

PDZ 400MW MOS

Concept Study Report



Apollo for Celtic Sea Power



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Contents

Executive Summary	5
1 Introduction	8
1.1 Background.....	8
1.2 Concept study purpose and objectives	10
1.3 Basis of concept design	11
2 Abbreviations	12
3 Study scenarios	14
4 Grid connection	16
4.1 Security and Quality of Supply and Standard (SQSS).....	17
4.2 Generation Connection Criteria Applicable to an Offshore Transmission System.....	19
4.3 Limits to Loss of Power Infeed Risks	19
4.4 Offshore Platforms	20
4.5 Generation Connection Capacity	20
4.6 Technical Risks of Different Transmission Levels	21
4.7 Grid Entry Characteristics	21
5 Export cables	24
5.1 Cable Route	24
5.2 Cable Sizing	30
6 Offshore substation – electrical design	41
6.1 System design	41
6.2 Platform Utilities – Electrical.....	44
7 Offshore substation – structural design	47
7.1 General Structural Concept.....	47
7.2 Conceptual Design	47
7.3 Design Specifications	49
7.4 Jacket Concept Design	52
7.5 Foundation Concept Design.....	55
7.6 Topside Concept Design.....	56
7.7 Fabrication	60
7.8 Transportation and Installation.....	61



8	Operation and maintenance	66
8.1	O&M Strategy	66
8.2	OPEX and Availability Modelling	74
8.3	Generator Maintenance Requirements.....	77
9	CAPEX Estimates.....	80
9.1	CAPEX estimate – Cable routes.....	81
9.2	Offshore Cable Installation – Programme Schedule.....	82
9.3	CAPEX estimate – Primary Costs.....	85
10	Project life costs (CAPEX & OPEX)	88
10.1	CAPEX and OPEX summary.....	89
11	Cost benefit analysis	89
11.1	Independent radial projects.....	89
11.2	Technical assumptions.....	91
11.3	Costs	93
11.4	Conclusion	96
12	Anticipatory investment.....	97
13	References.....	102
Appendix A	Supporting documentation.....	104



Executive Summary

Celtic Sea Power (CSP), a subsidiary of Cornwall Council, has funding from the Welsh European Funding Office and the Swansea Bay City Deal to develop the Pembrokeshire Demonstration Zone (PDZ), a leased area offshore from the South Pembrokeshire coastline of Wales. CSP have been progressing technical, environmental and commercial studies to develop a viable concept transmission solution which could enable future PDZ site located generators to connect to the grid, by providing more near-term potential FLOW projects a coordinated solution. The objective of this concept study was to evaluate the cost benefit of building a grid connected MOS to facilitate the coordination of 4 x 100MW generation projects and evaluating the benefits in comparison to independent radial connections. To enable the cost benefit analysis to be undertaken a concept level design of the MOS, transmission system and grid connection first had to be established. As part of the concept study, key project objectives had to be considered:

- A phased design approach for installation and connecting to the MOS.
- A single consented corridor from the MOS to the to the Point of Connection (POC).

To establish a concept design for the 400MW PDZ MOS, the study evaluated the following areas:

- 1 Phasing scenarios (Refer section 3)
- 2 Grid connection (Refer section 4)
- 3 Cable routing and design (Refer section 5)
- 4 Offshore substation – electrical design (Refer section 6)
- 5 Offshore substation – structural design (Refer section 7)
- 6 Operation and Maintenance (Refer section 8)

From studying the design in each of these areas, it was concluded that with a single circuit design there was no opportunity or cost advantage to phase the 400MW PDZ MOS. The optimum landing point for the export cables was at Freshwater West based on both offshore and onshore routing options. Further data is required as the project progresses to confirm this location. 10 scenarios were studied as part of the power systems analysis and transmission system design to incorporate two potential landfall points (Freshwater West and Greenala Point), conductor materials and export voltages. The three main cost components influencing the MOS CAPEX are SCADA design, offshore platform (including topside equipment) and the jacket. Those three category values are £4.13m, £44.16m and £20.87m, respectively. The analysis has shown that none of these primary costs are significantly impacted by the export system design (landfall point, export voltage or cable design). The preferred structural design of the MOS is a 2390 Te jacket with a topside footprint of 20m². This increases with a 1:15 batter to 31m² at the seabed. The jacket design is primarily driven by the environmental conditions and the J-tube requirements. The topsides is a braced integrated two deck arrangement with an approximate upper bound weight of 1499 Te and maximum topsides footprint of 30m x 30m (900m² area).

As discussed in Section 11, a minimum of a class 3 estimate cost benefit analysis was conducted for the 400MW PDZ MOS project. This analysis compared the connection costs for 4 x 100MW theoretical windfarms in various locations within the Celtic Sea regional DPO using two different concepts. The first scenario shows the estimated transmission costs for each project to connect to the grid independently of each other and the second scenario shows each project connected to the MOS as a single PCC.

A summary of the CAPEX and OPEX costs borne by each 100MW zone wind farm developer and the MOS in respect of connecting from the 100MW zones to the PCC (independent onshore PCC vs MOS PCC), is presented in Figure 1 below.

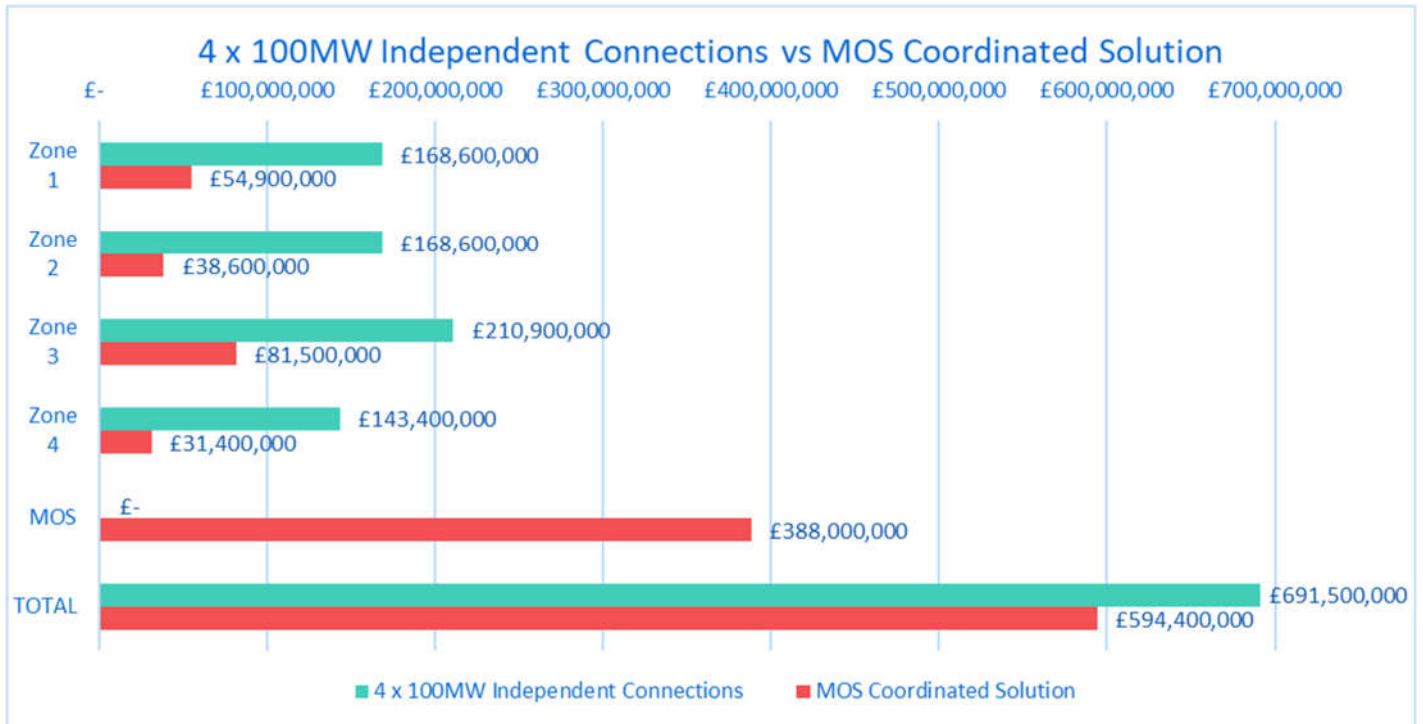


Figure 1 – Total project life costs comparison of 4 x 100MW Independent Connections vs MOS Coordinated Solution

The total whole life cost for the independent connection scenario is £691.5m vs a total cost of £594.4m for the MOS coordinated solution; a saving of £97.1m (14%). Tables 38 and 39 contain the cost breakdowns behind the comparison shown in Figure 1 above.

Considering the total project life costs, there is an average of £121.3m which could be saved by each 100MW wind farm developer by choosing the MOS solution rather than connecting to an onshore PCC independently. This saving does not include any fees the MOS developer may charge the wind farm developers to connect to the MOS, therefore the demonstrable saving to the wind farm developers cannot be fully determined at this stage.

The 'Coordinated' approach requires the Initial User/Developer (IU) to make an anticipatory investment to develop the primary common infrastructure that will then be shared with future users to facilitate their connection. The Later User(s) (LU) will then fund the further infrastructure required for their development. The IU recovers its additional design and construction costs from the OFTO auction and ongoing liabilities, securities and risk sit with the consumer until the later user connects. The anticipatory investment required is based on the 4 x 100MW coordinated developments is £137.4m. This report does not investigate the commercial model to recover the costs.

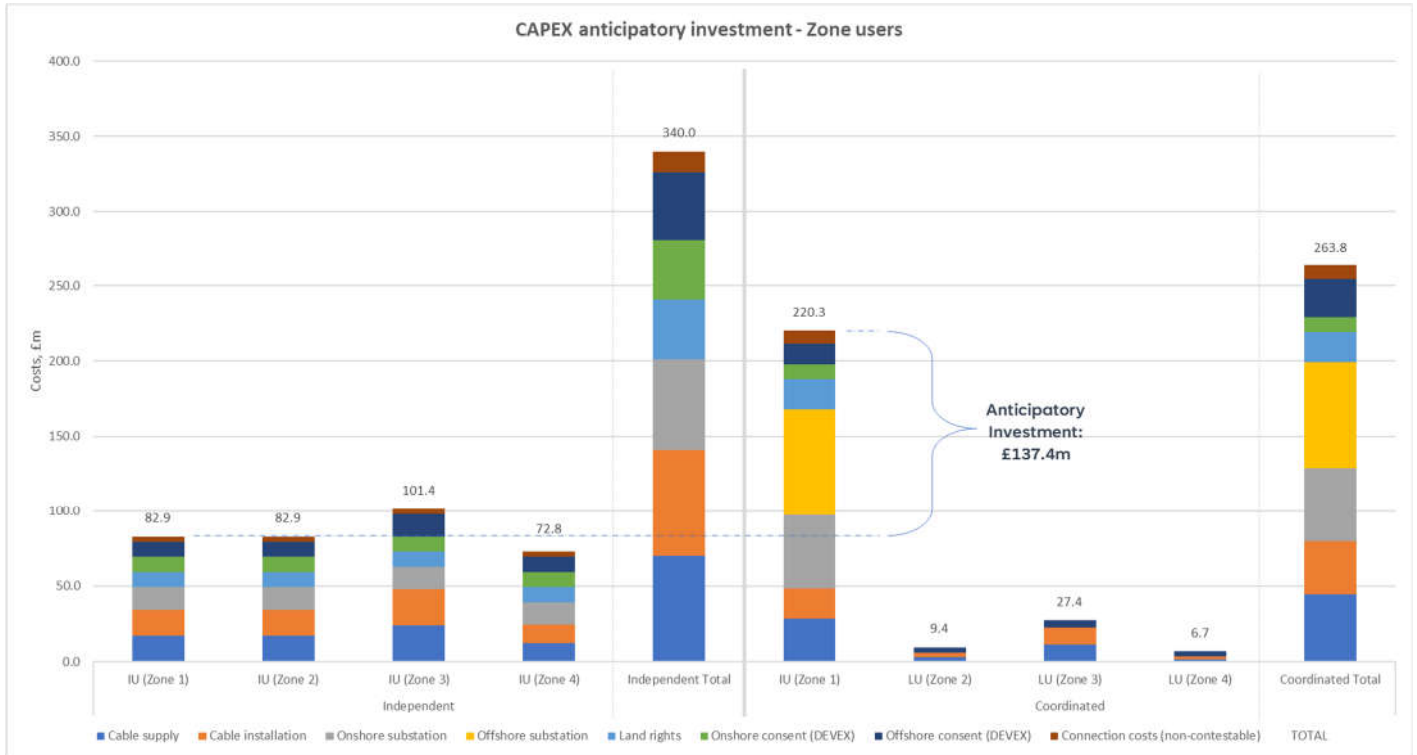


Figure 2 – Anticipatory investment

In conclusion, this conceptual study has examined different scenarios and designs to determine the optimal solution for developing a grid connected MOS that can aid in coordinating 4 x 100MW generation projects. The study has demonstrated that adopting a coordinated approach, as opposed to independent radial connections, can save up to £97.1m (14%).



1 Introduction

1.1 Background

Celtic Sea Power (CSP) is a 100% subsidiary of Cornwall Council with funding from the Welsh European Funding Office (WEFO) and the Swansea Bay City Deal (SBCD) to develop 'The Pembrokeshire Demonstration Zone' (PDZ).

CSP is the seabed lease holder of the PDZ, an area located approximately 19km offshore from the South Pembrokeshire coastline of Wales and comprising a 90km² area leased from The Crown Estate (TCE) for a period of 45 years. The PDZ is indicated as the black hatched area in Figure 3.

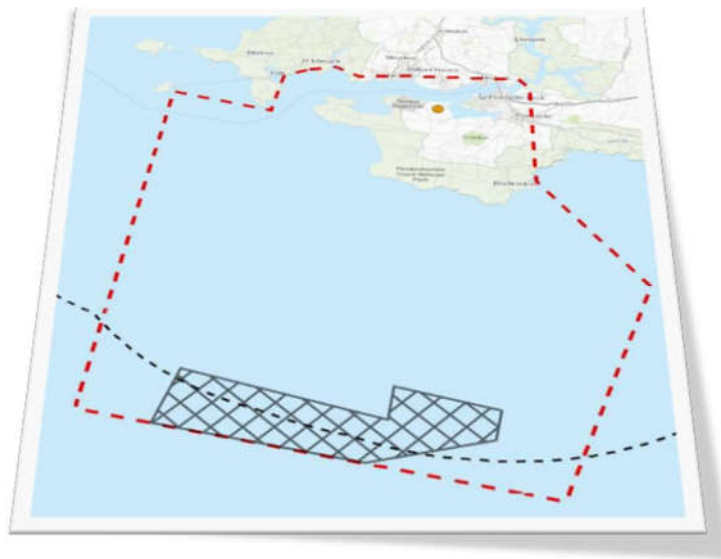


Figure 3 - PDZ lease area

The PDZ is part of the Pembroke Dock Marine programme whose sponsor is Pembrokeshire County Council and project delivery partners include Port of Milford Haven, Offshore Renewable Energy (ORE) Catapult and Marine Energy Wales. The project has secured funding up to the end of June 2023 to develop the PDZ and inform the next stage of the development pathway, securing the consents, discharging conditions, and working to finalise the investment for the capital build.

The emergence of Floating Offshore Wind (FLOW) has catalysed the potential for 'grid scale' test and demonstration activity in close proximity to the Pembrokeshire Demonstration Zone. The lease definition of the PDZ is a site for demonstrating multiple wave and tidal energy technologies. Constrained project delivery period due to a hard ERDF funding deadline and a co-funding delay resulted in Celtic Sea Power focusing project delivery activity on enabling infrastructure i.e., a Multi-connection Offshore Substation (MOS). This has been progressed to give confidence on the technical viability of a co-ordinated transmission solution that meets the requirements of both the FLOW test and demonstration projects, and the future requirements of the Wave Energy sector. This MOS aims to be capable of accommodating 400MW in a stepped approach.

Additionally, CSP is investigating design options for two commercial MOS's with the aim of accommodating up to 2GW in a stepped approach from Refined Area of Search A as the market matures and The Crown Estate's 4GW by 2035 aspirations are realised. As a base case, both the 400MW PDZ MOS and the two 1GW Commercial MOS's are planned to share the same single consented cable corridor to a Grid Supply Point (GSP) in Pembroke. This is shown indicatively in Figure 4.

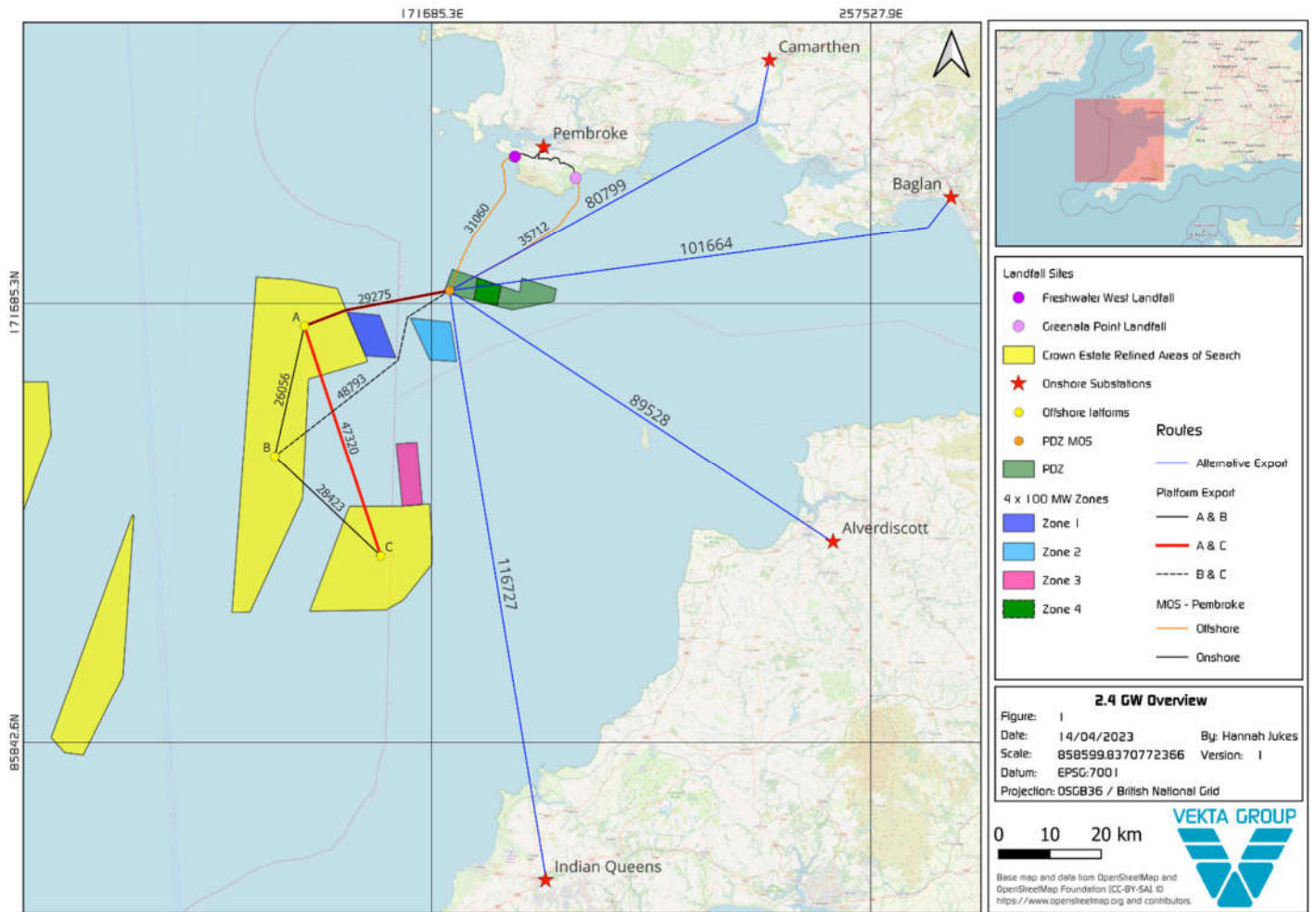


Figure 4 - Indicative 1GW MOS A & B and 400MW MOS locations and cable corridors

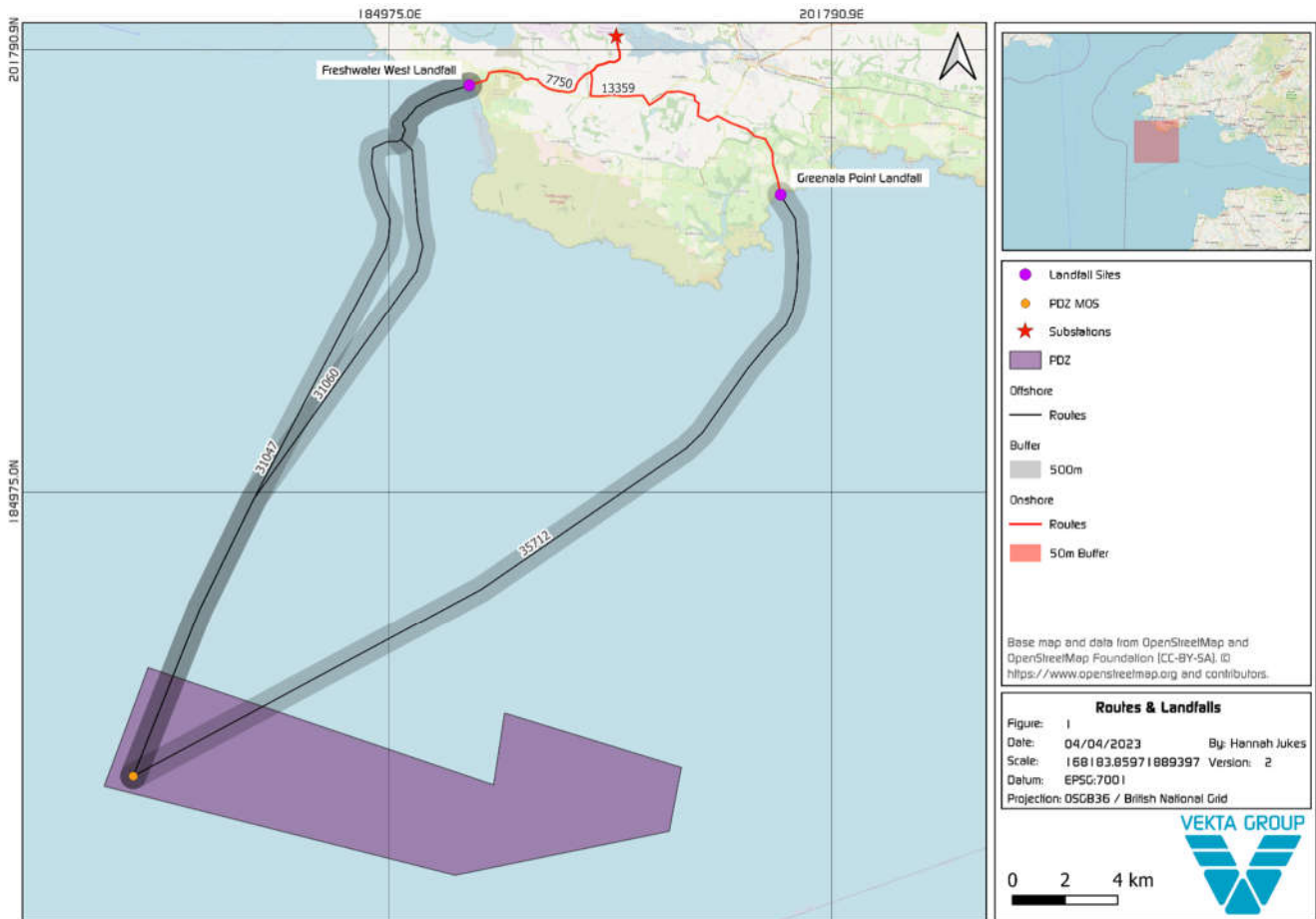


Figure 5 - Indicative 400MW MOS cable corridor options

However, NGENSO have identified 15 transmission substations as potential interface points [1], and consideration to the interface points east of Pembroke is required to maintain relevance to the HNDPUE output. These interface points include, but are not limited to Pembroke, Carmarthen and Baglan.

