure 5-5: Annual energy production (MWh/MW/year) for the various topologies and connection types across all assessed water depths. Radial (T1->T3), Radial Return (T4->T6), 20% Ring (T7->T9), 67% Ring (T10->T12), Fishbone (T13->T14), Fishbone Radial (T15->T16), Star (T17->T18), Branching (T19->T21), Branching Hub (T21->T23).

It can be seen that the chosen array topologies affect the AEP, this can then impact the operational flexibility and revenue potential of the project. The addition of redundancy for topologies like the ring designs (T7–T12) leads to a higher AEP, with (T13 and T14) 132 kV fishbone designs having some of the lowest AEP with the longest lengths of static cable.

5.4.5 Levelised Cost of Energy

LCoE assesses the total cost of generating electricity throughout projects' operational lifespans. It considers all aspects of the project, including development, installation, O&M, and decommissioning and is the basis for providing a comparison between the DC12 cable configurations and their respective water depths to the DC06 100 m shallow water benchmark.

The relationship between CAPEX, OPEX and AEP is provided below, where NPV is the net present value:

$$LCoE = NPV\left(\frac{CAPEX + OPEX}{AEP}\right)$$

ORE Catapult has a separate LCoE calculation tool to the calculations produced in this study; however, a simplified version of this tool is included within the DC12 internal cost model.

## 5.5 LCOE Results

Different cable system designs involve varying costs for construction, operation, and maintenance, making each design more desirable for specific reasons. The Levelised Cost of Energy (LCoE) is driven by CAPEX, OPEX, and AEP, with multiple assumptions influencing both CAPEX and OPEX, resulting in variability, as identified in this study. For example, CAPEX is heavily impacted by cable costs, which are critical when considering deep-water installations. OPEX, on the other hand, is influenced by factors like T2P duration and repair complexity, though in deeper waters, T2P costs are assumed to remain the same as the 100 m benchmark. Despite the detailed cost analysis provided in this report, a significant level of uncertainty exists in the results.

Branching designs were found to have low CAPEX across all water depths, primarily due to the use of a single feeder cable connecting two strings, requiring a relatively low cross-sectional area (CSA). Designs requiring multiple subsea hubs per string incurred much higher CAPEX, with the fishbone design featuring dry mate hubs ranking among the most expensive. Radial return topologies also showed higher CAPEX due to the larger CSA and extended cable lengths needed for redundancy back to the offshore substation.

Industry-supported sensitivity ranges were introduced, reflecting 0 – 95% reliability improvements and influencing failure rates used in the techno-economic analysis. At 0% reliability improvement, the wet mate star topology had the lowest OPEX due to it requiring smaller CSA dynamic cables and fewer hubs compared to designs like the fishbone. The radial design also exhibited low CAPEX – across all water depths, featuring established technology and simple design, outperforming more novel, redundant methods.

Table 5-3 through Table 5-12 summarise scenarios with the lowest LCoE across all water depths, under both 0 % and 95 % reliability improvements. Even components with high CAPEX can lead to significant OPEX savings over a 30-year project, particularly with 95 % reliability improvements. While some components increase CAPEX, they contribute to much lower OPEX, ultimately reducing LCoE. The subsea hubs, even without reliability improvements, have proven to lower OPEX and LCoE. Improving the reliability of novel connectors and dynamic cables enhances the value of designs like the star and fishbone topologies. The topologies have been ranked from 1-10, 1 being the most cost-effective:

### 5.5.1 100 m

Table 5-3: Most cost-effective topology and connector scenarios at 100 m identified in DC12 with a sensitivity of 0% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Star            | 7-way wet mate             | 4                 | 1    | 1    |
| Branching       | Conventional (future case) | 1                 | 2    | 2    |
| Radial          | Conventional (future case) | 3                 | 2    | 3    |
| Branching       | 3-way wet mate             | 2                 | 3    | 4    |
| Ring (67%)      | Conventional (future case) | 5                 | 2    | 5    |
| Ring (20%)      | Conventional (future case) | 6                 | 4    | 6    |

Table 5-4: Most cost-effective topology and connector scenarios at 100 m identified in DC12 with a sensitivity of 95% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector  | Numerical Ranking |      |      |
|-----------------|-------------------------|-------------------|------|------|
|                 |                         | CAPEX             | OPEX | LCoE |
| Fishbone        | 3-way wet mate          | 4                 | 1    | 1    |
| Star            | 7-way wet mate          | 1                 | 3    | 2    |
| Fishbone        | 3-way dry mate          | 5                 | 2    | 3    |
| Fishbone Radial | 3-way wet mate          | 3                 | 4    | 4    |
| Star            | Quick connect, wet mate | 2                 | 5    | 5    |