1.2 Concept study purpose and objectives

The purpose of this Concept Study Report is to create a design concept for the stepped 400MW PDZ MOS, including transmission and connection, whilst also evaluating the cost-benefit. The cost-benefit shall evaluate the coordinating of 4 x 100MW pre-commercial, test, or R&D projects in the PDZ area versus connecting 4 x 100MW projects independently. The 400MW MOS is to be located within the PDZ with an anticipated total cable length of 40km to a point of connection (PoC) at Pembroke power station (Figure 5).

The primary objective of this study is to provide a single Concept Study Report that informs on the following key project objectives:

- 1 Develop a preferred concept design to be taken into Pre-FEED.
- 2 Consider a phased approach to the design.
- 3 Utilise a single consented corridor to the POC.
- 4 Inform a cost benefit analysis for the stepped coordinated project (4 x 100MW) in comparison to 4 x 100MW independent generation projects.
- 5 Identify project risks to be carried into the Pre-FEED phase.



The concept study has been assessed and reported within the following sections:

- Grid connection
- Export cables
- Offshore substation – electrical design
- Offshore substation – structural design
- Operation and maintenance
- CAPEX estimates
- Project life costs (CAPEX & OPEX)
- Cost Benefit Analysis

1.3 Basis of concept design

Below is a high-level summary of the key design parameters considered as a basis for the concept design. Further details and parameters have been outlined in ‘PDZ 400MW MOS Concept – Basis of Design’ [2]

Table 1 - Overview of concept basis

Parameter	Unit
Commercial Operating Date (COD)	Q4 2026 or later
Operating life	Minimum of 30 years
Point of Connection (POC)	Pembroke Power Station
MOS location	Within Pembroke Demonstration Zone lease area from The Crown Estate
MOS facility type	Normally Unattended Installation (NUI)



2 Abbreviations

3LPE	3 Layer Polyethylene
AC	Alternating Current
Al	Aluminium
ALARP	As low as reasonably practicable
ALS	Accidental Limit State
ARM	Availability, Reliability & Maintainability
CBA	Cost Benefit Analysis
COD	Commercial Operations Date
CTV	Crew transfer vessel
Cu	Copper
DC	Direct Current
ESD	Emergency shutdown
FTE	Full-time employee
FWL	Freshwater West Landfall
GIS	Geographic Information System
GPL	Greenala Point Landfall
GSP	Grid Supply Point
HHOP	Helicopter Hoist Operations Passengers
HSE	Health and Safety Executive
HV	High voltage
HVAC	High voltage alternating current
HVDC	High voltage direct current
IS	Intrinsically Safe
ISO	International Organization for Standardization
kV	Kilovolt
MOS	Multi-connection Offshore Substation
MTBF	Mean time between failures
MTTR	Mean time to repair
MW	MegaWatt
NETS	National Electricity Transmission System
NGESO	National Grid Electricity System Operator Limited
OFTO	Offshore Transmission System Operator
PDZ	Pembrokeshire Demonstration Zone
PCC	Point of Common Coupling



PoC	Point of Connection
R&D	Research and Development
ROV	Remotely operated vehicle
SBCD	Swansea Bay City Deal
SCADA	Supervisory Control And Data Acquisition
SOV	Service Operation Vessel
SQSS	Security and Quality of Supply and Standard
SSoW	Safe System of Work
TCE	The Crown Estate
ULS	Ultimate Limit State
UTM	Universal Transverse Mercator
WEFO	Welsh European Funding Office
WTG	Wind turbine generator



3 Study scenarios

To build a 400MW MOS capable of connecting multiple offshore wind/tidal projects a variety of staging scenarios were considered. The phasing scenarios considered are shown in Table 2 below.

Table 2 – 400MW MOS Phased Capacity Scenarios

	Onshore Substation		Onshore Cabling			Offshore Cabling		Offshore Substation		Notes
	Minimum capacity based on initial user	All user capacity (0.4GW)	All user ducting	Minimum cabling based on initial user	All user cabling (0.4GW)	Minimum cabling based on initial user	All user cabling (0.4GW)	Minimum capacity based on initial user	All user capacity (0.4GW)	
#1		✓	✓		✓		✓		✓	Later users only need to connect to MOS
#2	✓		✓	✓		✓		✓		Each later user will need to install the required capacity above the already installed capacity
#3	✓		✓		✓	✓		✓		Each later user will need to install the required offshore capacity above the already installed capacity
#4	✓		✓	✓			✓		✓	Each later user will need to install the required onshore capacity above the already installed capacity

The consideration of these scenarios is necessary due to the absence of a precedent or standard in the UK for a large-scale offshore grid network intended to connect numerous wind farms. Despite the increasing amount of industry consultation and high-level design efforts by National Grid and Ofgem through the HND process, there is currently no definitive capacity and connection strategy, that has been released.

For 400MW MOS concept, only one phasing case was taken forward for detailed analysis, which was phasing according to case 1, where all users only needed to connect to the MOS. This was chosen as the base case because the design of the 400MW offshore substation was based on a single transformer solution, which included a minimum of 4 x 66kV switchgear bays on the platform.

The decision to use a single circuit was made as it provides the best balance of cost and reliability, given the total capacity required. In the early round one OFTO projects, which initially used 132kV transmission technology, there was a focus on maximising redundancy based on the N-1 requirements of SQSS. As a result, each export circuit was fully rated for the full power of the wind farm, and the grid SQSS standards had a much lower MW value that was allowed to be dropped from the grid in the event of a circuit outage or failure.

However, today the typical offshore transmission voltage has risen to a minimum of 220kV, and the current maximum limit for a single circuit loss to the grid is 1300MW, which is only going to increase in future standard updates. The ideal size limit for a single circuit at either 220kV or 275kV is 400MW, as it complies with the SQSS standard, uses standard and proven cable sizes, and can utilise a simple and relatively light single-deck, single-transformer platform.

Due to this design approach, there is no opportunity for phasing the offshore or onshore infrastructure, as there is only a single circuit and a single voltage being used for connecting projects offshore. There is no significant difference in the number of electrical equipment items required, whether 100MW or 400MW worth of projects



are being connected, except for the 66kV switchboard. This is considered a low-cost item, with no advantage to installing and commissioning offshore rather than during onshore fabrication. Therefore, there is only a single realistic staging methodology for the 400MW PDZ MOS.

Consideration of a design based on phasing with two transformer circuits and an increased level of redundancy would add significant cost to the project and thus reduce the attraction of the 400MW PDZ MOS. Furthermore, if a single project was 400MW and required its own transmission system, it is highly likely that a single circuit 220kV design would be used based on previous project precedent.

Whilst a single circuit design is being employed, there are multiple scenarios available in terms of the system design to balance cost, risk, and electrical losses. These consider voltages, conductor materials and landing points. It is also possible to use a second export cable without adding another transformer, as the highest likely mode of failure is the cables rather than the transformer and switchgear.

The electrical design scenarios being considered for 400MW PDZ MOS are shown in Table 3 below, all of which have similar installation timeframes.

Table 3 - 400MW MOS Electrical Scenarios

Scenario Name	Landing Point	Voltage (kV)	Conductor Material
400MW MOS Freshwater-LP 2x220kV Al	Freshwater West	2 x 220	Al
400MW MOS Freshwater-LP 220kV Al	Freshwater West	220	Al
400MW MOS Freshwater-LP 220kV Cu	Freshwater West	220	Cu
400MW MOS Freshwater-LP 275kV Al	Freshwater West	275	Al
400MW MOS Freshwater-LP 275kV Cu	Freshwater West	275	Cu
400MW MOS Greenala-LP 2x220kV Al	Greenala Point	2 x 220	Al
400MW MOS Greenala-LP 220kV Al	Greenala Point	220	Al
400MW MOS Greenala-LP 220kV Cu	Greenala Point	220	Cu
400MW MOS Greenala-LP 275kV Al	Greenala Point	275	Al
400MW MOS Greenala-LP 275kV Cu	Greenala Point	275	Cu



4 Grid connection

The grid connection point is identified as the point where the offshore transmission system interfaces with the grid. The grid connection point for the 400MW PDZ MOS is the Pembroke substation point of common coupling (PCC). This is a 132/400kV double circuit located in the Pembrokeshire area as shown in Figure 6.



Figure 6 - Pembroke 132/400kV Substation

An onshore substation will require building with a dedicated transformer as an intermediary between the incoming power from the MOS to the PCC. Electrical simulations were conducted using DigSILENT Powerfactory for the different scenarios. The variations in the scenarios account for the number of export cables, the landfall positions, and the circuit rating. All these variations help determine which is the optimal option for connecting to the grid. To build a picture of the grid network, both present and future, data from National Grid [3]-[13], was considered. National Grid has made recommendations required for connecting an extra 1GW of power to the Pembroke substation and it is adopted in this report NGESO Pathway to 2030 report [4]. The report recommendations, as outlined in Table 4, aim to significantly increase the reliability of the network.



Table 4 – Recommendations of onshore works [4].

Short Description of Works	Type of works	Interface Point
Install new bays at Pembroke 400kV substation	Interface point	Pembroke
Uprating equipment on the Pembroke - Swansea circuits	Interface point	Pembroke
Install new bay at Pembroke 400kV substation	Interface point	Pembroke
Turn-in the Pembroke-Walham circuit at Swansea North and substation modifications	Connection	NGET for the South West England Options
Reconductor the Cowley - Minety circuit	Connection	NGET for the South West England Options
Reconductor the Cowley - Walham circuit	Connection	NGET for the South West England Options
Reconductor the Feckenham - Walham circuit	Connection	NGET for the South West England Options
Reconductor the Feckenham - Minety circuit	Connection	NGET for the South West England Options

4.1 Security and Quality of Supply and Standard (SQSS)

The SQSS is a standard maintained by the National Grid Electricity System Operator (NGESO) which sets out the criteria and methodology for planning and operating the National Electricity Transmission System (NETS). Generation companies connected to the Great Britain transmission system are required to comply with the stipulations of this standard. As part of this study, the standard was reviewed in detail to certify that the proposed electrical studies comply with the latest release of the SQSS by NGESO [5] and NETS SQSS version 2.6 [6]. The SQSS criteria for offshore transmission are separated according to their functional parts as discussed below. The functional parts of an AC transmission system include:

- 1 The offshore connection facilities on the offshore platform/s, which may include:
 - The offshore grid entry point/s (GEP) at which offshore power stations connect into an offshore transmission system,
 - Any offshore supply point/s (OSP) where offshore power station demand is supplied from an offshore transmission system,
 - AC or DC offshore transmission circuits.
- 2 The cable circuit/s, which may include:
 - AC or DC cable offshore transmission circuits connecting an offshore platform either directly to an onshore overhead line forming part of the offshore transmission system or to onshore connection facilities forming part of the offshore transmission system.
- 3 An overhead line section, which may include:
 - AC or DC overhead line offshore transmission circuits connecting the cable offshore transmission circuits either directly to the first onshore substation or to onshore AC transformation or AC/DC conversion facilities not forming part of the first onshore substation.
- 4 Onshore connection facilities, which may include:



- AC/DC conversion facilities connecting DC overhead line or DC cable offshore transmission circuits to the interface point or user system interface point (as the case may be). Such facilities may constitute the first onshore substation,
- AC transformation facilities connecting AC overhead line or AC cable offshore transmission circuits to the interface point or user system interface point (as the case may be). Such facilities may constitute the first onshore substation.

The above constitute the functional parts of an offshore transmission system as stipulated in the NETS SQSS latest release [6]. This will be further explored, and two different variations will be considered for the transmission interfaces and hence the same SQSS criteria are applicable to both. The variations exist due to the different interface points and hence criteria to be met on the part of the offshore transmission owner. Similarly, the extent of the offshore generation and demand connection criteria also move with the interface point or user system interface point.

Concept 1

The owner of the transmission export system (OFTO) will own the first onshore substation and the offshore transmission circuit it is connected to. The OFTO will have to comply with standards for the transmission system and establishment of an onshore substation. This is the most likely concept to be adopted for this project. This concept is shown in Figure 7.

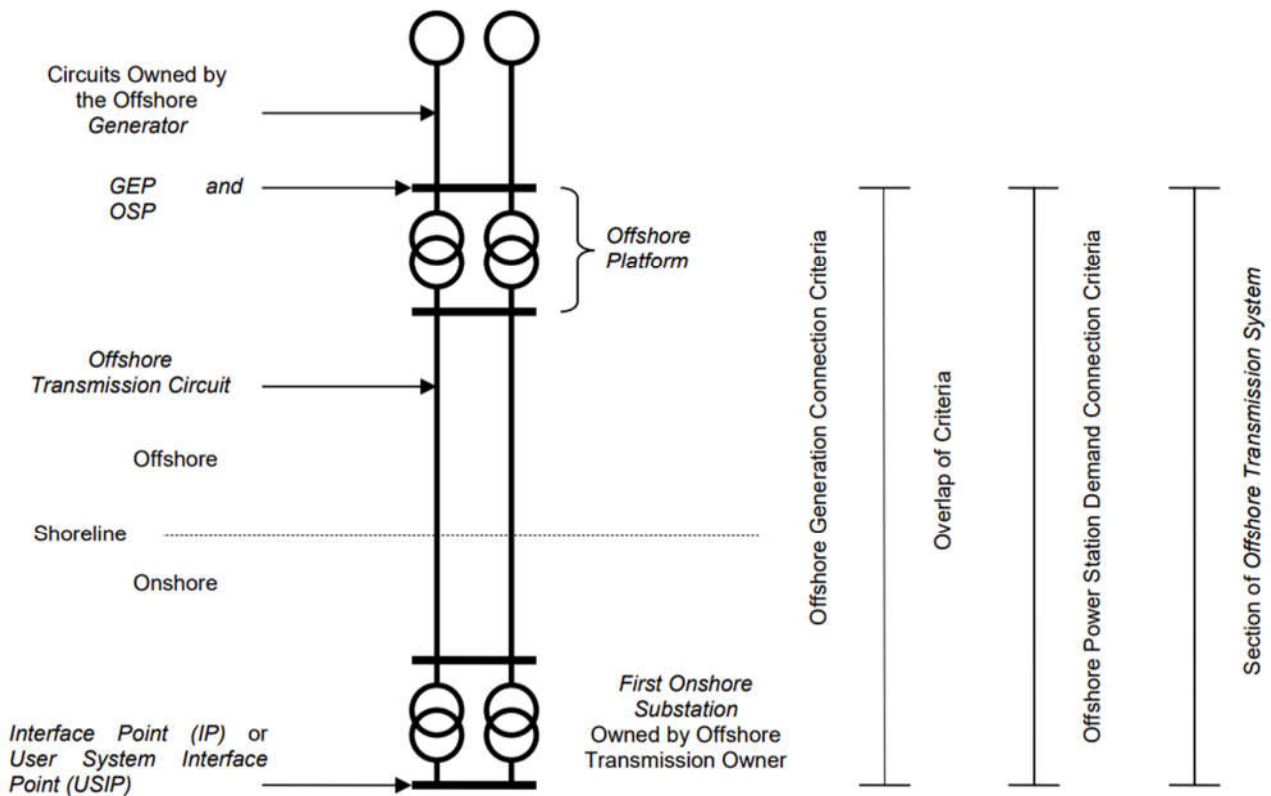


Figure 7 - An offshore transmission system with a directly connected power station and first onshore substation owned by the offshore transmission owner (adopted from NGENO NETS SQSS V2.6) [5].



Concept 2

This concept considers the first onshore substation, that the offshore transmission is connected to, is owned by the onshore transmission owner or user system interface point, as shown in Figure 8. This is a concept that assumes the transmission export system owner will have responsibility only up to the point of the overhead line connection to the onshore substation, from which the Transmission operator (TO) will be responsible. This concept only serves for comparison as the 400MW PDZ MOS design is more likely to adopt the more typical Concept 1.

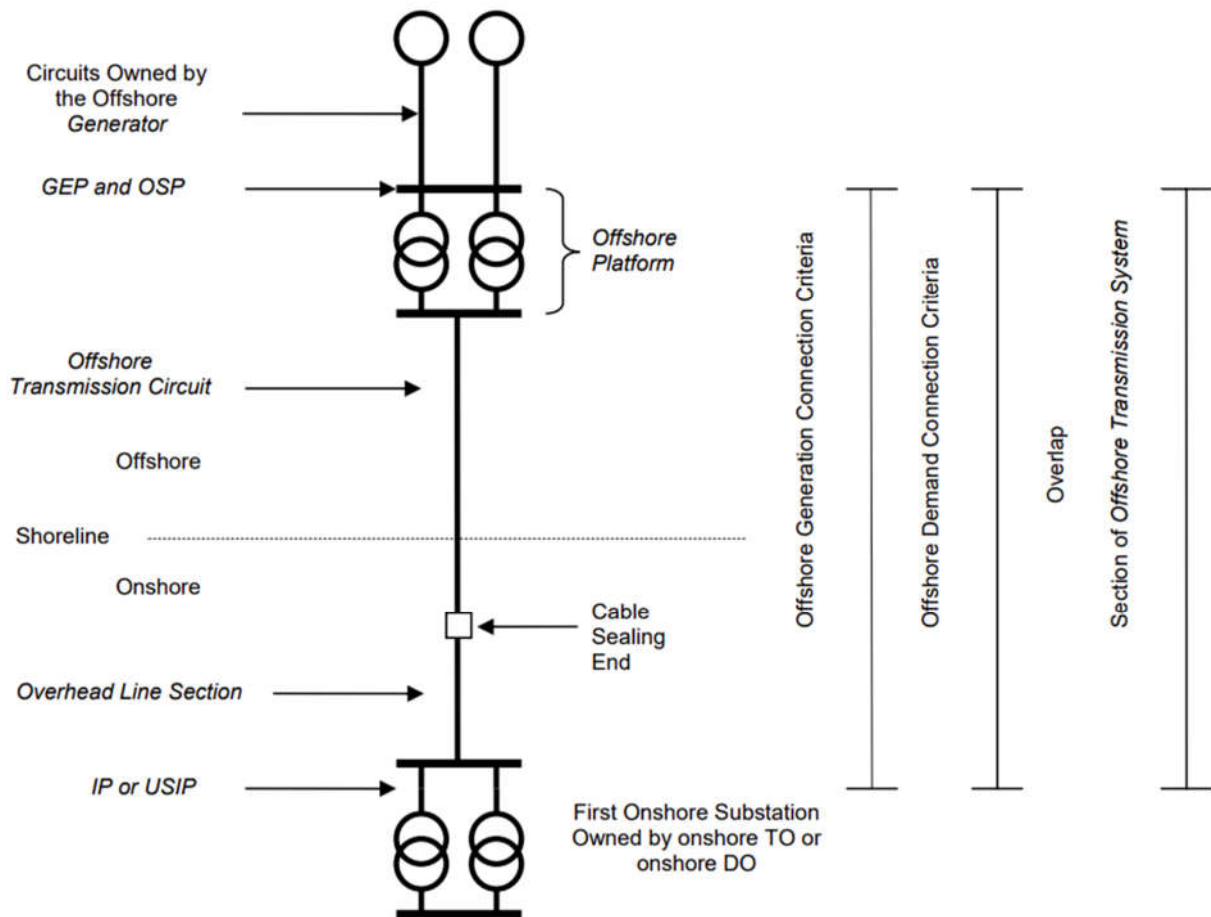


Figure 8 - An offshore transmission system with a directly connected power station and first onshore substation owned by the offshore transmission owner (adopted from NGENO NETS SQSS V2.6) [5].

4.2 Generation Connection Criteria Applicable to an Offshore Transmission System

The NGENO SQSS have provided criteria for generation connection applicable to an offshore transmission system, which will be explored in this section. The criteria apply from the offshore grid entry point(s) (GEP) at which each offshore generator connects to an offshore transmission system, through the remainder of the onshore substation (the interface point (IP) in the case of direct connection), to the onshore transmission system (the user system interface point (USIP) in the case of a connection), to an onshore user system.

4.3 Limits to Loss of Power Infeed Risks

According to paragraph 7.6 of the NGENO NETS SQSS v2.6 [6], for the purpose of applying the criteria of paragraphs 7.7 to 7.12, the loss of power infeed resulting from a secured event shall be calculated as follows:



- 7.6.1 the sum of the registered capacities of the offshore power park modules or offshore gas turbines disconnected from the system by a secured event,
- 7.6.2 the forecast minimum demand disconnected from the system by the same event but excluding (from the deduction) any demand forming part of the forecast minimum demand which may be automatically tripped for system frequency control purposes and excluding (from the deduction) the demand of the largest single end customer.

4.4 Offshore Platforms

According to paragraph 7.7 of the NGESO NETS SQSS v2.6 [6], Offshore generation connections on offshore platforms shall be planned such that, starting with an intact system, the consequences of secured events on the offshore transmission system shall be as follows:

- 7.7.1 AC Circuits on an offshore platform
 - 7.7.1.1 in the case of offshore power park module only connections, and where the offshore grid entry point capacity is 90MW or more, following a planned outage or a fault outage of a single AC offshore transformer circuit on the offshore platform, the loss of power infeed shall not exceed the smaller of either: 50% of the offshore grid entry point capacity; or the full normal infeed loss risk;
 - 7.7.1.2 in the case of gas turbine only connections, and where the offshore grid entry point capacity is 90MW or more, following a planned outage or a fault outage of a single AC offshore transmission circuit on the offshore platform, there shall be no loss of power infeed;
 - 7.7.1.3 following a fault outage of a single AC offshore transmission circuit on the offshore platform, during a planned outage of another AC offshore transmission circuit on the offshore platform, the further loss of power infeed shall not exceed the infrequent infeed loss risk.

4.5 Generation Connection Capacity

The connection of an offshore station is expected to comply with the criteria set out in paragraph 7.14 to 7.23 of the NGESO NETS SQSS V2.6 [6]. There are expected to comply under the following background conditions:

- 7.13.1 the active power output of the offshore power station shall be set to deliver active power at the offshore grid entry point equal to its registered capacity or, for the purpose of Sub-Synchronous Oscillations studies, that which provides the lowest level of damping for the Sub-Synchronous mode under consideration;
- 7.13.2 the reactive power output of the offshore power station shall normally, and unless otherwise agreed, be set to deliver zero reactive power at the offshore grid entry point with active power output equal to registered capacity; and the reactive power delivered at the interface point shall be set in accordance with the reactive requirements placed on the offshore transmission licensee set out in Section K of the STC (System Operator – Transmission Owner Code); and
- 7.13.3 conditions on the national electricity transmission system shall be set to those which ought reasonably to be expected to arise in the course of a year of operation. Such conditions shall include forecast demand cycles, typical power station operating regimes and typical planned outage patterns modified where appropriate by the provisions of paragraph 7.16.



4.6 Technical Risks of Different Transmission Levels

The scenarios adopted consider two voltage levels options – 220kV and 275kV as shown in Table 3. The voltage levels considered present different technical risks to the different transmission voltage options. The National Grid has a standard for cable construction and connection to substations [7]. According to the National Grid, when work involves any kind of ground disturbance, it is expected that a safe system of work is put in place and that the appropriate guidance is followed such as the HSG 47 [7]. According to Paragraph 10.1 [6], The pre-fault planning voltage limits and steady-state voltage limits on an offshore transmission system are shown in Table 5.

Table 5 – Pre-fault planning voltage

Nominal Voltage	Minimum	Maximum
400kV	-10%	+5%
Less than 400kV down to 132kV inclusive	-10%	+10%
Less than 132kV	-6%	+6%

Notes: For 400kV, the maximum limit is aligned with the equivalent onshore limit pending review in the light of technological developments.

Also, as part of the implementation for GSR026 [8], the steady state voltage limits and targets in operational timescales have been adjusted as shown in Table 6.

Table 6 - Adjusted steady-state voltages

Nominal Voltage	PU Value (1pu relates to the Nominal Voltage)	Maximum (percentage of Nominal Voltage)	Maximum (percentage of Nominal Voltage)
Greater than 300kV	0.90pu-1.05pu	-10%	+5%
200kV up to and including 300kV	0.90pu-1.09pu	-10%	+9%
132kV up to and including 200kV	0.90pu-1.10pu	-10%	+10%

4.7 Grid Entry Characteristics

Pembroke is a 132kV/400kV double circuit substation and the connections to this station must comply with the grid code as earlier outlined in the Electrical system study section of this report. The design limits and maximum grid parameters of the Pembroke substation are shown in Table 7.

Table 7 – Pembroke substation grid contribution

Scenario (400kV)	3ph-fault		1ph-fault	
	SCC (kA)	X/R	SCC (kA)	X0/R0
Design Limits	100	-	100	-
Max	9.11	13.57	9.44	13.57

Data taken from: National Grid ESO, NOA Stability Pathfinder - Phase 3 Detailed Site Data Tool, including Effectiveness Factors and Sizing Guidance, January 2022



The closest 132kV substation to the Pembroke 400/132 kV substation in the region is the Golden Hill Primary BSP Substation number 600014. The fault level characteristics of the Golden Hill Primary substation are described in Table 8.

Table 8 – Golden Hill Primary Substation Fault Level Characteristics

	Make	Break
HV Ratings 3Ph	100.00 kA	40.00 kA
HV Fault Level 3Ph	21.10 kA	8.58 kA
HV Ratings 1Ph	100.00 kA	40.00 kA
HV Fault Level 1Ph	21.87 kA	9.94 kA
LV Ratings 3Ph	62.50 kA	19.29 kA
LV Fault Level 3Ph	37.58 kA	14.18 kA
Fault Level Limitation	Pembroke 132kV	

The transmission entry characteristics for Pembroke substation was obtain from National Grid ESO webpage [9]. It provides up-to-date information about the present features of this substation as shown in Table 9.

Table 9 - Transmission entry characteristics data for Pembroke substation [9].

Project Name	Customer Name	Connection Site	MW Connected	MW Increase / Decrease	MW Effective From	Project Status	Plant Type
Erebus	BLUE GEM WIND LIMITED	Pembroke 132kV Substation	0	91	02/11/2026	Scoping	Wind Offshore
Llŷr Floating Wind	Llŷr Floating Wind Limited	Pembroke 400kV	0	1800	31/10/2031	Scoping	Wind Offshore
Llywelyn Extension Offshore Wind Farm	RENANTIS UK LIMITED	Pembroke 400kV	0	1000	06/12/2036	Scoping	Wind Offshore
Llywelyn Floating Offshore Wind Farm	RENANTIS UK LIMITED	Pembroke 400kV	0	300	31/03/2029	Scoping	Wind Offshore
Mereid Offshore Wind Farm	South West Wind Holdco Limited	Pembroke 400kV	0	1008	06/12/2036	Scoping	Wind Offshore
Pembroke (spare bay)	ENSO GREEN HOLDINGS LIMITED	Pembroke 132kV Substation	0	120	30/10/2026	Scoping	Energy Storage System; PV Array (Photo Voltaic/solar)



Project Name	Customer Name	Connection Site	MW Connected	MW Increase / Decrease	MW Effective From	Project Status	Plant Type
Pembroke BESS	RWE GENERATION UK PLC	Pembroke 400kV	0	350	01/10/2026	Awaiting Consents	Energy Storage System
Pembroke BESS and Solar Station	Renesola Hercules Energy 1 Ltd	Pembroke 400kV	0	99.9	31/10/2028	Awaiting Consents	Energy Storage System; PV Array (Photo Voltaic/solar)
Pembroke Power Station	RWE GENERATION UK PLC	Pembroke 400kV	2199	0		Built	CCGT (Combined Cycle Gas Turbine)
Valorous Offshore Wind Farm	BLUE GEM WIND LIMITED	Pembroke 400kV	0	300	02/04/2029	Scoping	Wind Offshore

Table 9 provides descriptive information about Pembroke substation and the power plants connected to it. “MW Increase/Decrease” refers to the amount of capacity contracted to connect or to be removed at a future date and the “Project Status” indicates what stage the project is at in its build cycle. All projects connected to Pembroke substation site are currently directly connected, which means the power plants are connecting directly to the National Grid.



5 Export cables

5.1 Cable Route

This section of the report will discuss the cable route and burial assessment undertaken. The cable routing report [10] summarises the technical, desk-based assessment and high-level engineering assessment of the wind farm layouts, landfall and substation locations and offshore and onshore cable routes. Below is a description of the assumed wind farm layouts, a discussion of the landfall and substation locations and discussion of factors considered for the offshore and onshore cable routes. As more data is gained and technical understanding improves, the assessment in this report may change to reflect new findings.

5.1.1 Wind Farm Layouts

In order to generate the 400MW of energy feeding into the PDZ MOS, 4 x 100MW hypothetical wind farms have been considered, each with 6 x 16MW WTGs (wind turbine generators) and positioned with alignment to 90° to the prevailing wind direction for maximum energy production:

- 4 x 100MW wind farms within the PDZ

The PDZ area has the potential to hold 400MW of WTGs and the MOS itself. Indicative WTG locations are shown in Figure 9.

- 4 x 100MW independent wind farms, 3 from nearby development zones, 1 within the PDZ

There is significant potential for a range of demonstrator and pre-commercial floating wind projects within the Celtic Sea and in close proximity to the PDZ to connect to the MOS, some of which can be seen in Figure 9. However, this requires significant regional stakeholder cooperation and a clear grid connection strategy design to enforce offshore connection strategy and programme dates. Section 9.5 contains a cost benefit analysis for this approach.

Potential cable routes from the development zones to the MOS have been considered but have not been presented visually in Figure 9 at this stage.

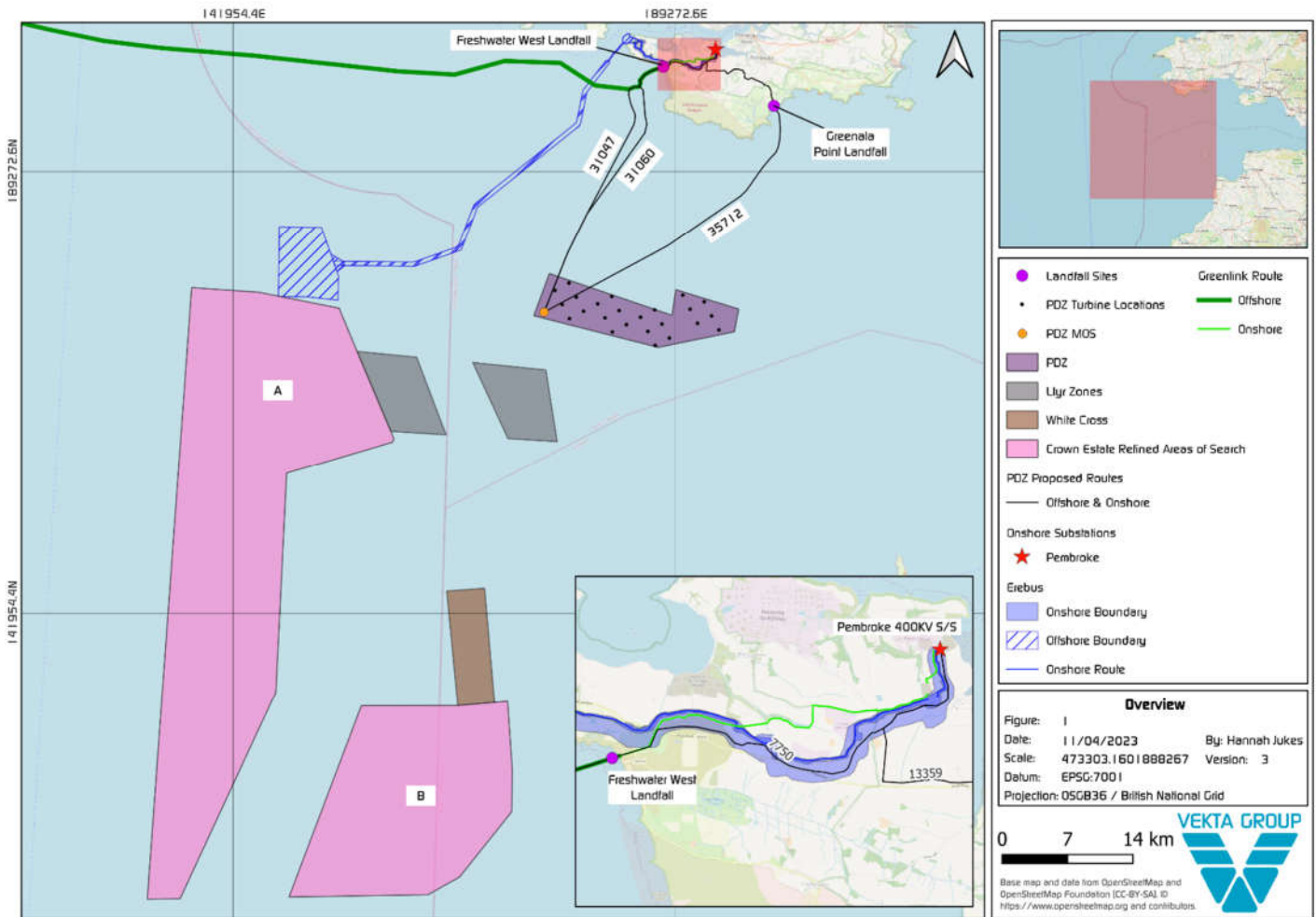


Figure 9 – Potential PDZ wind farm layout, landfall options and regional development zones.

5.1.2 Landfall Locations

Two landfall locations have been identified (Freshwater West and Greenala Point, Figure 10). These locations have been selected due to the presence of other wind farm projects within the Celtic Sea which are proposed to make landfall at similar locations; the projects with planning consent and a more clearly defined landfall and cable route are Erebus [11] and Greenlink Interconnector [12], hence minimising the number of landfalls and reducing disruption to landowners.

Freshwater West Landfall (FWL) is located to the east of Gravel Bay at the western edge of the Freshwater West beach. The landfall here is a sand flat leading up to a sand dune, approximately 3 m high at the northern extent, which extends westerly to become a steeper rock face (this rock face will not be crossed with the proposed onshore cable route).

Greenala Point Landfall (GPL) is situated on the eastern side of the Castlemartin Ranges, c. 2.5 km south of the village of Trewent and c. 1 km west of the headland at Greenala Point. This locality is a steep rockface which increases from 16 – 58 m elevation between sea level and the coastal path, less than 150 m inland [10].

FWL has the shortest offshore and onshore cable routes in comparison to GPL and will link into the Greenlink Interconnector landfall location, thereby minimising visual impact and destruction for locals. FWL also has consent from the MoD (Ministry of Defence) for the Greenlink Interconnector landfall. Therefore, FWL appears to be the most favourable landing location given current understanding.

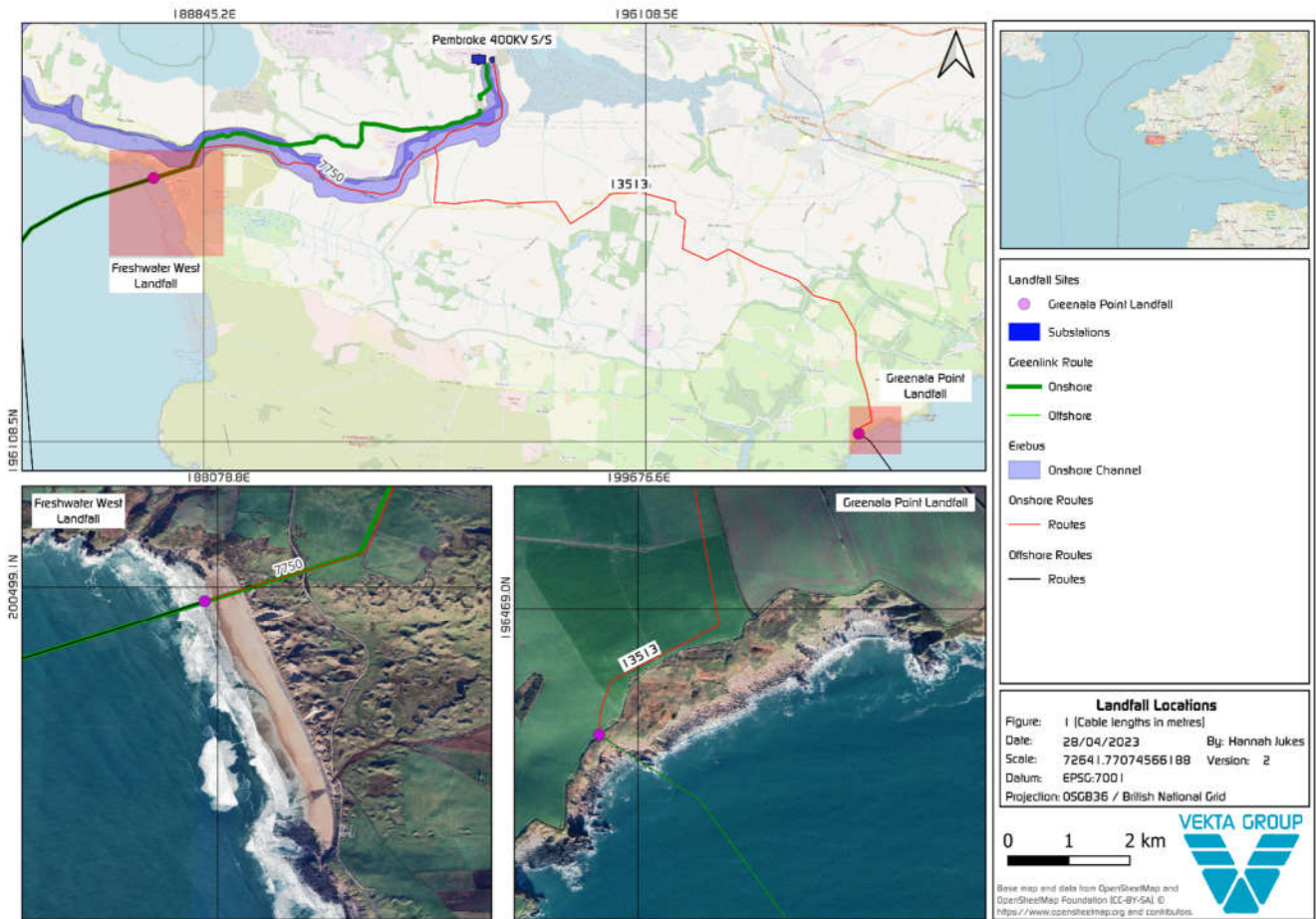


Figure 10 - Overview of landfall locations considered. Satellite imagery close up of Freshwater West (bottom left) and Greenala Point (bottom right). Source: Google Satellite Maps.

5.1.3 Substation Locations

For this work package, a single point of connection to the grid at Pembroke has been taken forward for a more detailed analysis. This has allowed for the siting of the PDZ substation, taking into consideration the Erebus Greenlink Interconnector and potential LIÿr substations, as well as environmental and physical factors and other existing infrastructure (Figure 11).

The onshore substation location has been identified based on numerous factors, these include:

- Proximity to the cable route
- Proximity to the grid connection at Pembroke substation
- Avoidance of existing infrastructure, for example roads, telecom cables, overhead lines, pipelines and buildings
- Consented location of Greenlink Interconnector and Erebus substations.

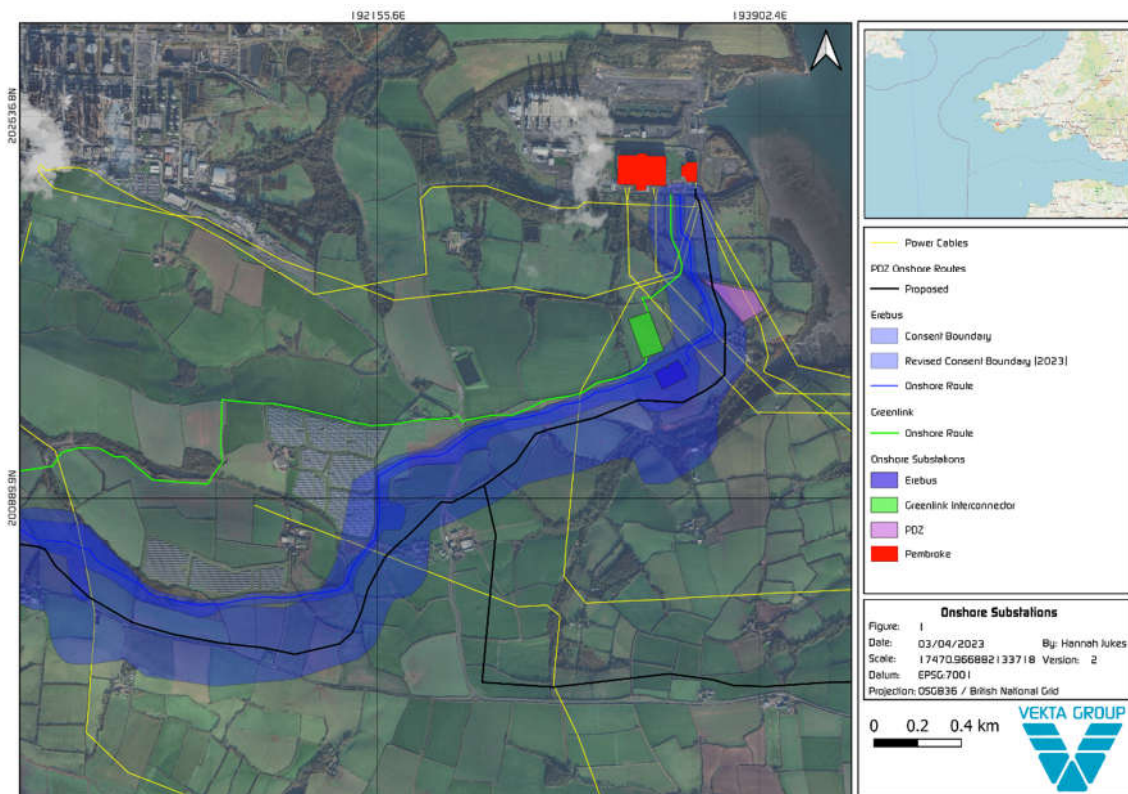


Figure 11 - Onshore substation locations with overhead cables. Base map: Google Satellite Maps.

5.1.4 Offshore Routes

The shortest route from the PDZ MOS to the Pembroke substation is that which follows the westerly route to FWL and from there to the Pembroke substation. Although, it should be noted that the easterly offshore route is 0.013 km longer and provides more favourable conditions in the near shore area. This offshore route is a length of 31.060 km and allows for a c. 300 m gap between sub-tidal reef zones in the nearshore region, in comparison to the westerly route which is restricted to a c. 60 m channel. Therefore, the easterly route is favourable for the drilling, operations and maintenance of cables, allowing vessels a greater area to manoeuvre (Figure 12).

It is difficult to comment on the geomorphology (seabed features) of the route to GPL as there is little data. However, it is noted that megaripples, ripples and sandwaves are present along the routes to FWL. While these do not pose great risks as they are most likely to be encountered in shallow seas, there is clear evidence of sediment migration along the FWL routes [13], posing the risk of exposed cables over time. However, it cannot be suggested whether the same could be said along the route to GPL therefore this factor cannot be properly assessed between the two routes at this time. It is recommended that further geophysical surveys are undertaken along the route to GPL to gain a greater understanding of this risk.

Again, the geology across this region is detailed from BGS data with the route to FWL supported by the studies undertaken as part of the Greenlink project. It is difficult to assume that the results and interpretation of the shallow geology which are understood along the nearshore Welsh coast area can be applied to the route leading to the GPL. This is due to the seabed sediments and bedforms being susceptible to different ocean currents and conditions which will result in different features. Also, due to the presence of faults displayed on geological maps [14], it is difficult to assume bedrock geology as faults create alternative sediment deposition patterns and rates.