### 5.5.2 300 m

Table 5-5: Most cost-effective topology and connector scenarios at 300 m identified in DC12 with a sensitivity of 0% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Star            | 7-way wet mate             | 2                 | 1    | 1    |
| Branching       | Conventional (future case) | 1                 | 2    | 2    |
| Branching       | 3-way wet mate             | 1                 | 3    | 3    |
| Radial          | Conventional (future case) | 3                 | 2    | 4    |
| Ring (67%)      | Conventional (future case) | 5                 | 3    | 5    |
| Ring (20%)      | Conventional (future case) | 4                 | 4    | 6    |

Table 5-6: Most cost-effective topology and connector scenarios at 300 m identified in DC12 with a sensitivity of 95% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Fishbone        | 3-way wet mate             | 4                 | 1    | 1    |
| Star            | 7-way wet mate             | 1                 | 3    | 2    |
| Fishbone Radial | 3-way dry mate             | 3                 | 4    | 3    |
| Fishbone        | 3-way wet mate             | 5                 | 2    | 4    |
| Star            | Conventional (future case) | 2                 | 5    | 5    |

### 5.5.3 500 m

Table 5-7: Most cost-effective topology and connector scenarios at 500 m identified in DC12 with a sensitivity of 0% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Star            | 7-way wet mate             | 2                 | 1    | 1    |
| Branching       | Conventional (future case) | 1                 | 2    | 2    |
| Branching       | 3-way wet mate             | 1                 | 3    | 3    |
| Radial          | Conventional (future case) | 3                 | 2    | 4    |
| Ring (67%)      | Conventional (future case) | 5                 | 3    | 5    |
| Ring (20%)      | Conventional (future case) | 4                 | 4    | 6    |

Table 5-8: Most cost-effective topology and connector scenarios at 500 m identified in DC12 with a sensitivity of 95% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector | Numerical Ranking |      |      |
|-----------------|------------------------|-------------------|------|------|
|                 |                        | CAPEX             | OPEX | LCoE |
| Fishbone        | 3-way wet mate         | 4                 | 1    | 1    |
| Star            | 7-way wet mate         | 1                 | 3    | 2    |
| Fishbone Radial | 3-way wet mate         | 2                 | 4    | 3    |
| Fishbone        | 3-way dry mate         | 5                 | 2    | 4    |
| Star            | 7-way dry mate         | 3                 | 5    | 5    |

### 5.5.4 1000 m

Table 5-9: Most cost-effective topology and connector scenarios at 1000 m identified in DC12 with a sensitivity of 0% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Branching       | 3-way wet mate             | 1                 | 1    | 1    |
| Radial          | Conventional (future case) | 2                 | 2    | 2    |
| Ring (20%)      | Conventional (future case) | 3                 | 4    | 3    |
| Ring (67%)      | Conventional (future case) | 4                 | 3    | 4    |

Table 5-10: Most cost-effective topology and connector scenarios at 1000 m identified in DC12 with a sensitivity of 95% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector  | Numerical Ranking |      |      |
|-----------------|-------------------------|-------------------|------|------|
|                 |                         | CAPEX             | OPEX | LCoE |
| Branching       | Disconnectable I-tube   | 1                 | 2    | 1    |
| Radial          | Disconnectable I-tube   | 2                 | 2    | 2    |
| Radial          | Quick connect, wet mate | 4                 | 1    | 3    |
| Ring (20%)      | Disconnectable I-tube   | 3                 | 3    | 4    |

### 5.5.5 2000 m

Table 5-11: Most cost-effective topology and connector scenarios at 2000 m identified in DC12 with a sensitivity of 0% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Branching       | 3-way wet mate             | 1                 | 1    | 1    |
| Radial          | Conventional (future case) | 2                 | 2    | 2    |
| Ring (20%)      | Conventional (future case) | 3                 | 4    | 3    |
| Ring (67%)      | Conventional (future case) | 4                 | 3    | 4    |

Table 5-12: Most cost-effective topology and connector scenarios at 2000 m identified in DC12 with a sensitivity of 95% reliability improvements for novel connector failure rates.

| Topology Design | Substructure Connector     | Numerical Ranking |      |      |
|-----------------|----------------------------|-------------------|------|------|
|                 |                            | CAPEX             | OPEX | LCoE |
| Branching       | Disconnectable I-tube      | 1                 | 2    | 1    |
| Radial          | Disconnectable I-tube      | 3                 | 2    | 2    |
| Radial          | Quick connect, wet mate    | 4                 | 1    | 3    |
| Branching       | Conventional (future case) | 2                 | 3    | 4    |

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