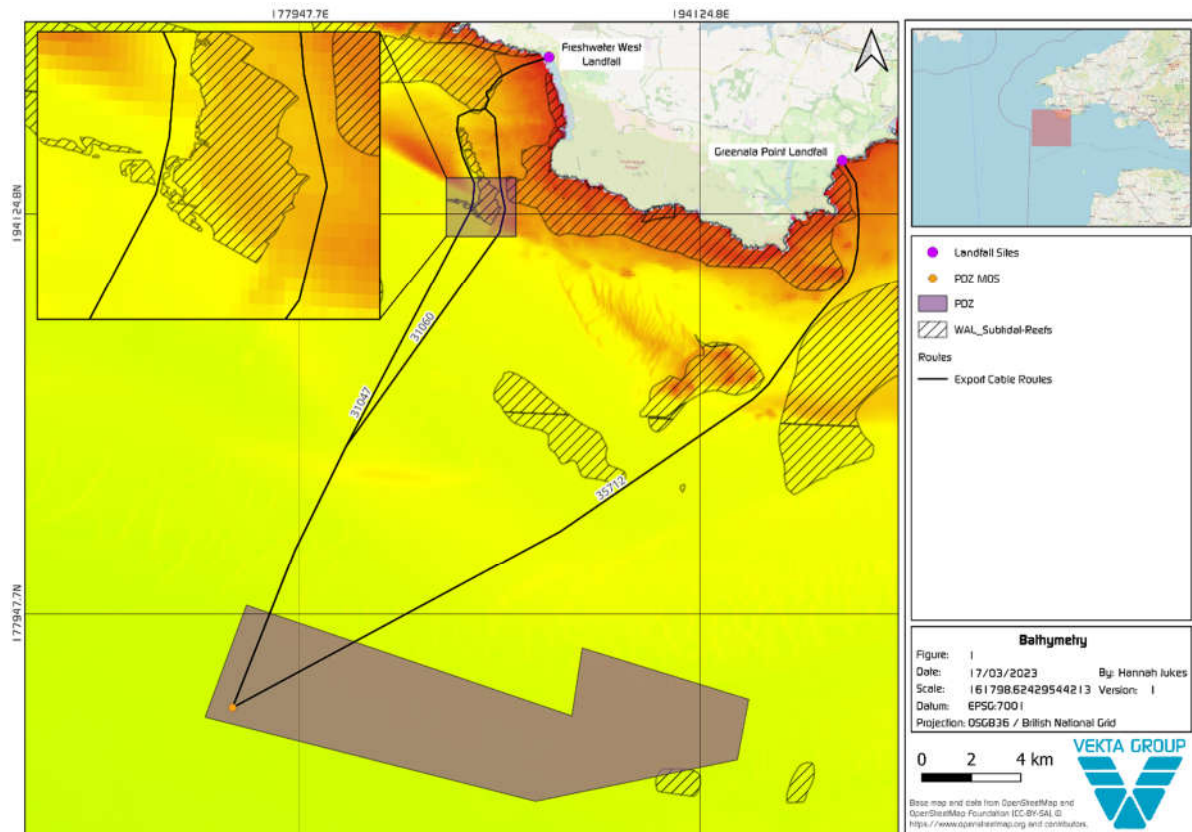


Figure 12 - Bathymetry data displayed in the Celtic Sea with proposed offshore routes, landfalls and PDZ locations superimposed. Source: GEBCO.

5.1.5 Onshore Routes

The onshore route from FWL to Pembroke is nearly half the length of that from GPL, also meaning half the number of HDD hazards to consider. Both onshore routes appear to have some dubious portions of the route regarding the slope, specifically the route from GPL. The route appears to cross a trough, potentially a river course or paleochannel, providing slope values reaching in excess of 50°. Whilst this is definitely not ideal there may be a simple alternative route to avoid such feature. Further analysis of this route and potentially a site walk through should be undertaken to fully understand this feature.

In terms of the onshore geology, the route from GPL is slightly more preferable as there is less of the route which is covered with superficial sediment and the majority of the route in a sandstone formation for the top bedrock layer (Figure 13). This would allow not having to alternate between cutting methods and reduce time spent during installation.



Finally, the onshore route from GPL does pass through c. 100 m of tree woodland which would pose a greater challenge for drilling efforts, in comparison to the route from FWL which does not intersect with any woodland tree inventory areas.

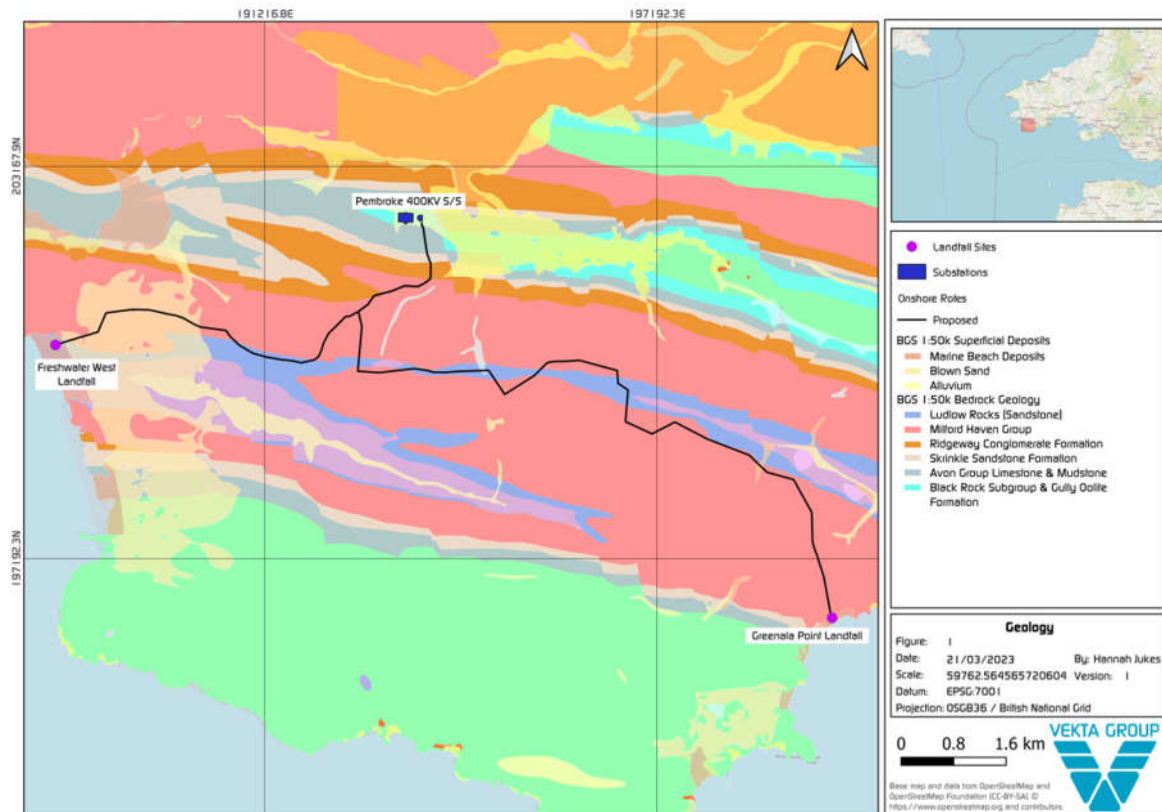


Figure 13 - Onshore bedrock and superficial geology with onshore proposed cable routes. Source: 1:50 BGS WMS feeds.

5.1.6 Summary

In summary, there are limitations to this assessment due to a lack of detailed data for the proposed onshore and offshore export cable routes. Therefore, while the route towards FWL appears the most favourable at this stage, this may not be the case once more data is collected. At this stage of the project, the data and recommendations will suffice.

The combined total length from the MOS to the onshore substation for the currently preferred option is 38.612 km, with the breakdown of each route detailed in Table 10.

Table 10 - Cable lengths for all discussed routes.

Route	Length (km)
PDZ MOS – FWL 1 (left)	31.047
PDZ MOS – FWL 2 (right)	31.060
PDZ MOS – GPL	35.954
FWL – Substation	7.552
GPL – Substation	13.349



5.2 Cable Sizing

This section of the report will discuss the cable sizing studies and general design of the export cable and what technical options provide the best capex and whole life cost solutions. As part of this section the primary considerations will be 220kV or 275kV based on a single circuit with an alternative dual cable circuit solution. This will be summarised in the capex section of the report which details a recommended design as well as whole life cost.

5.2.1 Assumptions

The electrical calculations displayed are calculated using the following assumptions:

- All faults have zero arc impedance.
- Cable burial depth assumed to be 1m.
- Cable operating temperature assumed to be 90°C.
- Seabed temperature assumed to be 15°C.
- Thermal resistivity of seabed assumed to be 0.7°K-m/W.
- Capacity factor for any generation is assumed to be ~0.56.
- Minimum cable rating is 50% as per SQSS.
- The boundary point of the study is the 400kV busbar.
- Onshore and offshore transformers are super grid transformers.
- Transformers are sized as follows:
 - 500 MVA 400/220/52 kV
 - 500 MVA 400/275/52 kV
 - 450 MVA 220/66 kV
 - 450 MVA 275/66 kV
 - 180 kVA 66/0.4 kV
- For faults & electrical losses, export system is modelled at nominal power (400MW).
- The capital cost for the offshore substation will be omitted for this report, as it is the same cost for all scenarios and will not be used for comparison.
- For comparison purposes, a project lifetime of 30 years and a median energy strike price of £90 / MWh were chosen. It should be noted that for these values to have a significant effect on the analysis they must be pushed to extreme cases, such as an energy strike price of £200 / MWh or a project lifetime of 40 years.
- The cable design is based on a static cable only; an electrically dynamic cable design could potentially provide further cost savings but is usually part of the FEED stage.



5.2.2 Cable Sizes and Loading

The chosen cable sizes, current loading, and estimated price per metre is shown in Table 11.

Table 11 – Cable Sizing Proposals

Case name	Cable type	Loading, %	Price (£/m)
Freshwater West Landfall 2 x 220kV Al	Static 0400Al 220kV	82.55	439.25
	Static 0400Al 220kV	82.55	439.25
Freshwater West Landfall 220kV Al	Static 1400Al 220kV	96.97	694.52
Freshwater West Landfall 220kV Cu	Static 1000Cu 220kV	97.63	958.65
Freshwater West Landfall 275kV Al	Static 0800Al 275kV	96.49	565.69
Freshwater West Landfall 275kV Cu	Static 0500Cu 275kV	96.28	678.35
Greenala Point Landfall 2 x 220kV Al	Static 0400Al 220kV	84.53	439.25
	Static 0400Al 220kV	84.53	439.25
Greenala Point Landfall 220kV Al	Static 1400Al 220kV	98.11	694.52
Greenala Point Landfall 220kV Cu	Static 1000Cu 220kV	98.45	958.65
Greenala Point Landfall 275kV Al	Static 0800Al 275kV	98.10	565.69
Greenala Point Landfall 275kV Cu	Static 0500Cu 275kV	96.71	678.35

5.2.3 Electrical Losses

The hourly weather data for the last 40 years is used at the beginning to estimate the hourly Capacity Factor of the generation (CF_{GEN}). Then based on those capacity factors the losses are estimated:

The change of the generation power output will cause (approximately) a proportional change of all active currents in all cables. The power loss calculations are calculated with the following equation for the purpose:

$$P_{loss,total} = 3 \cdot [I_{reactive}^2 + (CF_{GEN} \cdot I_{Active})^2] \cdot R_{core} \quad (1)$$

So, if we use no-load and full-load power losses instead we can get this equation, that is for a single cable as for the whole array system:

$$P_{loss,total} = P_{No-load} + (P_{Full-load} - P_{No-load}) \cdot CF_{GEN}^2 \quad (2)$$

So, to estimate the energy losses from the generation first we need to find an average value of CF_{GEN}^2 using the hourly data. The value for our data is $(CF_{GEN}^2)_{AV} = 0.3744$.

The (average) yearly energy loss is calculated based on the following equation:

$$E_{loss,year} = [P_{No-load} + (P_{Full-load} - P_{No-load}) \cdot CF_{GEN}^2] \cdot 8760 \quad (3)$$

To obtain the operational (whole life) energy loss for the transmission network the $E_{loss,year}$ needs to be multiplied by the operational time in years. A comparison of the lifetime energy costs of each scenario is shown in Figure 14.

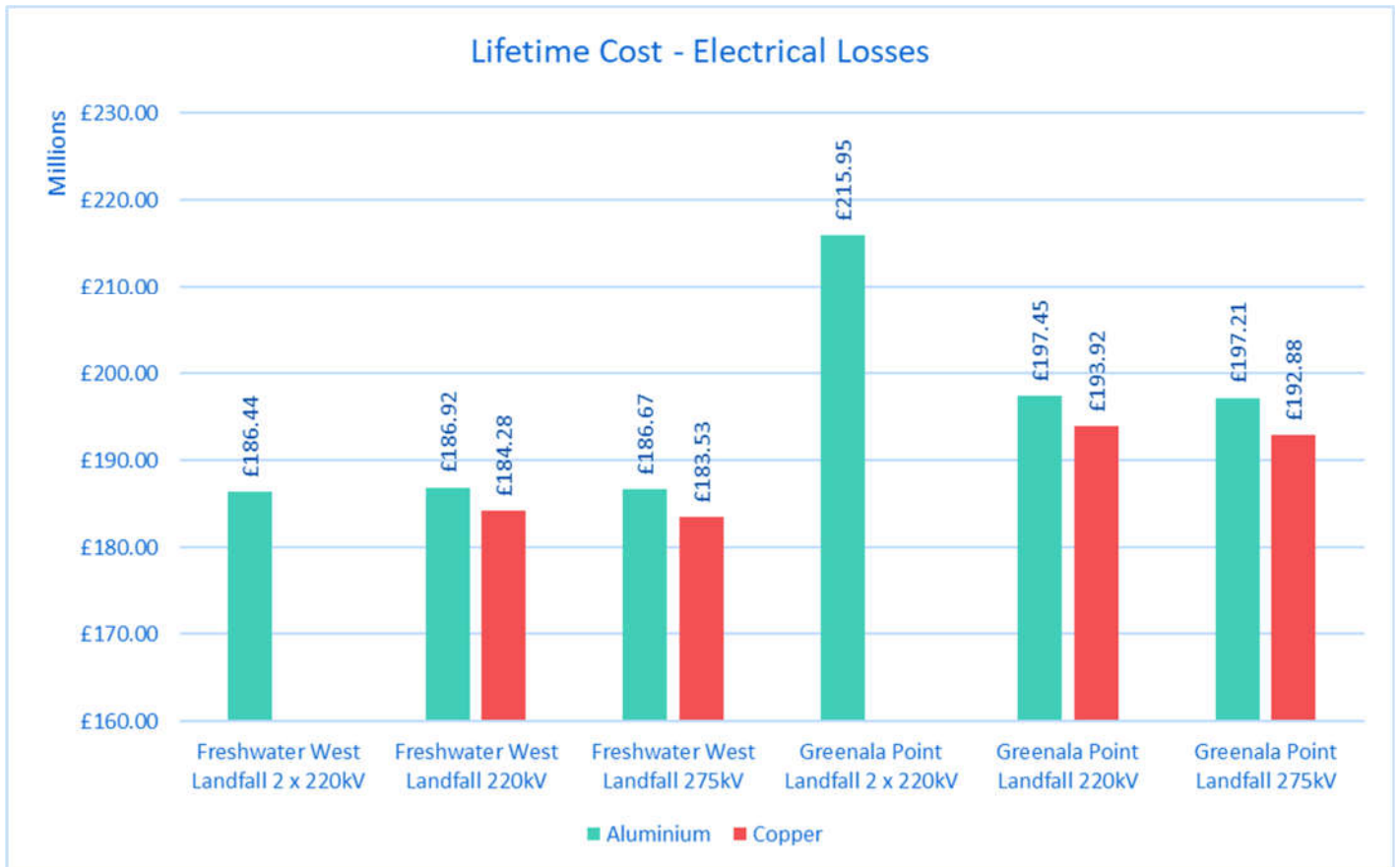


Figure 14 – Lifetime Energy Loss Cost [15]

If the lifetime electrical losses are considered with the initial capital cost of the system, the total cost of the system changes significantly. A comparison of each scenario with lifetime energy losses and capital expenditure is shown in Figure 15. The capital cost for the offshore substation will be omitted for this section as it is the same cost for all scenarios and will not be used for the purpose of comparison.

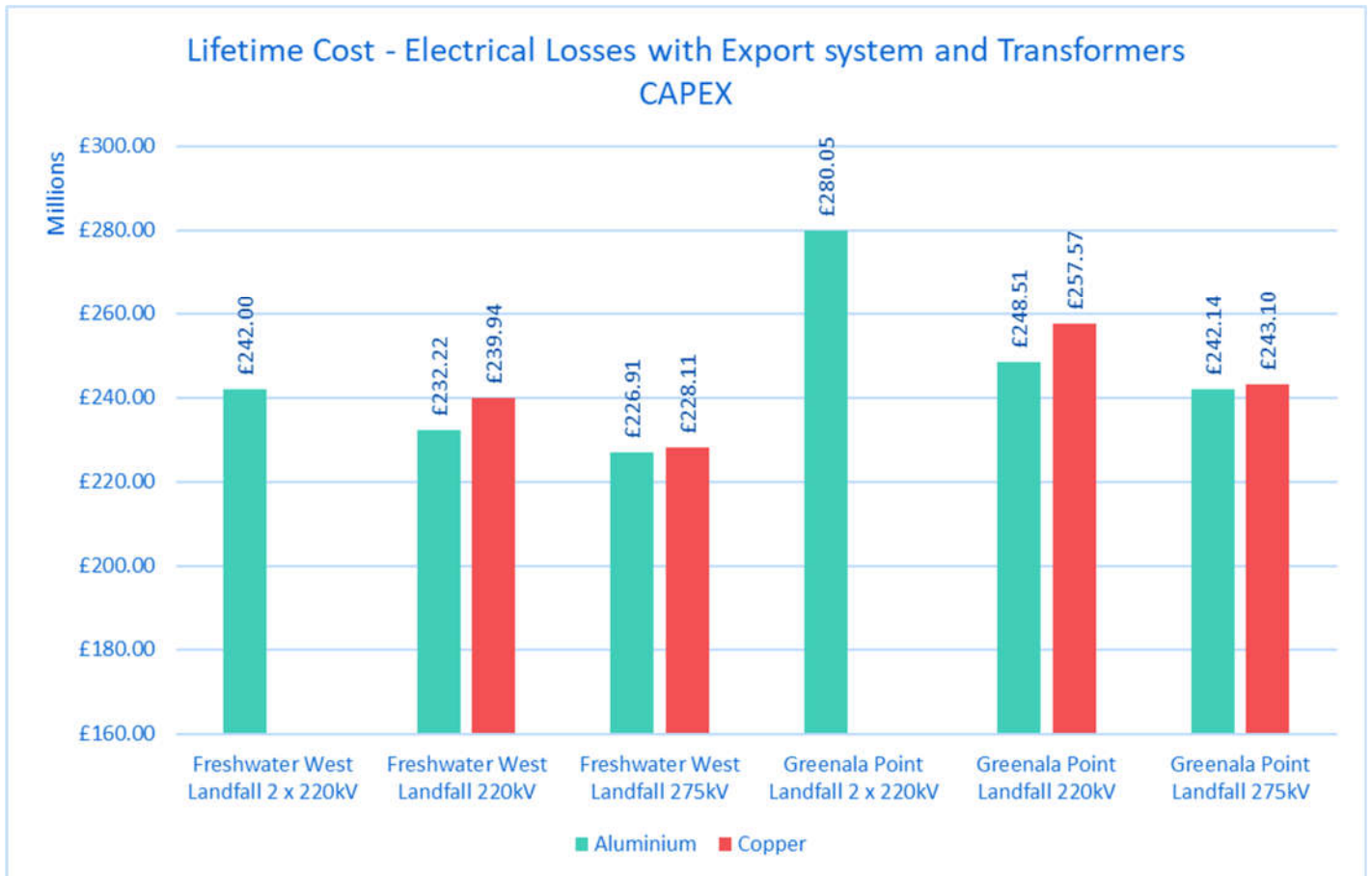


Figure 15 – Lifetime Energy Losses with Capital Expenditure Cost [15]

5.2.4 Fault Analysis

In order to conduct a fault analysis for offshore cables Vekta Group uses a custom in-house tool in conjunction with DigSILENT PowerFactory in order to review multiple fault scenarios of any given array network. For the purposes of this project there was one type of fault prediction method used:

Singular event fault analysis with predefined fault location

For this approach, the analysis is always considering a singular fault incident. The location of the fault on the chosen array is predetermined. The analysis is made for different fault times on monthly bases, with different generation capacity factors and repair times.

So the cost of singular fault event for radial layout types is calculated according to the following formula:

$$C_{FR,A}[\text{£}] = CF \cdot P_N[\text{MW}] \cdot t_{F,cl}[\text{days}] \cdot c_{el}[\text{£/MWh}] \cdot 24 \quad (4)$$

Where:

CF – Average capacity factor of generation,

P_N – nominal power of generation,

$t_{F,cl}$ – Average time of the failure clearance,

c_{el} – The electricity price.

A fault analysis was conducted using the methodology described above. Fault analysis for the export cables is conducted under the following repair time assumptions:



Table 12 – Repair Time Assumptions by month.

Month	Repair time, days
Jan	120
Feb	120
Mar	120
Apr	80
May	80
Jun	40
Jul	40
Aug	40
Sep	40
Oct	80
Nov	80
December	120

Using the energy loss cost for the repair time of a fault, the single fault cost by month for single and double cable solutions is shown in Figure 16.

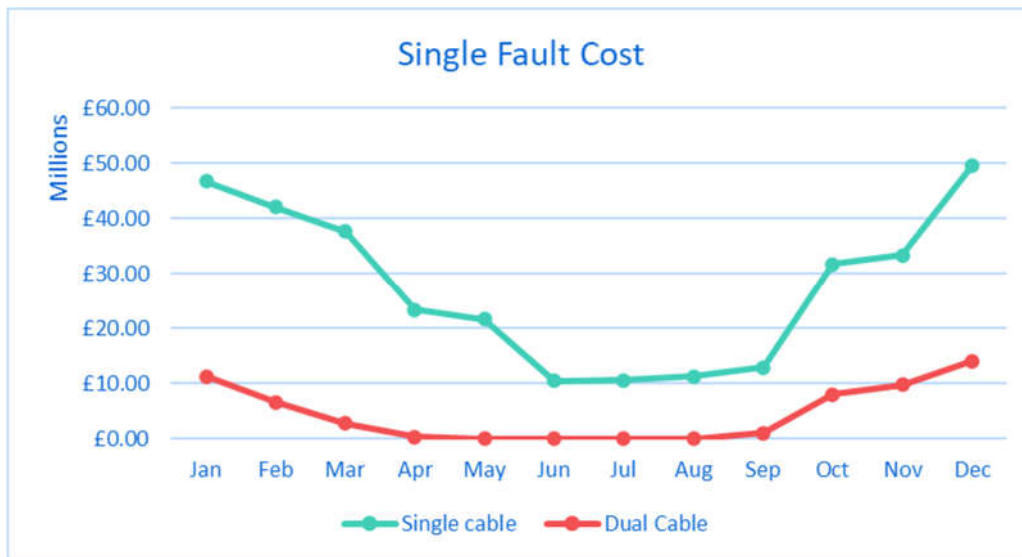


Figure 16 – Single Fault Cost

It should be noted that the cost of a single fault is significantly lower for dual cable solutions. This is due to there being less energy lost since power equal to the spare capacity of the adjacent export cable can still be transmitted via the remaining cable. When considering the probability of a single fault per cable as per Table 13, the number of expected faults for the lifetime of the project can be calculated, as shown in Table 14.

Table 13 – Assumed Cable Failure Rate (per km per year)

Low Failure Rate	Medium Failure Rate	High Failure Rate
0.0007	0.00125	0.0018

Table 14 – Number of Faults over Project Lifetime per Scenario



Landing Site	Single Cable Solution			Double Cable Solution		
	Low Failure Rate	Medium Failure Rate	High Failure Rate	Low Failure Rate	Medium Failure Rate	High Failure Rate
Freshwater West	3	6	8	6	11	17
Greenala Point	4	6	9	7	13	18

Using the estimated cost of a single fault and the estimated number of faults per scenario, the lifetime fault cost of each scenario can be estimated. For this purpose the fault of single fault for each of the cable in the network was calculated according to the eq (4) (using average yearly CF), then it was multiplied by the failure rates from Table 13 and by the exploitation time (in years). After that all those cost for individual cables were summarized into the final lifetime fault cost. Due to the difference in fault cost per month of year, a worst case (every fault occurring in December) and a best case (every fault occurring in June) has been calculated using a probabilistic fault cost study as shown in Figure 17.

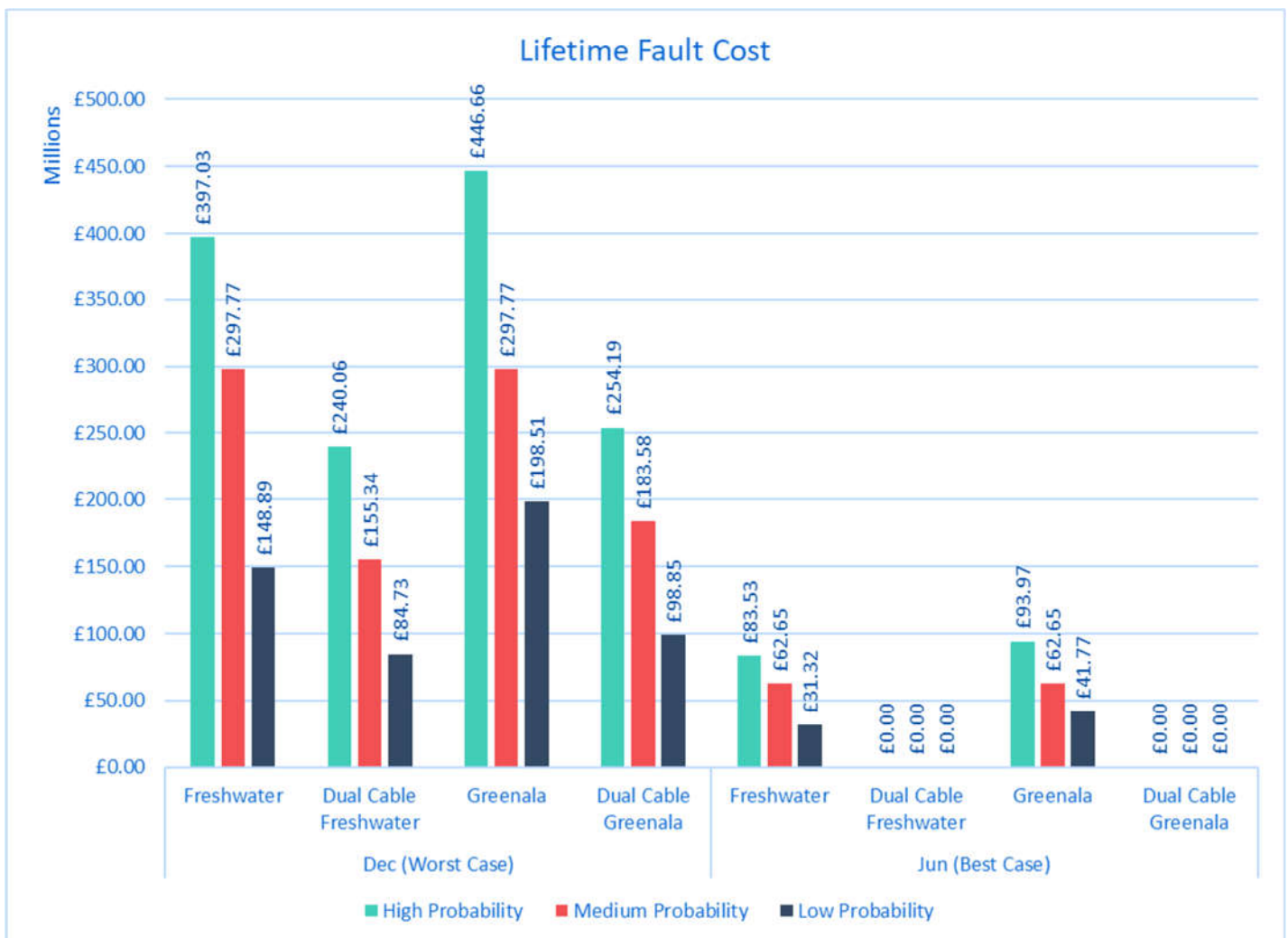


Figure 17 – Lifetime Fault Cost





5.2.5 Lifetime Cost Comparison

If all of the above factors are taken into consideration the total lifetime cost can be calculated using the lifetime cost of energy losses, the capital expenditure (supply and installation cost of cables, supply cost of reactors and supply cost of transformers), and the lifetime fault loss cost. A comparison of total lifetime cost for worst case (all faults occurring in December) and a best case (all fault occurring in June) for each scenario is shown in Figure 18 and Figure 19.

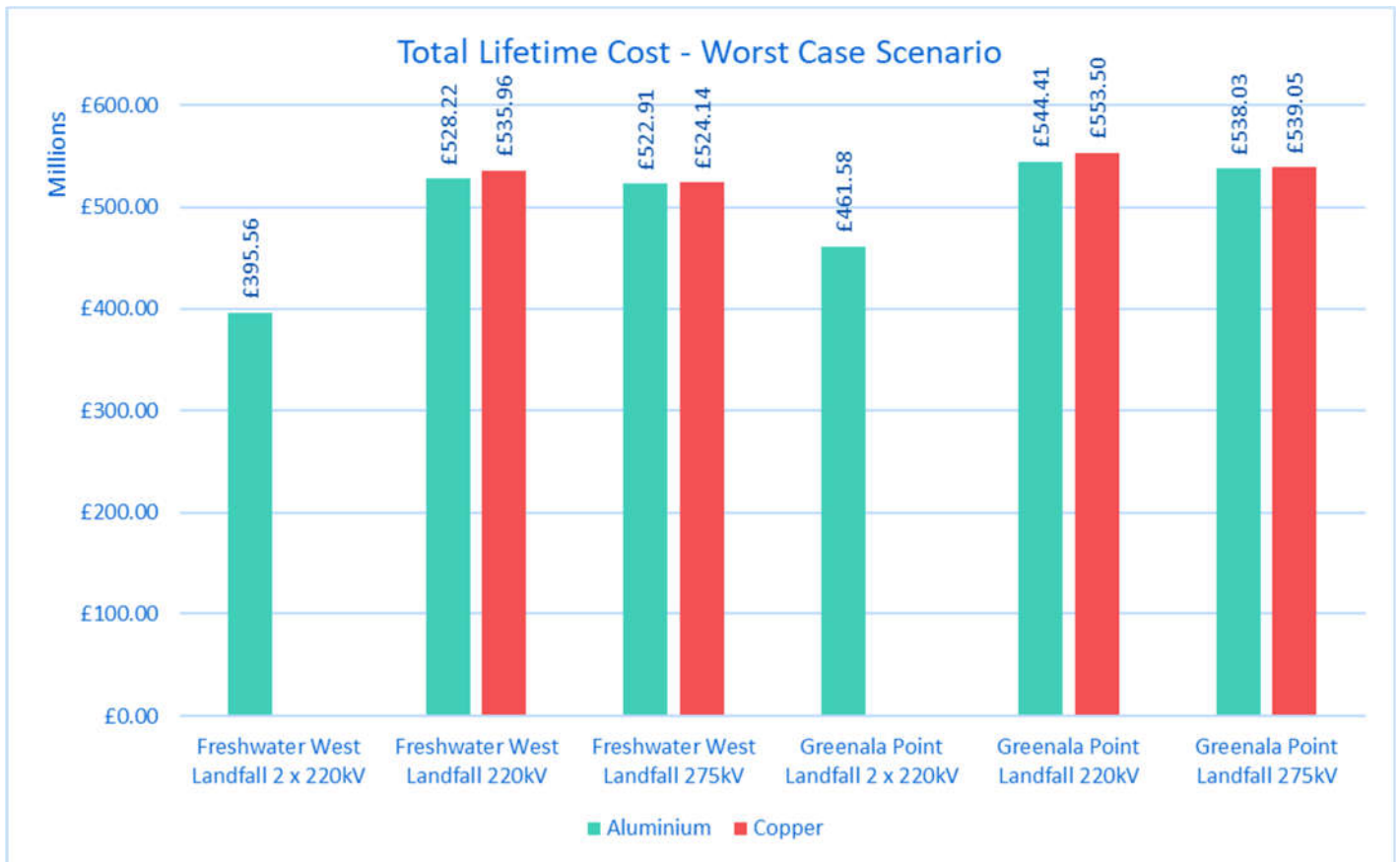


Figure 18 – Total Lifetime Cost (Worst Case)



Figure 19 – Total Lifetime Cost (Best Case)

A cost breakdown for the total lifetime costs of the system is shown in Figure 20 and Figure 21. The cable and transformer CAPEX value includes supply and installation cost of cables, supply cost of reactors and supply cost of transformers.

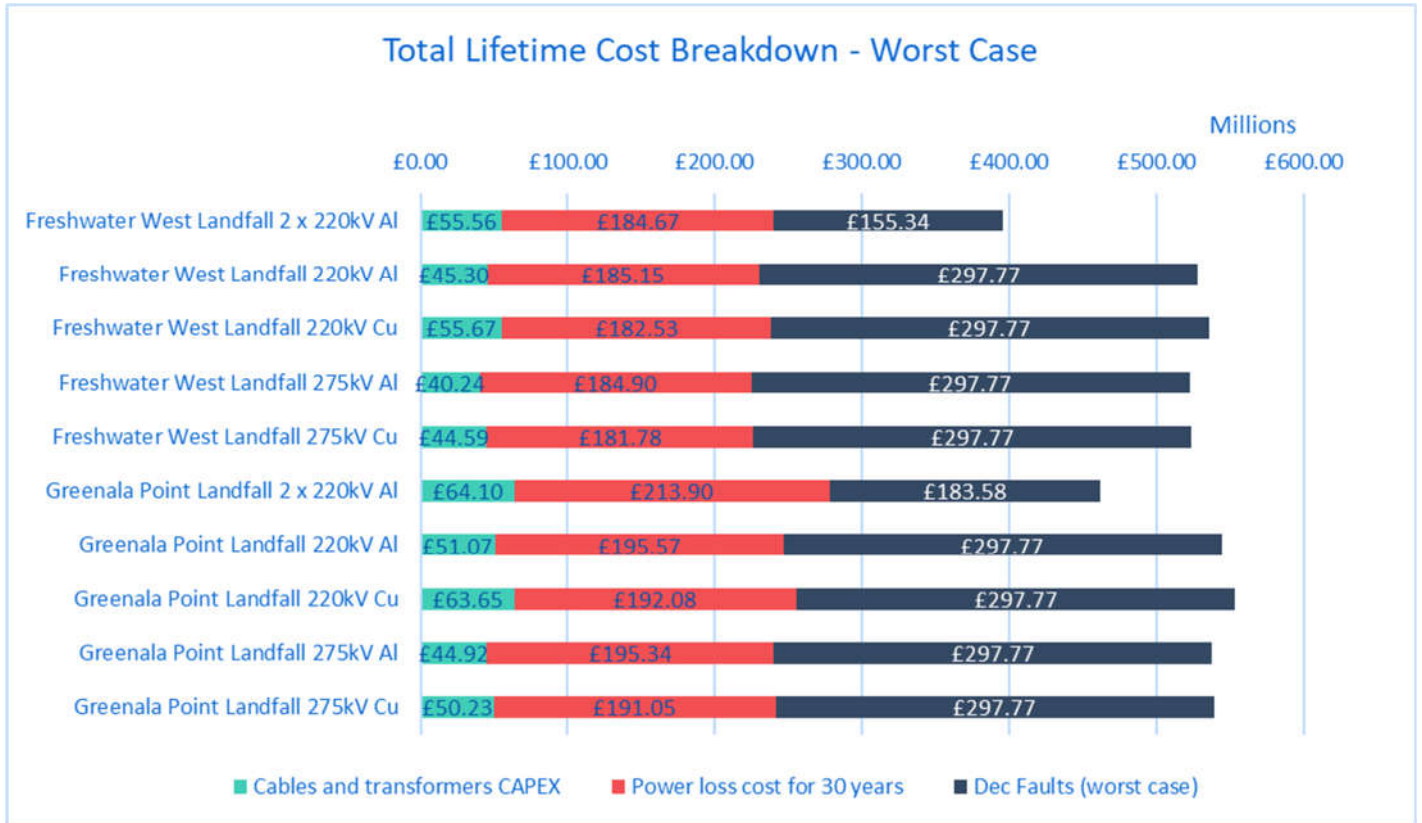


Figure 20 – Worst Case Lifetime Cost Breakdown

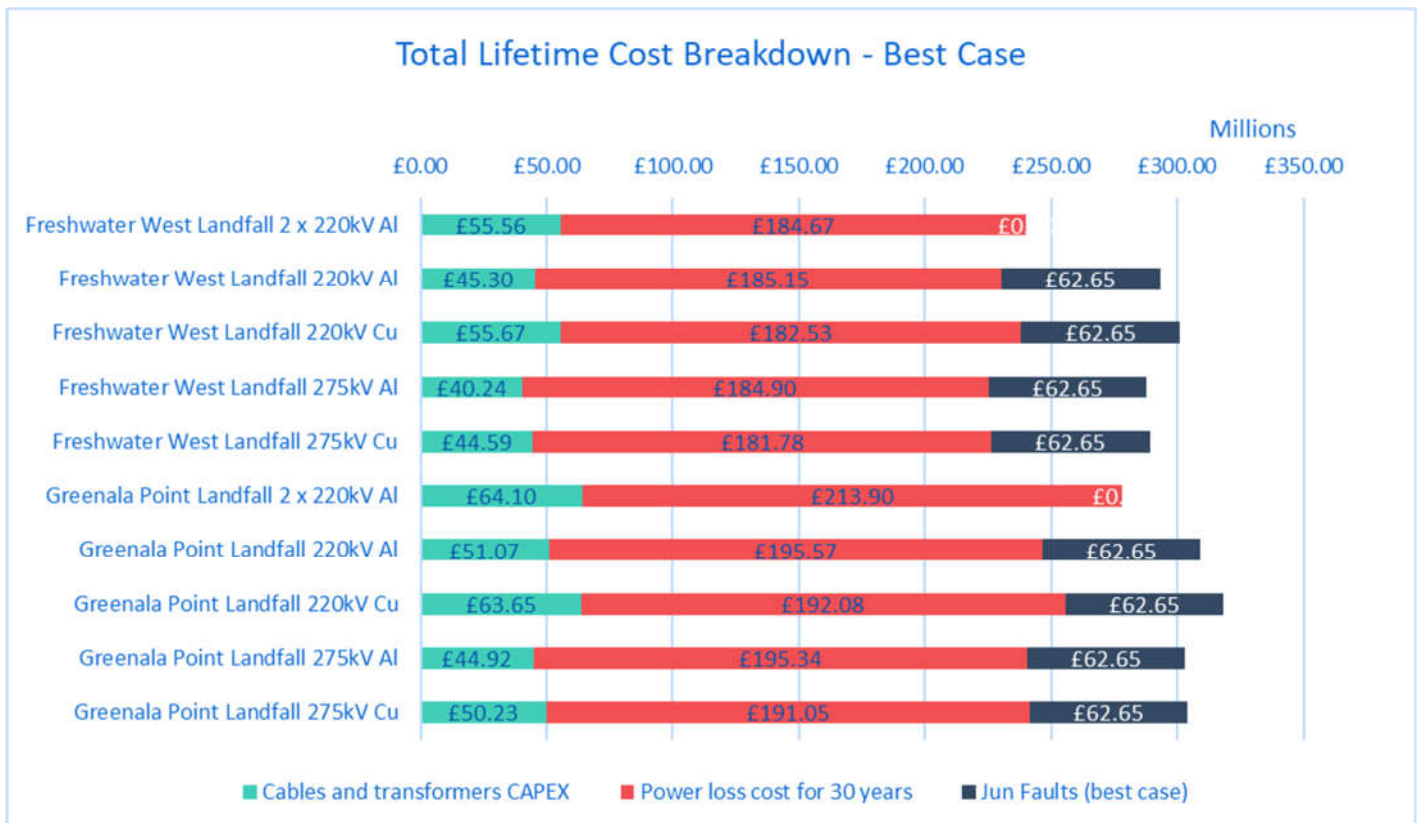


Figure 21 – Best Case Lifetime Cost Breakdown



Factors that could go into estimating the cost of a system include but are not limited to electrical losses, capital expenditure, and losses from a fault. It can be seen from the results found in this report that all copper cases are more electrically efficient in terms of losses. However, the reduced capital expenditure associated with aluminium cable cases is more significant for the scope of this project. When the probability of an electrical fault is taken into account, the double export cable scenarios provide the most redundancy and protection from the cost associated with electrical losses due to a fault. Taking all of this analysis into account, the proposed case that is estimated to be the most cost-effective throughout the lifetime of this project is the Freshwater West Landfall 2x200kV Al scenario.



6 Offshore substation – electrical design

This section considers the electrical design of the offshore substation, including the power system studies, HV/LV equipment considerations and critical services.

6.1 System design

The architecture of the electrical systems for the platform topside for all considered scenarios were created in DigSILENT PowerFactory. The outputs are Single Line Diagrams (SLD) with the equipment, power flow simulation results and short circuit simulation results. The equipment list for all the scenarios is presented in Table 15.

Table 15 - Main equipment list for the topside of the offshore platform.

Case name	Switchgear		Transformer		Busbar	
	Type	No	Type	No	Type	No
WPA Freshwater West Landfall 2 x 220kV AI	220kV live with circuit breaker	3	450 MVA 220/66 kV	1	220kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	66 kV single busbar	1
WPA Freshwater West Landfall 220kV AI	220kV live with circuit breaker	1	450 MVA 220/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Freshwater West Landfall 220kV Cu	220kV live with circuit breaker	1	450 MVA 220/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Freshwater West Landfall 275kV AI	275kV live with circuit breaker	1	450 MVA 275/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Freshwater West Landfall 275kV Cu	275kV live with circuit breaker	1	450 MVA 275/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Greenala Point Landfall 2 x 220kV AI	220kV live with circuit breaker	3	450 MVA 220/66 kV	1	220kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	66 kV single busbar	1
WPA Greenala Point Landfall 220kV AI	220kV live with circuit breaker	1	450 MVA 220/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Greenala Point Landfall 220kV Cu	220kV live with circuit breaker	1	450 MVA 220/66 kV	1	66 kV single busbar	1



Case name	Switchgear		Transformer		Busbar	
	Type	No	Type	No	Type	No
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Greenala Point Landfall 275kV Al	275kV live with circuit breaker	1	450 MVA 275/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-
WPA Greenala Point Landfall 275kV Cu	275kV live with circuit breaker	1	450 MVA 275/66 kV	1	66 kV single busbar	1
	66kV live with circuit breaker	4	180 kVA 66/0.4 kV	1	-	-

From the platform perspective, the different landing points have minimal impact on the electrical system design and the requirements to compensate for the export cable capacitance via reactors. From the cable type perspective, one difference will be the diameter of the J-Tube that needs to be used on the platform. The electrical system architecture for all the scenarios is presented on separate SLDs, listed in Table 16. The simplified system architecture is presented in Figure 22.

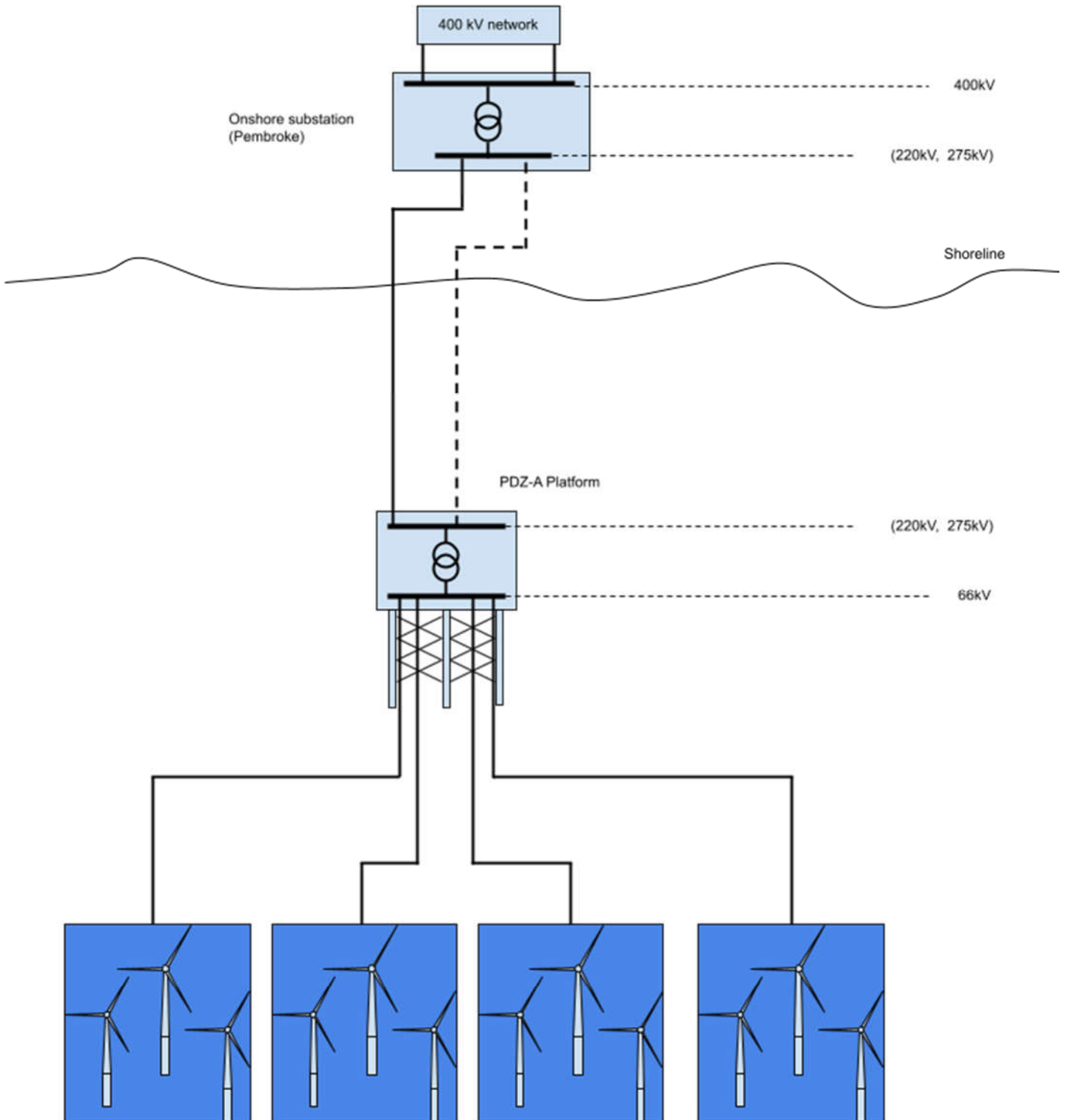


Figure 22 - Simplified architecture of the PDZ WPA Platform



Table 16 – Document numbers for all 400MW PDZ MOS SLDs

Case Name	SLD with power flow results	SLD with 3 phase short circuit results	SLD with single phase short circuit results
400MW MOS Freshwater-LP 2 x 220kV Al	395-003-ELE-SLD-1002	395-003-ELE-SLD-1012	395-003-ELE-SLD-1022
400MW MOS Freshwater-LP 220kV Al	395-003-ELE-SLD-1003	395-003-ELE-SLD-1013	395-003-ELE-SLD-1023
400MW MOS Freshwater-LP 220kV Cu	395-003-ELE-SLD-1004	395-003-ELE-SLD-1014	395-003-ELE-SLD-1024
400MW MOS Freshwater-LP 275kV Al	395-003-ELE-SLD-1005	395-003-ELE-SLD-1015	395-003-ELE-SLD-1025
400MW MOS Freshwater-LP 275kV Cu	395-003-ELE-SLD-1006	395-003-ELE-SLD-1016	395-003-ELE-SLD-1026
400MW MOS Greenala- LP 2 x 220kV Al	395-003-ELE-SLD-1007	395-003-ELE-SLD-1017	395-003-ELE-SLD-1027
400MW MOS Greenala- LP 220kV Al	395-003-ELE-SLD-1008	395-003-ELE-SLD-1018	395-003-ELE-SLD-1028
400MW MOS Greenala- LP 220kV Cu	395-003-ELE-SLD-1009	395-003-ELE-SLD-1019	395-003-ELE-SLD-1029
400MW MOS Greenala- LP 275kV Al	395-003-ELE-SLD-1010	395-003-ELE-SLD-1020	395-003-ELE-SLD-1030
400MW MOS Greenala- LP 275kV Cu	395-003-ELE-SLD-1011	395-003-ELE-SLD-1021	395-003-ELE-SLD-1031

The influence of the export system voltage level and number of the export system cables have minimal impact on the CAPEX values of the platform. The three main components of the platform total CAPEX are SCADA design cost, Offshore platform cost (including topside equipment) and the Jacket cost. Those three category values are £4.13m, £44.16m and £20.87m, accordingly.

The detailed analysis about the system redundancy is presented within Section 8.2. In summary, a two-circuit solution will help improve the transmission availability with minimal impact on OPEX. This will need to be considered from a whole life cost analysis including CAPEX for further consideration.

6.2 Platform Utilities – Electrical

Platform utility systems will be fed at low voltage via a dedicated auxiliary transformer which also acts as the point of earthing for the 66kV system.

Accurate loadings for the platform will be developed at Pre-FEED phase but are provisionally sized to be <300kVA which allows a dedicated feed to be taken from the 66kV switchgear. All loads will be categorised in accordance with the importance and functionality they provide but can be considered to fall under the below categories:

- **Normal loads** – loads associated with normal platform operation. Loads will not be maintained in the event of mains power loss.



- **Essential loads** – loads that are required under loss of mains power and will be connected to the diesel generator connected switchboard section.
- **UPS loads** – loads requiring a secure supply. These are fed from the main power system under normal conditions and battery backed UPS under mains power failure.

6.2.1 Low Voltage Main Distribution

A new main LV switchboard will be installed in the low voltage switchroom and be fed from a 66kV supply via a single 66/0.4kV step down transformer. The switchboard will consist of 2 incoming feeds (one via transformer and one generator incomer), split bus and bus-coupler. The inclusion of a bus coupler allows for the incoming transformer to be taken out of service whilst still providing continuity of supply by generator.

6.2.2 Low Voltage Essential Services

Power for essential services on the platform will be provided by diesel backed generator connected to the essential section of the main low voltage switchboard. The switchboard will operate in a 2oo3 mode to ensure the generator and transformer supply cannot be operated in parallel.

It is envisaged that the below services will be fed from the generator supply:

- Emergency lighting
- Battery chargers and UPS
- Critical cooling supplies
- Fire suppression systems

Sub-Distribution

Multi-way distribution boards equipped with MCBs will be provided to provide power to the below services:

- Small power outlets
- Heating loads
- Trace Heating
- Lighting
- UPS
- DC tripping and closing circuits

Uninterruptible Power Supplies

Dual redundant AC UPS systems will be provided in the LV switchroom with a dedicated room provided for battery storage. UPS sizing and battery autonomy will be determined at the next project phase. It is anticipated the below systems will be supplied by AC UPS systems:

- Life safety systems
- Generator control panels

SCADA system switches and servers

In addition to AC UPS, dual redundant DC chargers will be located in the LV switchroom and will provide power to breaker tripping/closing and protection relays.



Protection, Control and Metering

Protective relay schemes will be installed to protect the electrical system and equipment against abnormal occurrences. Schemes will be arranged to disconnect faulted equipment as quickly as possible and be time or current graded to provide a fully discriminating arrangement.

Arc flash detection will also be included for all main switchgear to ensure instantaneous tripping in the event of an arcing fault.

All main switchgear will be provided with intelligent electrical devices which will be networked on a ring topology using IEC 61850 allowing remote monitoring and control from the local control room. PQM devices will be provided to interface with the SCADA system.

Back-up power

A diesel generator is included in the topsides equipment as a means of back-up power. This is like previous scenarios investigated [16] and is typical of existing offshore substations. Back-up generators can be designed for an extended supply period in the event of a large outage or severe weather compared to batteries with a similar area footprint. This may be beneficial to allow controllers to make operational systems safe and monitor the health of the network as long as possible during an outage. There are alternative options for power sources available such as biofuel or hydrogen batteries. Conceptually, it is considered that the area footprint and weight of other alternative solutions can be designed to be comparable to what has been considered for the generators. The final selection of the back-up power source should consider the long-term storage, leakage potential, and supply period of the fuel source.



7 Offshore substation – structural design

7.1 General Structural Concept

The overall structural concept previously identified [16] for a 1GW platform remains feasible and appropriate for a 400MW platform.

The XH brace jacket with an integrated deck and vertical pile sleeves are highly proven design for this capacity of offshore substation with the supply chain being well set-up to deliver. The concept is also highly proven for offshore structures in the water depth ranges and environmental conditions considered.

Therefore, the general concept remains consistent with what was previously reported. Further details on the individual structural components are given in the following sections. A summary of the weights for the design are given in Table 17. This includes 30% contingency in addition to allowances for unmodelled steelwork.

Table 17 Projected concept structure weight summary

Description	Weight (Te)
Jacket (Substructure)	2390
J-Tubes	178
Topside Structure	409
Topside Equipment	751
Topside Miscellaneous	339
TOTAL	4067

7.2 Conceptual Design

7.2.1 J-tubes

Jackets and topsides should be suitably sized to house and support the numerous export and array cables that are routed to and from the electrical equipment on the substation. A major component of the structural design is the number of J-tubes (the pipe used for guiding and protection of the cables).

Table 18 presents the envisaged J-tube requirements for the 400MW MOS.

Table 18 Envisaged J-tube Requirements

Description	Details
Export Cables Capacity	220 / 275kV (400MW)
No. of Export J-tubes	1
No. of Array J-tubes	4
No. of Spare J-tubes*	1
Maximum no. of J-tubes	6

*Utilised for scenarios with 2 export cables

The 400MW MOS concept considers a structure-internal routing of the cables, where J-tubes are internally fixed to the steel jacket and extend from the cable deck to the bottom bend near the seabed. Guidance is taken from



DNV-RP-0360 [17] regarding the minimum centreline distances and fanning details. Details for the advantages of this design and layout are detailed in the previous phase’s concept design report [16].

DNV code guidance stipulates that the inner diameter of the J-tube should not be less than 2.5 times the cable outer diameter to facilitate cable cooling and avoid excessive pull-in forces [17]. For the 400MW concept, the J-tubes have been initially specified as having an outside diameter of 711mm (28”) and a wall thickness of 20 mm. This concept should be sufficient to house cables up to a maximum of 268mm in outer diameter. It is envisaged that the maximum outside diameter of the cable required is 255mm.

The j-tubes are spaced not less than 1.5m centres, which exceeds the requirements in the code. The J-tubes maximum span between the jacket horizontal/diagonal members does not exceed 25m which is adequate for the environmental loading available at this stage.

7.2.2 Toppersides Equipment

The substation will house key electrical and safety equipment on its decks. It is essential to identify the required major equipment for the topsides requirement to be understood. The permanent loads (in-place condition) are the most important load condition for the design of the structure.

Initial sizes and weights of the major electrical and safety equipment are estimated based on data available for existing 400MW offshore substations. Table 19 presents the equipment basis for the design of the topsides. These exclude details for laydown areas, access, and egress routes, and padeye arrangements.

The concept currently allows for space to locate a shunt reactor. This may not be required offshore based on the estimated length of the cables required for the PDZ area. It may become economical to have an offshore balanced reactor system where this distance increases to over 45km. The use of this available area can be refined in the next stages. The space may provide contingency for any additional minor equipment or increase in main equipment sizes. Otherwise, the main deck dimensions can be optimised for the refined equipment sizes as well as maintenance and access requirements.

Table 19 400MW MOS Equipment Basis (Estimated)

Equipment	Number	Length (m)	Breadth (m)	Weight each (Te)
Transformer	1	9.7	5.5	280.0
220kV GIS	1	9.0	8.0	11.0
66kV Switchgear	1	12.0	5.3	70.0
Metering and SCADA	1	9.5	6.0	8.5
Shunt reactor (if required)	1	7.7	5.6	99.0
Diesel generation	1	5.5	4.0	5.0
Diesel tank	1	6.0	2.0	18.0
Fire mist	1	8.9	4.0	25.0
HVAC room	1	6.0	4.0	10.0
Oil separator room	1	6.0	4.0	10.0
Control room	1	10.0	4.0	5.0
LV Utilities switchroom	1	9.0	4.5	10.0
Refuge	1	8.5	3.0	5.0



Equipment	Number	Length (m)	Breadth (m)	Weight each (Te)
Workshop	1	8.5	3.0	6.0
Crane	1	1.0	1.0	10.0
Other (assumed 5 kN/m ² on unused area)	1	3.4	3.4	73.9
Main deck total		900 m ²		634.4 Te
Cable deck (assumed 5 kN/m ² blanket)		400 m ²		260.8 Te
Total without contingency				838.3 Te
Contingency (30%)				490.4 Te
OVERALL TOTAL				1089.7 Te

7.3 Design Specifications

The design specifications listed below, which were considered for the former PDZ MOS scenarios studied [16], are fundamentally valid for the 400MW PDZ MOS.

- Structural steel classification
- Manning and substation type
- Safety class
- Personnel access and transfers
- Equipment transfers
- Load conditions
- Air gap

However, to enable an optimal structural size and weight design appropriate for the 400MW capacity concept, the overall topsides footprint has been reduced from those considered at the previous phase. Refined environmental conditions are also available at this stage. The below sections detail the minor amendments applied to the design specifications to account for these changes.

7.3.1 Personnel Access and Transfers

The heli-hoist zone will be a minimum 5-meter clear zone sufficiently marked on the roof the main deck. Due to lack of specific guidance for heli-hoist zones for offshore substations, guidance is taken from CAP 437 [18] for helicopter winching areas on WTG platforms. The code stipulates a minimum clear diameter of 4.0m plus a minimum safety zone and access route for Helicopter Hoist Operations Passengers (HHOP) (see Figure 23). No obstacles are permitted to extend above the top of the 1.5m railing within a horizontal distance of 1.5m measured to the winching (clear) area.

Figure 24 shows a representative 10m x 14m heli-hoist zone above the transformer and the Metering & SCADA module. The zone is situated at the roof deck to ensure efficient use of the main deck and meet the minimum obstruction requirements. This design allows for flexibility in the equipment layout without compromising the



overall topsides footprint. The size and location of the heli-hoist zone should be revisited in the next phases to confirm it meets helicopter operation requirements.

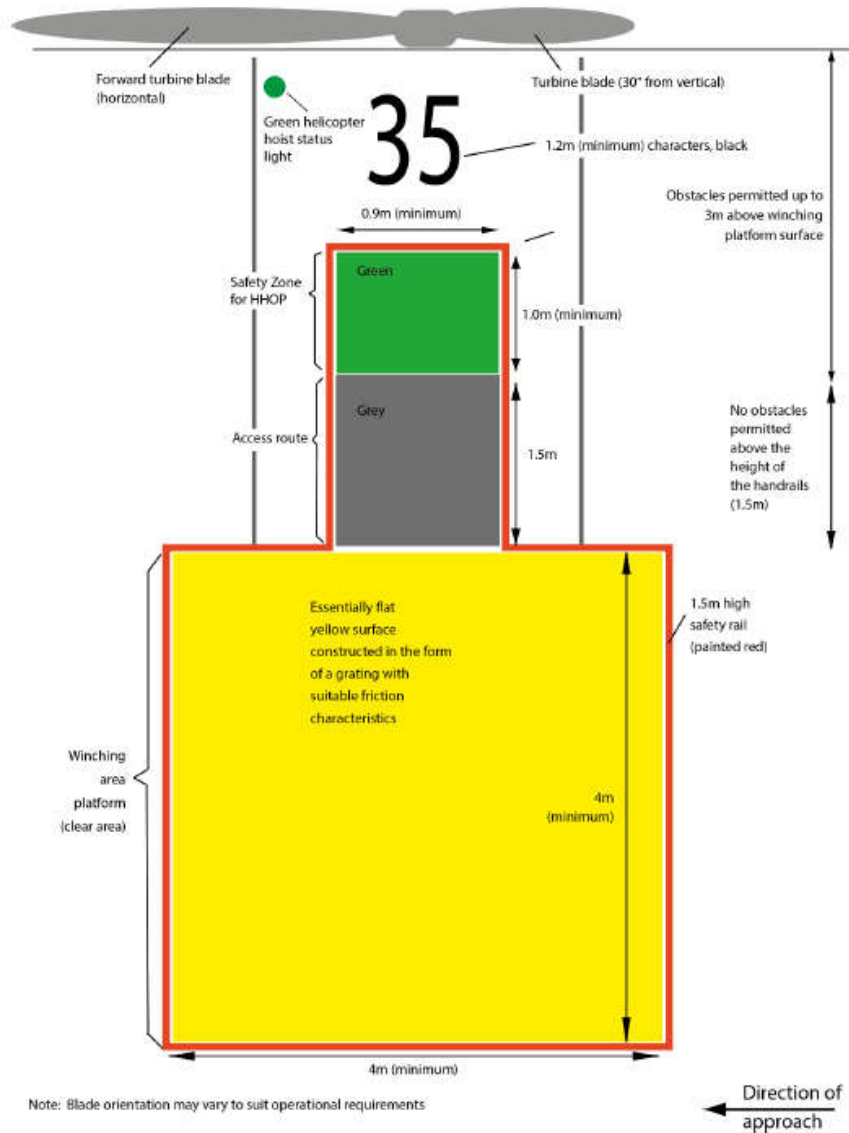


Figure 23 - Winching area, access route, and safety zone minimum requirements [18]

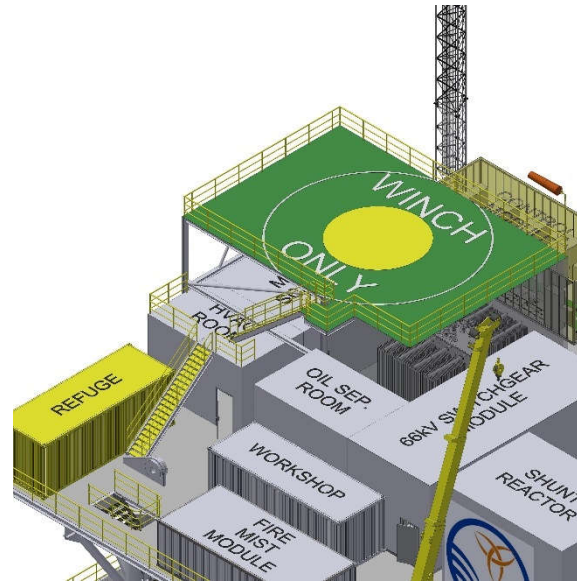


Figure 24 – Representative heli-hoist zone

7.3.2 Equipment Transfers

It is envisaged that a single crane of a relatively small capacity (between 6 to 10 tonnes) is sufficient for general maintenance and transfer of tools and spare parts from a CTV to the main deck for a 400MW substation. Other means of equipment transfers are available and should be investigated in the next phases of design. It is not thought that larger capacity transfer methods will be required and therefore the final selected method is unlikely to affect the primary steelwork design. Figure 25 shows a single telescopic crane situated on the south-west corner of the asset.

Load-handling and laydown area requirements are unknown at this stage, but a general assessment of the available space has been carried out. A representative 10m x 5m laydown area is shown on the south-west corner adjacent to the telescopic crane.

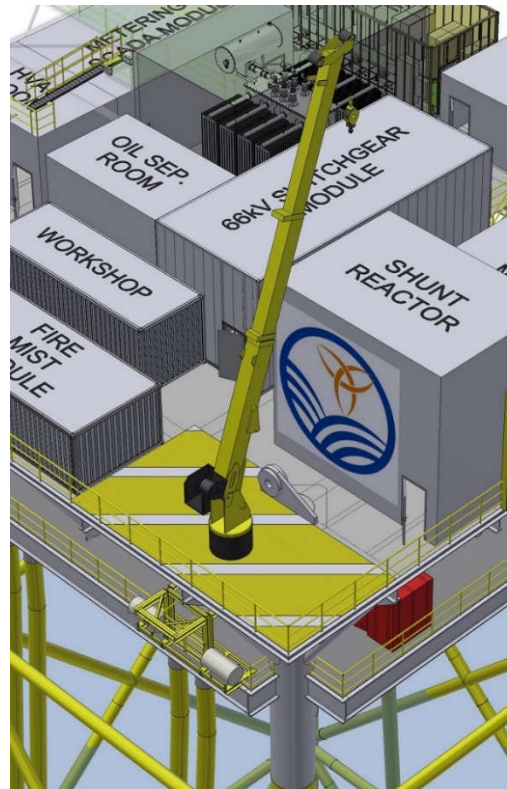


Figure 25 – Telescopic crane model representation

7.3.3 Air gap

The design of the jacket structure allows for an air gap in accordance with DNV-STL-0145 [19]. The still water mean sea level (MSL) have been identified as 65m with tidal and surge values refined from previous concept assumptions based on values provided in ERA5 data set and typical values for UK waters [2]. Based on these, the minimum air gap for the 400MW MOS between the MSL and the Cable Deck should be 23.1m.

The Cable Deck top of steel (TOS) elevation for the concept design is 24.136m from MSL. This provides allowance for sizing primary beams without encroaching the minimum required air gap.

7.4 Jacket Concept Design

7.4.1 Conceptual sizing

A jacket topside footprint of 20m² has been selected and is considered sufficient for the number of J-tubes anticipated for this substation (see Section 7.2.1). A jacket batter of approximately 1/15 is used on all four sides based on typical batter values. This gives a jacket seabed footprint of 31m². There may be some benefit in optimising the batter requirements once more specific metocean data becomes available, which is to be considered in Pre-FEED.

The concept design is primarily driven by the permanent and environmental loading which occurs in its in-place condition. Table 20 presents the conceptual section sizes selected for the jacket. These sizes are derived using basic principles and recommended practices for offshore structures, which are detailed in the previous concept report [16].



Table 20 Concept section sizes and associated properties

Jacket element	Section Size	Mass (kg/m)	Cross-Section Area (cm ²)	Elastic Modulus (cm ³)
Legs	1400 OD x 50 WT	1665	2121	69108
Bracing – Upper jacket	600 OD x 20 WT	286	364	5114
Bracing nodes – Upper jacket	600 OD x 30 WT	422	537	7293
Bracing – Bottom bay	600 OD x 25 WT	416	530	8639
Bracing nodes – Bottom bay	600 OD x 35 WT	574	731	11580

The overall concept jacket design is estimated to weigh approximately 2390 Te which includes an allowance for unmodelled steel and a 30% contingency. This weight excludes the weight of the J-tubes and pile guides. It is common practice to reduce the leg diameter up the jacket as the stress contributions from wave loading reduce. Cones are used at transitions between diameters and should normally be introduced beneath plan levels to minimise the weight of nodal constructions. This is currently not considered in the conceptual design but will be investigated in the next phase to optimise the jacket weight further.

The concept design model currently does not include plan bracing. However, plan bracing will likely need to be added in the next phase of the scope. The location and size of the plan bracing depends on the selected fabrication, lifting, and transportation methods. Discussion will be required with fabrication and installation contractors to confirm feasible methods and initial engagement will be carried out during Pre-FEED (see Sections 7.7 and 7.8).

Corrosion protection systems such as minimum wall thicknesses, anodes, and coatings need to be considered as the design progresses. The type of corrosion control depends on the zone location of the jacket member (atmospheric, splash, or submerged zones). Submerged members shall be cathodically protected, preferably in combination with coating in accordance with DNV-RP-0145 [19]. Anodes are currently represented in the model and should be confirmed in detailed design. As with all offshore assets, an inspection and maintenance programme should be developed to ensure the jacket is structurally sound throughout its design life.

7.4.2 J-tube layouts

The array J-tubes are located on the south-west corner of the jacket whilst the export J-tube is located on the North face which is nearest to the onshore substation. A spare export J-tube is also represented on the North face. As with the previous concepts investigated, all J-tubes are located just internal to the faces of the jacket. This allows supports to be attached from the jacket brace members. Figure 28 shows the conceptual layout of J-tubes. The estimated mass of the J-tubes is 178 Te based on the size and number detailed in Section 7.2.1.

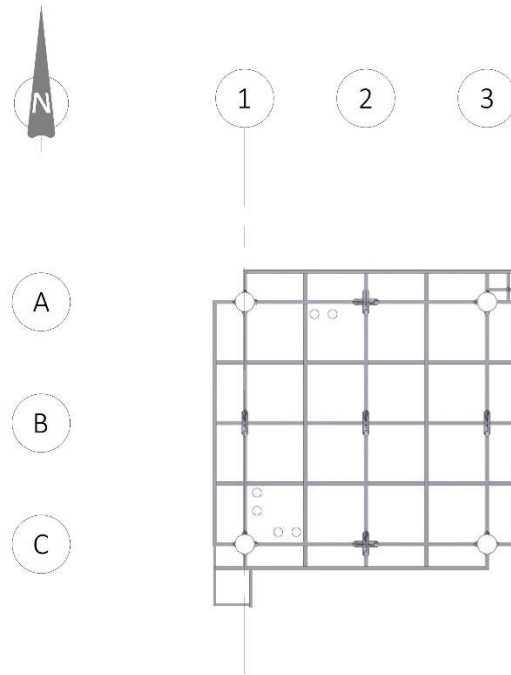


Figure 26 – Cable Deck primary steelwork plan showing J-tube layout

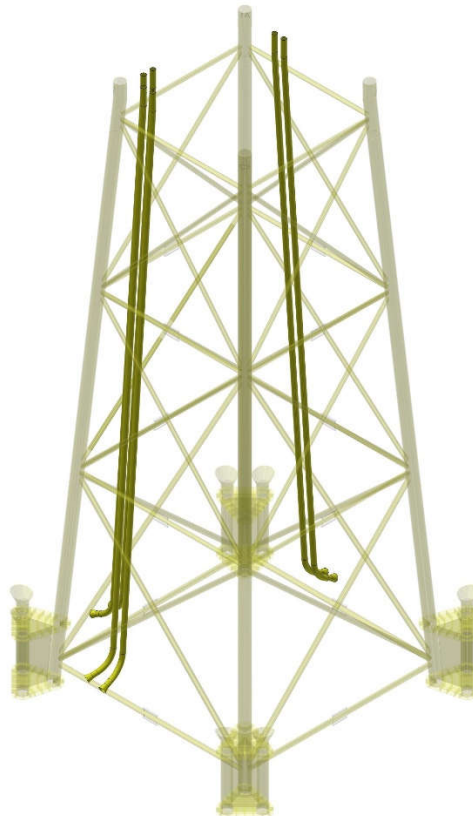


Figure 27 – Model representation of J-tubes on jacket structure

One face of the jacket is left free of any J-tubes. This allows any jack-up rig operations to take place, where required. The design of the jacket structure has allowance for the J-tube layouts to be refined as necessary to suit selected cable installation and pulling methodologies.



The jacket bracings have sufficient strength to laterally support the J-tubes. The supports can be in the form of welded stubs, clamped arrangements, or a combination of both. The type of support depends on the phasing of the J-tube installation. Conceptually, it is assumed that all J-tubes are to be supported by welded stubs to the jacket. This allows the jacket to be installed, with the J-tubes attached, in a single lift.

7.5 Foundation Concept Design

Vertical pin piles are still considered as the most practicable solution for a 400MW MOS concept. The advantages of this pile type are detailed in the previous concept report [16].

However, the publicly available information for the PDZ area shows significant formations of chalk. This has a risk of preventing the installation of driven piles. This could lead to the requirement to drill and grout the piles, potentially leading to an alternative concept being required to connect the piles to the jacket. This would likely be pin piles installed using a template on the seabed prior to the jacket.

A geotechnical site investigation needs to be carried out to refine the expected soil conditions for the specific substation site. The feasibility of the selected jacket foundation will be further investigated in the next phase of design by Geotechnical specialists.

The number, arrangement, diameter, and penetration depth of the piles depend on the environmental loads and soil condition at the substation location. Based on the estimated weight of the jacket, the weight of the piles required is approximated to be in the region of 700 to 800Te. This is equivalent to two 1600mm x 50mm thick piles per leg piled to around 40m below the seabed (765 tonnes weight).

Pile sleeves are required to be welded at the base of the jacket on each leg. The exact required length and thickness of pile sleeves and connecting plates should be based on the shear plate area required to transfer the foundation loads into the legs. These are currently estimated to be in the region of 10 metres. The section of jacket legs where the sleeves are attached will use a larger diameter, typically referred to as the bottle legs, the sizing of this section will be developed in the Pre-FEED.

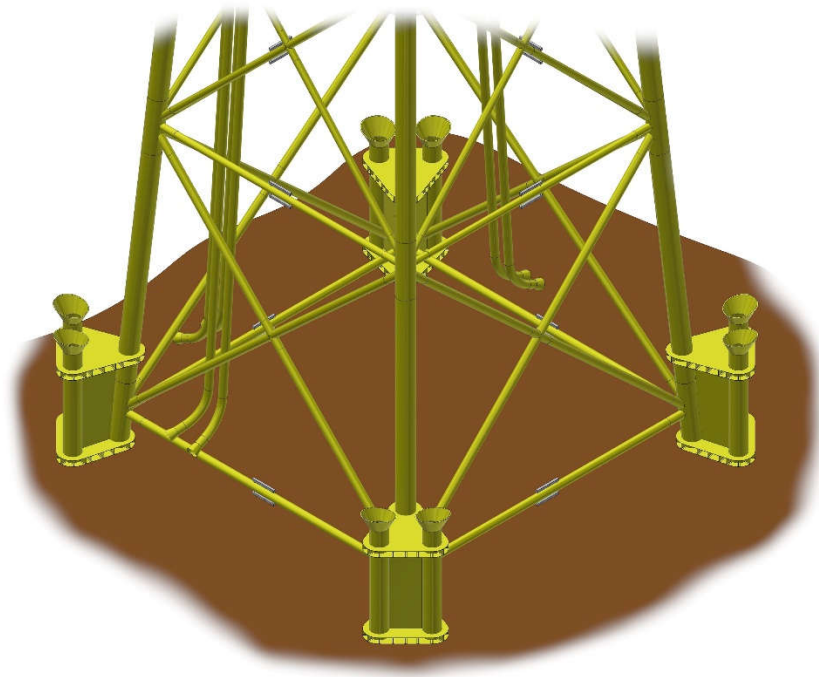


Figure 28 – Representative pile sleeves

7.6 Topside Concept Design

The selected concept for the topsides structural design is a braced integrated deck, which is ideal for a jacket topsides concept. This consists of an open main deck which houses majority of the main equipment and a bottom cable deck which allows for routing of the cables from the J-tubes to the various topside equipment as well as access for personnel to the secondary refuge and boat landing. The advantages for this type of topside concept are detailed within the previous concept report [16].

The braced integrated deck arrangement is typical of existing offshore substations of a similar capacity within the UK. Examples are shown in Figure 29. It should be noted that there are existing standardised modular solutions available for offshore substation topsides such as the Offshore Transformer Module (OTM®) from Siemens, which have been used for the Moray East and West substations and the Triton Knoll substations. These could potentially be used to save on detail design given they have been deployed and certified for similar sized substations. Further investigation is required to assess its applicability for multi-connection as well as for the environmental conditions of the PDZ.



Figure 29 – Top left: Rampion Offshore Substation (2017); Bottom left: Triton Knoll Offshore Substation (2022); Right: Moray East Offshore Substation (2020)

7.6.1 Cable deck requirements

The cable deck height should be sufficient for routing the selected cable sizes for the MOS. The minimum required height is typically two times the minimum bending radii of the maximum cable size used.

For the current concept, a cable deck height of 7m is representatively assigned and is approximately aligned with existing installed 400MW substations. This height can be refined in the next phase once the cable sizes are further defined. The concept design currently assumes that the cable pulling is carried out after the installation of the topsides. The phasing of the cable pulling needs to be identified in the next phases to determine whether a separate access deck on the jacket is required. Table 21 presents the points that need to be considered to determine the optimal solution for cable pulling.



Table 21 Cable and access deck options and considerations for design

Description	Advantages	Disadvantages
Single cable deck integrated with topside	<ul style="list-style-type: none"> • The design of the cable path may allow pull of the cable to final length in one work step • No additional fabrication required for the jacket structure 	<ul style="list-style-type: none"> • Subsea cables can only be pulled in after installation of the topsides • Distance between the topside decks need to be adequate, and potentially bigger, for maximum cable bends • Depending on the stabbing design, the J-tubes may not be allowed to protrude above the substructure and “filler” sections may have to be inserted after topside installation to bridge the distance to the cable deck
Substructure deck	<ul style="list-style-type: none"> • Cables can be pulled in prior to installation of the topsides, decoupling installation steps • Can provide additional height for cable bends minimising the height between the topside decks 	<ul style="list-style-type: none"> • Typically cables cannot be pulled to final length in one step, but attachment of an approved pulling stocking and pull of additional length will be required. • Additional steelwork may be required for laydown space and cable pulling loads • Mechanical protection and sealing of the cable ends may be required for the period until topsides installation • Design should permit future repair (including replacement) of a power cable with topsides installed. This will require the minimum air gap and associated height of the access structure relative to MSL to be investigated to meet this requirement. • Additional fabrication required for the jacket structure

7.6.2 Equipment layout

The topside equipment has been laid out with considerations for cable routing, access/egress requirements, and refuge area location. The refuge area is situated away from the hazardous equipment and is easily accessible from all areas of the main deck.

Figure 30 shows the concept main deck layout for the 400MW substation. This layout is approximate and should be refined in the FEED stage when equipment sizes, room requirements, and access & maintenance requirements are fully defined. Refer Appendix A for 400MW MOS concept sketches.

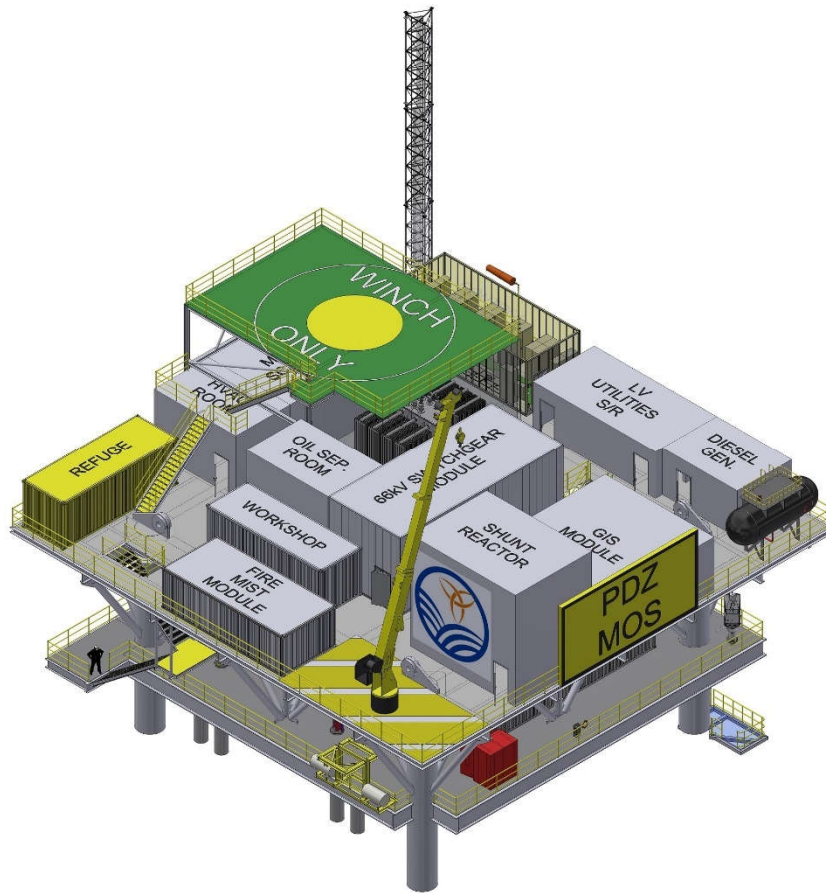


Figure 30 – 400MW MOS Main deck concept layout

A topsides footprint of 30m x 30m (900m² area) has been selected to ensure sufficient spacing for the equipment footprint anticipated (see Section 7.2.2). The concept topside steelwork weight is approximated as equivalent to between 40 to 50% of the topside equipment weight. The below table shows the estimated weights of the topside structure. A 30% contingency is also included to account for uncertainties in the design at the current stage and allow for any future increases. This contingency will be refined as the project proceeds through the next phases. The overall estimated topside weight is comparable to existing 400MW capacity substations installed in UK waters as presented in Table 23.

Table 22 - Estimated topside weight

Concept Structure Weight	Weight (tonnes)	Contingency (tonnes)	Upper Bound Weight (tonnes)
Topside structure	315	96	409
Topside equipment	578	173	751
Topside miscellaneous	261	78	339
Topside total (Lift weight)	1154	346	1499



Table 23 - Existing UK offshore substations of similar capacity

Windfarm	Overall Capacity (MW)	No. of Substations	Approx. capacity per Substation (MW)	Approx. Topside Weight (t)	Topside Maximum Dimension (m)	Topside Type
Triton Knoll	857	2	429	1200	24	Braced integrated deck
Rampion	400	1	400	2000	35	Braced integrated deck
Moray East	950	3	316	1252	30	Braced integrated deck

During Pre-FEED design, the steelwork will be sized and aligned with the equipment locations. This may affect the overall structure weight, although it is estimated that the total topside structure weight, including all secondary and tertiary steelwork will be in the region of the above estimate.

7.7 Fabrication

No lifting calculations have been performed at this stage. However, the design can be made to work for lifting and fabrication scenarios with minimum modifications by comparison with previously installed structures. Both topside and jacket structures can be designed to optimise fabrication complexity as noted in the previous concept report [16].

The size and type of structure will define which yards are suitable for the fabrication of the structures. Table 24 presents an updated list of current capabilities and capacities of the UK fabrication section which may provide the basis for determining feasible local fabrication options for the MOS. Alternatively, either or both topsides and jacket structures can be fabricated in fabrication yards within Europe. The preferred fabrication methodology, e.g., stacked jacket sections vs jacket faces fabricated horizontally, will vary depending on the available space and crane capacity of the selected fabrication yard. These options shall be investigated in the next phase of the scope once stakeholder engagement has commenced.

Table 24 - UK Fabrication section capabilities and capacities [20]

Company	Location	Fabrication Area (m ²)	Stated Capacity & Capability
Able UK Limited	Middlesbrough	21,000	8,000 Te jacket, 10,000 Te deck
A&P (Tyne) Group	Falmouth	4,108	1000 Te jacket, 8,000 Te topsides
	Tyne	17,500	
Babcock Appledore	Devon	Not stated	132m vessels (10,000 Te)
Babcock Marine (Rosyth) Limited	Rosyth	5,600	Subsea modules (500 Te)
Cammell Laird Shiprepairers & Shipbuilders Limited	Wirral	Not stated	8,000 Te jacket, 10,000 Te deck
Global Energy Group	Ross-shire	67,000	50,000 Te jacket, 10,000 Te deck
Harland and Wolff	Belfast	81,097	8,000 Te jacket, 10,000 Te deck



Company	Location	Fabrication Area (m ²)	Stated Capacity & Capability
	Methil ¹	7,900 (x3)	>10,000 Te jacket, 10,000 Te deck. 22,000 tonnes load out.
Heerema Hartlepool Limited	Hartlepool	74,000 (x2)	8,000 Te jacket, 10,000 Te deck
Hertel	Teeside	8,000	8,000 Te jacket, 10,000 Te deck
	Merseyside	1,500	
McNulty Offshore Limited	South Shields	4,950	8,500 Te module, 2,500 Te substation jacket & topside
Offshore Group Newcastle	Wallsend	16,500	4,500 Te jacket, 8,400 Te drilling facilities, 1,068 Te substation
Pallion Engineering Limited	Sunderland	30,000	10,000 Te jacket/topside structures, 35,000 Te ships
Shepherd Offshore Services Limited	Newcastle Upon Tyne	Not stated	8,000 Te jacket, 10,000 Te deck
SLP Engineering Limited	Suffolk	2,640	6,000 Te jacket, 10,000 Te deck
Smulders ²	Newcastle Upon Tyne	35,000 Production 104,000 Open Fabrication & assembly	13,000 Te load out >5,000 Te jacket / deck
Teeside Alliance Group	Teeside	5,882	6,000 Te jacket/deck
Wilton Engineering Services Limited	Middlesbrough	8,514	10,800 Te topside

1. Harland and Wolff has acquired the Methil facility in February 2021
2. Smulders has acquired the Wallsend facility from Offshore Group Newcastle in January 2017

7.8 Transportation and Installation

The lift strategy should be defined as part of the overall construction strategy. It is anticipated that the jacket would be transported to the site horizontally and lifted and upended by a heavy lift vessel. However, options for launching the jacket are also available, where it can be launched off the barge with the heavy lift vessel used to position the jacket. Lifting points in the form of either padeyes or trunnions are to be added in FEED. Some additional bracing is likely required to support the transportation and installation operations.

As previously stated, the selection of an appropriate transportation and installation vessel will be based on the lift capacity, market availability, and technologies required. It should be noted that the estimated water depth within the PDZ area is deeper than installed similar capacity offshore substations. It is likely that floating installation vessels will be required.

Conceptually, the 400MW installation is assumed to be the same as the previous concepts investigated, where both jacket and topside structure will be lifted individually into position.

It is estimated from the HIS Markit graph of the global heavy lift fleet in 2020 that there are approximately 30 vessels with a capacity of between 3000 to 5000Te. A non-comprehensive list is provided in Table 25 for reference. The allowable hook heights and reaches of the vessel cranes need to be investigated in the next phases to refine the list of potential vessels that can be used for the 400MW MOS.



Figure 31 – Triton Knoll OSP West en-route to the site [21]

Table 25 - Installation Vessels

Vessel Name	Details			
Asian Hercules II	IMO Number	8639297	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	3,200	Build year	1996
	Type	Crane Barge	Self-propelled [y/DP/n]	y
	Length [m]	91	Max speed [knots]	7
	Beam (Breadth) [m]	43	Max for legs depth [m]	n/a
	Laden draft [m]	n/a	Jacking limit, [Hs m]	n/a
Asian Hercules III	IMO Number	9660396	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	5,000	Build year	2015
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	y
	Length [m]	106.42	Max speed [knots]	7
	Beam (Breadth) [m]	52	Max for legs depth [m]	n/a
	Laden draft [m]	5.5	Jacking limit, [Hs m]	n/a
Gulliver	IMO Number	9774094	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	4,000	Build year	2018
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	DP
	Length [m]	108	Max speed [knots]	7
	Beam (Breadth) [m]	49	Max for legs depth [m]	n/a
	Laden draft [m]	4.9	Jacking limit, [Hs m]	n/a
OOS Gretha	IMO Number	9650963	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	3,600 (Tandem)	Build year	2012
	Type	Semi-submersible	Self-propelled [y/DP/n]	DP
	Length [m]	137.75	Max speed [knots]	11
	Beam (Breadth) [m]	81	Max for legs depth [m]	n/a



Vessel Name	Details			
Orion	Laden draft [m]	11.28	Jacking limit, [Hs m]	n/a
	IMO Number	9143415	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	5,000	Build year	2019
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	DP
	Length [m]	216.5	Max speed [knots]	16.5
	Beam (Breadth) [m]	49	Max for legs depth [m]	n/a
Pioneering Spirit	Laden draft [m]	-	Jacking limit, [Hs m]	n/a
	IMO Number	9593505	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	48,000	Build year	2014
	Type	Catamaran	Self-propelled [y/DP/n]	DP
	Length [m]	370	Max speed [knots]	14
	Beam (Breadth) [m]	124	Max for legs depth [m]	n/a
Rambiz	Laden draft [m]	10	Jacking limit, [Hs m]	n/a
	IMO Number	9136199	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	3,300	Build year	1976
	Type	Shearleg crane barge	Self-propelled [y/DP/n]	y
	Length [m]	85	Max speed [knots]	~4-6
	Beam (Breadth) [m]	44	Max for legs depth [m]	n/a
Saipem 7000	Laden draft [m]	5.6	Jacking limit, [Hs m]	n/a
	IMO Number	8501567	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	14,000 (tandem)	Build year	1987
	Type	Semi-submersible	Self-propelled [y/DP/n]	y
	Length [m]	197.95	Max speed [knots]	9.5
	Beam (Breadth) [m]	87	Max for legs depth [m]	n/a
Seaway Strashnov	Laden draft [m]	10.5	Jacking limit, [Hs m]	n/a
	IMO Number	9452701	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	5,000	Build year	2011
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	DP
	Length [m]	183	Max speed [knots]	12
	Beam (Breadth) [m]	47	Max for legs depth [m]	n/a
Seven Borealis	Laden draft [m]	8.5 – 13.5	Jacking limit, [Hs m]	n/a
	IMO Number	9452787	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	5,000	Build year	2012
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	DP
	Length [m]	182	Max speed [knots]	11
	Beam (Breadth) [m]	46	Max for legs depth [m]	n/a
Sleipnir	Laden draft [m]	8.5 – 11.35	Jacking limit, [Hs m]	n/a
	IMO Number	9781425	CAPEX (estimate) [\$m]	n/a



Vessel Name	Details			
	Max lift [t]	10,000	Build year	2019
	Type	Semi-submersible	Self-propelled [y/DP/n]	y
	Length [m]	220	Max speed [knots]	10
	Beam (Breadth) [m]	102	Max for legs depth [m]	n/a
	Laden draft [m]	12	Jacking limit, [Hs m]	n/a
Stanislav Yudin	IMO Number	8219463	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	2,500	Build year	1985
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	n
	Length [m]	185	Max speed [knots]	8 - 10
	Beam (Breadth) [m]	36	Max for legs depth [m]	n/a
	Laden draft [m]	9 (13)	Jacking limit, [Hs m]	n/a
Svanen	IMO Number	9007453	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	5,175	Build year	1991
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	n
	Length [m]	102.75	Max speed [knots]	7
	Beam (Breadth) [m]	71.8	Max for legs depth [m]	n/a
	Laden draft [m]	6	Jacking limit, [Hs m]	n/a
Thialf	IMO Number	8757740	CAPEX (estimate) [\$m]	\$1Bn
	Max lift [t]	14,200	Build year	1985
	Type	Semi-sub HLV	Self-propelled [y/DP/n]	DP
	Length [m]	201.6	Max speed [knots]	7
	Beam (Breadth) [m]	88.4	Max for legs depth [m]	n/a
	Laden draft [m]	11.8 - 31.6	Jacking limit, [Hs m]	n/a
Voltaire	IMO Number	9190705	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	3,000	Build year	2000
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	DP
	Length [m]	216	Max speed [knots]	12.5
	Beam (Breadth) [m]	43	Max for legs depth [m]	n/a
	Laden draft [m]	9	Jacking limit, [Hs m]	n/a
Zhen Hua 30	IMO Number	9107021	CAPEX (estimate) [\$m]	n/a
	Max lift [t]	12,000	Build year	1995
	Type	Heavy lift vessel	Self-propelled [y/DP/n]	y
	Length [m]	297.6	Max speed [knots]	12
	Beam (Breadth) [m]	58	Max for legs depth [m]	n/a
	Laden draft [m]	13.5-17.6	Jacking limit, [Hs m]	n/a



No detailed engineering of the lift points has taken place, although the jacket and topsides members have been sized appropriately. Local stiffening would be required to account for transportation and installation loads, and this should be covered in the overall weight contingency (30%).



8 Operation and maintenance

This section of the report details operation and maintenance (O&M) of the MOS Concept Design Study project. A high-level O&M strategy, maintenance requirements, and OPEX & availability modelling outputs are presented in the subsequent sections.

8.1 O&M Strategy

This section provides a high-level O&M strategy for operating a 400MW MOS platform. The following topics are covered as part of this:

- logistics concept (incl. access & egress, and onshore requirements),
- project staff requirements,
- operational requirements,
- contract strategies,
- maintenance requirements.

8.1.1 Logistics

Logistics Concept:

As part of the concept study a detailed logistics study was completed, which included: port assessment (along the Welsh, Devon and Cornwall coastlines), review of logistics concepts and means of access & egress used in offshore renewables. The findings of these can be found in the logistics strategy [22] and the platform transfer strategy [23].

From these strategies it was determined that the optimum logistics strategy for day-to-day operations on the project is to use 1 crew transfer vessel (CTV) (12 PAX), with 1.5m Hs transfer capability. Personnel primary means of access & egress via boat-landing system (BLS) and equipment & tools transferred using a davit crane.

Below approximate specifications for a CTV with 1.5m significant wave height (Hs) transfer capability are provided:

- Length (m): 20-25;
- Beam (m): 6-8;
- Capacity (PAX):12-24;
- Service speed (knts): 25 (in Hs 0-1.5m);
- Free deck space (m²): 25-50;
- Cargo (t): 5-10;
- Cargo Deck Capacity (t/ m²): 1-1.5; and
- Crane max. lifting capacity: 1.2t @ 8m.

It should be noted that other vessels/ logistics concepts may be required throughout the operating life to support maintenance tasks, such as, Service Operation Vessels (SOVs), Remotely Operated Vehicles (ROVs), helicopters, specialist lifting vessels, etc. As such the MOS design will need to incorporate access gates for walk-to-work systems and a heli-hoist zone.



O&M Base Requirements:

From the port assessment it was determined that Milford Haven was the optimum port for the location of the project O&M base, for all scenarios. Milford Haven was preferred due to its proximity to site, the port has capacity to accommodate the requirements of the MOS project, and the port is located in Wales, which would provide a boost to the local economy and garner local support for the project.

For a 400MW substation the following would likely be required for an O&M Base at Milford Haven.

- Office Facility (incl. offices, meeting room, Supervisory Control and Data Acquisition (SCADA) room, toilets & shower rooms, locker room, kitchen).
- Warehouse facility (incl. goods receipt, outbound area, quarantine area, pallet racks, shelves, workshop, electrical area, forklift area, COSHH area) – footprint c. 150m².
 - Workshop to be outfitted with compressed air, electrical outlets, hot & cold running water, work benches, tool racking.
 - Area for storage of electrical components kept between 15-30°C and relative humidity of c. 50%.
- External storage (car spaces, cable & cable accessories storage).
 - Spare cable & accessories could be stored at an alternative location.
- Quayside – berth for CTV with cargo handling area (load capacity 15-20 t/m²), and cranes (3t capacity).
 - Berth to have the following supply systems: diesel, water electrical power, sewage.

8.1.2 Operations

Project Resource

To support operations a project team will need to be established. The extent of which will be determined based on the approach taken to maintenance of the assets, i.e., perform in-house maintenance or utilise service providers. Figure 32 shows an indicative project organogram.

To operate the MOS project it is advised that the following personnel are employed:

- General Manager – to minimise personnel on the project the General Manager may also assume the role of Commercial Manager;
- HSE Manager; and
- Office Manager.

Should the project take operations in-house then the following roles should also be filled. However, if maintenance is outsourced to a service provider, then these roles would likely be filled by the service provider.

- Operations Manager;
- Planner;
- Admin Support;
- Warehouse Coordinator; and
- Senior Authorised Personnel (SAP)/ technicians.

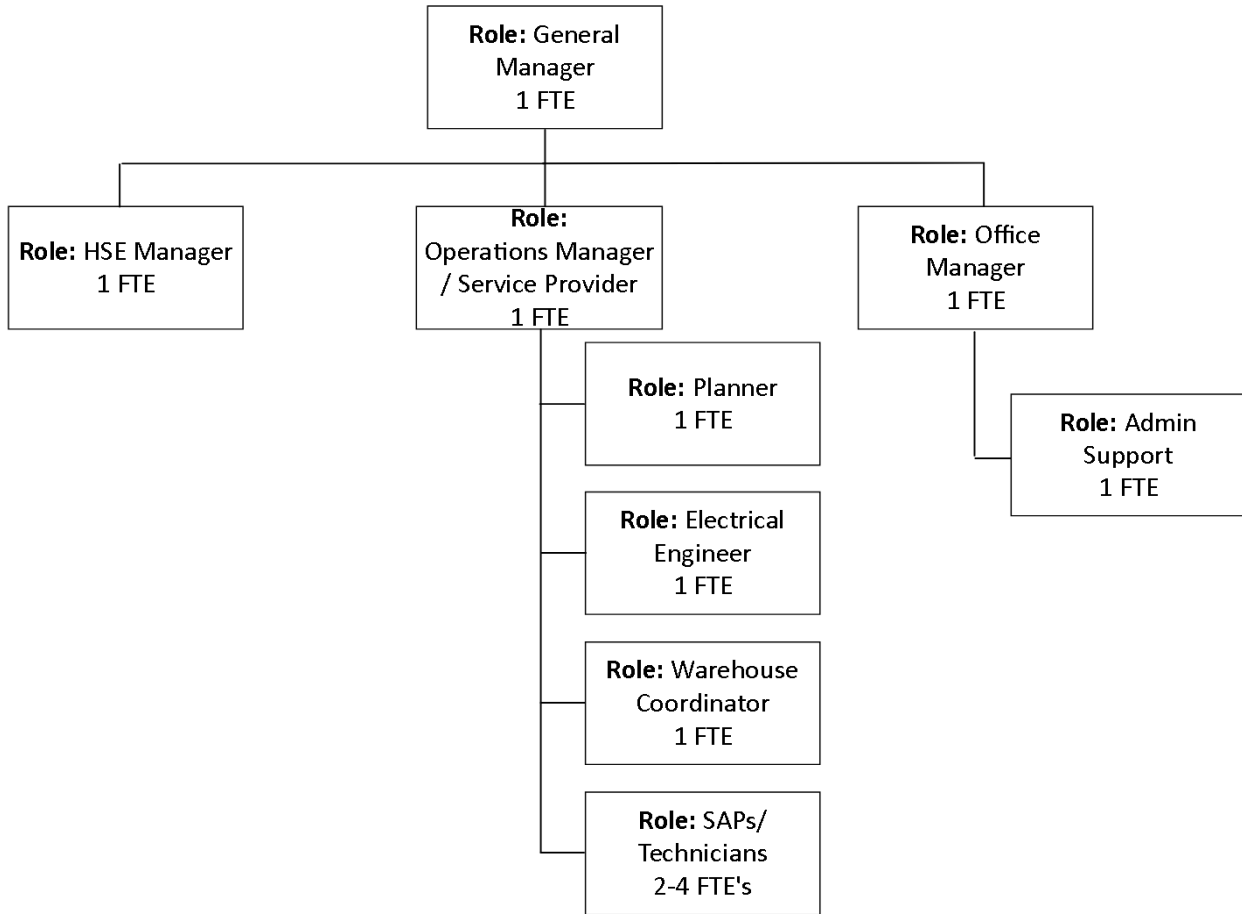


Figure 32 - Indicative Project Organogram

Contracting Strategies

As the project moves into FEED, a decision will need to be made in relation to how the project intends to operate the site to refine the O&M strategy, as well, determine the contracting strategy. There are 2 main approaches that could be adopted, which are, in-house O&M or contract out to a service provider.

If the project is contracted out to a service provider, then they would be responsible to provide all service personnel, for performing all scheduled and corrective maintenance, management of HV safety rules, alarm monitoring and control, and marine coordination. Some contracts also include the provision of spares, tooling, etc.

If an in-house approach was adopted, then the project would be responsible for all the above.

The project may elect to procure a service provider during the warranty period of the equipment and following the expiry of the warranty period move to an in-house approach.

The project may also want to consider entering into cable repair framework agreements to have a guaranteed response time should there be a cable failure on the project. This could be critical to maintain a high-level of availability, which would be requested by generators connecting into the MOS. It would be expected that the project would have to provide a MOS system availability of c. 98%, as per Offshore Transmission System Operator (OFTO) requirements. CSP may want to consider discussing a multi-operator framework agreement with generators looking to connect into the MOS platform, current demo projects in the Celtic Sea and/or winners of the upcoming TCE Celtic Sea seabed leasing round.



Should the project not enter into a framework agreement, a number of cable manufacturers offer a variety of cable repair services. Companies that offer these services include: JDR, NKT, Prysmian, Hellenic Cables and Boskalis Cable in collaboration with EDS.

Operational Control

A robust set of rules and codes of practice to provide a Safe System of Work (SSoW) for the operation of all HV equipment will be implemented on the project, the HV safety rules. These rules will cover all HV equipment. For HV safety rules the project could:

- Choose to develop & manage their own HV safety rules;
- Request the appropriate service provider develop & implement this SSoW;
- Engage a 3rd party specialist to develop and manage the HV safety rules; or
- Adopt the Electricity Safety Rules

(<https://www.nationalgrid.com/electricity-transmission/document/83511/download>)

published by National Grid, the project may choose to adopt these or an edited version.

These rules will apply from handover of the assets to the operator and procedures will need to be developed and maintained to implement and monitor the effectiveness of the HV safety rules.

Under normal operation, the platform will be controlled and monitored on a 24/7/365 basis from a control centre location.

- Control operations will be carried out from a dedicated location, this is often located at the project O&M base. The control centre will manage MOS control & switching, marine coordination and emergency response.
- The project may elect for control operations to be carried out from an outsourced location, say 3rd party provider, during periods out with standard operating hours, i.e., when technicians are off-shift (7pm – 7am, bank holidays, etc.)

IT infrastructure will be in place to enable full control from the open internet, utilising a private network.

The local control room will require:

- SCADA data from the assets;
- Weather information – live from the site and forecast data from external provider;
- Access to asset management systems;
- Mimic boards/ single line diagrams (SLD's);
- Communications equipment including digital mobile radios, very high frequency (VHF) radios and telephones;
- Feeds from CCTV cameras (if installed);
- Automatic identification system (AIS) vessel tracking system; and
- PCs.

To enable opportunities for remote monitoring and to facilitate efficient operations to be delivered there should be a data historian which will retain data from all areas of the systems and facilitate the engineering and commercial analysis of historical data to improve future performance.



8.1.3 Maintenance Requirements

Availability, Reliability & Maintainability (ARM) Study

An ARM study was undertaken to determine the failure rates of switchgears, transformers, and export cables. The approach taken to determine the failure rates was based on the methodology proposed by H. Stiesdal & P.M. Madsen in “Design for Reliability” [24]. The following steps are used in this methodology:

- 1 Determine consequences of failure for relevant error types (infant failure, random failure, wear-out failure, and premature serial failure and component failures, i.e., identify failure modes.
- 2 Determine the mean time between failures (MTBF) and mean time to repair (MTTR) for each component.
- 3 Determine failure rate of each component based on the above information, for the 4 error types and then sum these to determine the overall failure rate on an annual basis.
- 4 Sense check failure rates against industry benchmarks, such as, CIGRE.

Table 26, below, shows the failure modes that would result in a full component exchange identified for each component, MTTR, and MTBF.

Table 26 - Overview of Main Component Failure Modes, MTTR, & MTBF

Component	Failure Modes	MTTR (days)	MTBF (years)
Switchgear	High resistance at bolted connection Control and protective relay failure Corrosion due to installation in harsh environment Shutter assembly Insulation barrier failure	13	66-100kV = 2000 100-200kV = 69 200-300kV = 116 300-500kV = 36
Transformer	Cracks in transformer supporting structure Cracks in isolation Failure at windings External short circuit with inadequate protection switches Operation beyond design specifications (overloading) Lightning surges from inadequate lightning protection Tap changer design, maintenance flaw Deterioration of oil Bushing failure Partial discharge	60	100-200kV = 234 200-300kV = 213 300-500kV = 189
Export Cable	Trawling or anchor strike Electrical fault Thermal error (poor design/ installation) Wear & tear due to cable movement (if cable is exposed) Mechanical faults Poor installation (during pull-in, load out, etc.)	50	25

The information in the table above was derived through review of offshore wind substation failure data, several academic papers, and industry knowledge.



Table 27 below shows the average failure rates for each component. Low, medium, and high failure rates are presented for the export cable, for the purpose of modelling the low failure rate was used.

Table 27 - Calculated Ave. Annual Failure Rates

Component	Calculated Ave. Failure Rate pa. (over 30yrs of ops)
Switchgear 66-100kV	0.0017
Switchgear 200-300kV	0.0110
Transformer 100-200kV	0.0055
Transformer 200-300kV	0.0059
Export Cable – Low Rate	0.0007 /km
Export Cable – Medium Rate	0.00125 /km
Export Cable – High Rate	0.0018 /km

The figures below show the derived failure rates of each main component on the MOS platform and the export cables, respectively.

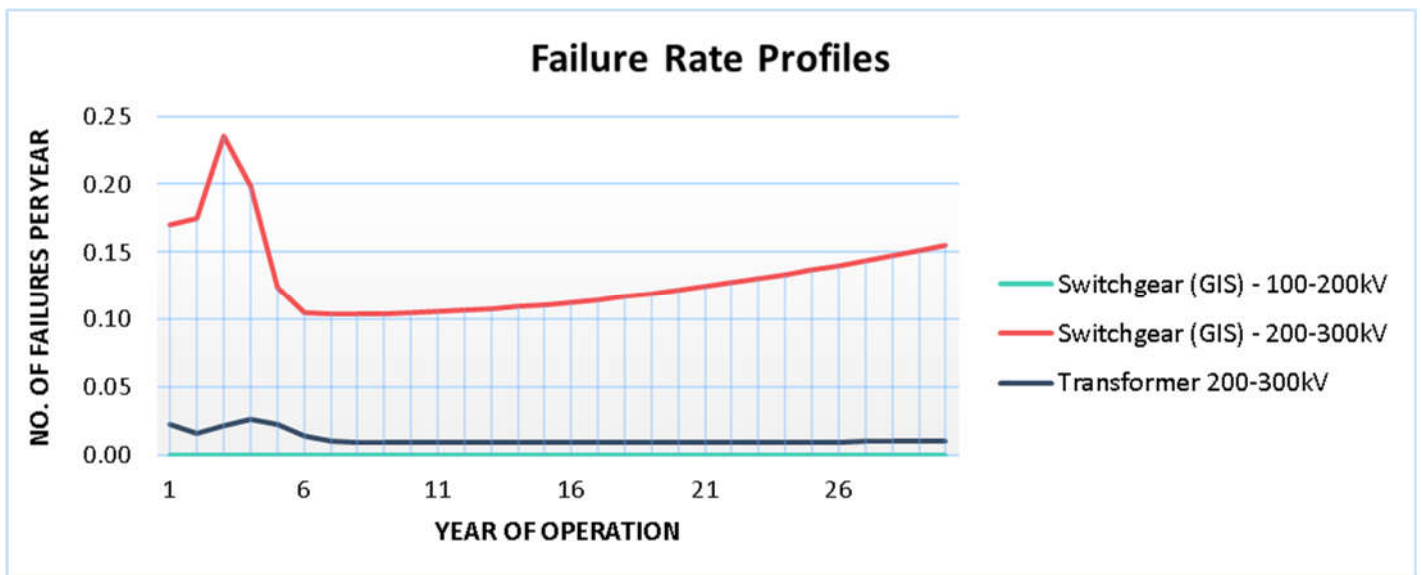


Figure 33 - Calculated Failure Rate Profiles for MOS Platform Main Components

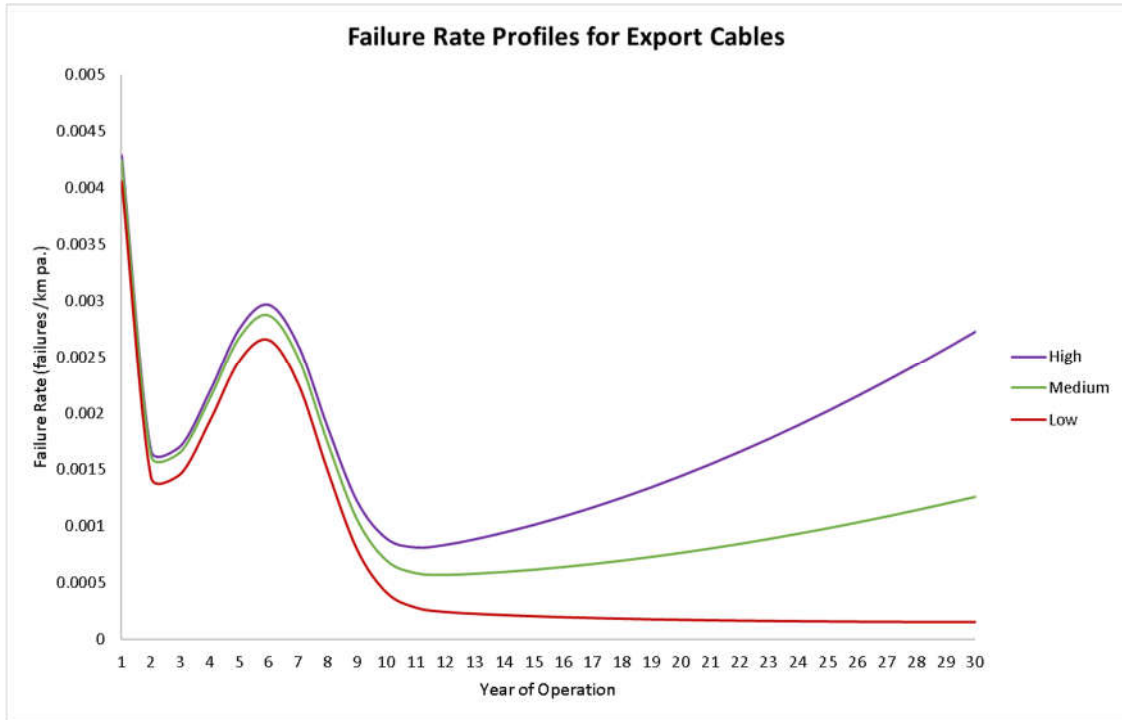


Figure 34 - Calculated Failure Rate Profiles for Export Cables

General Maintenance Requirements

As part of this study an overview of the general or “day-to-day” maintenance required for the MOS platform has been summarised. These tasks have been broken down into planned/ scheduled maintenance and corrective/ reactive maintenance.

The majority of general maintenance can be conducted from the project CTV; however, some tasks may need additional vessels to be mobilised (for example, ROVs would be required for subsea inspections).

Table 28 below provides an overview of the scheduled maintenance tasks required for an offshore transmission system. Approximately, 40 days would be required annually to complete the below scheduled maintenance tasks. However, certain tasks, such as subsea inspections would not require the platform to be de-energised so would not impact the system availability. Additionally, scheduled maintenance tasks should be planned to be completed simultaneously again reducing impact to system availability. Approximately, 380 technician hours should be accounted for annually for scheduled maintenance.

Table 28 - Scheduled / Planned Maintenance Requirements for an Offshore Substation

Asset	Activity	Frequency
MOS Platform	Routine inspection of transformers & circuit breakers	Annually
	Routine inspection of secondary & auxiliary systems, firefighting & life-saving equipment, switchgears, and cleaning	Quarterly
	Topside structure inspection, incl. handrails, grating, lighting, navigational aids	Annually
	Inspection of lifting equipment & anchor points	Semi-Annually
	General maintenance following inspections, i.e., oil replacement, mechanical works, filter	As required



Asset	Activity	Frequency
	replacements, sealing replacements, coolant top-up, etc.	
Jacket Foundation	Below waterline inspection of foundation, by ROV	Initially, on an annual basis then at pre-defined intervals
	Above waterline inspection, by drone or rope access technicians	Initially, on an annual basis then at pre-defined intervals
	Inspection of cable hang-offs, fall arrest systems & davit cranes	Semi-Annually
	Davit crane scheduled servicing	As per manufacturer's guidelines
	Marine growth/ Guano cleaning	3 years or as required
	Corrosion analysis/ corrosion protection system inspection	Annually
	Planned repairs, i.e., painting BLS	As required, based on inspections
Onshore Substation	Routine inspection of main components	Annually
	Routine inspection of building and exterior compound	Quarterly
Export Cable	Cable survey by ROV (incl. cable end & entry, j-tube, pile, scour) – this can be in tandem with the foundation ROV survey	Initially, on an annual basis then at pre-defined intervals

There are a significant number of corrective/ reactive maintenance tasks that may be required throughout the operating phase of the project. A non-exhaustive list of reactive maintenance events is provided below.

Following review of data published by NGESO for offshore transmission systems c. 1-3 reactive maintenance campaigns can be expected on an annual basis. Excluding the impact of weather 12 hours of downtime should be accounted for each reactive maintenance event. This duration will vary depending on the extent of the reactive maintenance event and whether the root cause can be easily identified.

Table 29 - High-level overview of potential reactive maintenance events

Asset	Reactive Maintenance Events
MOS Platform & Onshore Substation	Circuit breaker replacement, SF6 leak repair, earthing repairs, transformer repairs, fault location, bushing repair, tap changer repair/ replacement, minor switchgear repair, battery/ UPS failure, protection relay failure, trip coils (circuit breaker) failure & fuse failure, lightning strike, etc.
Foundation	Coating damage repair, repair/ replacement of BLS or access ladder, replacement of corrosion protection anode, navigational aid failure, davit crane repair, fall arrest system repair, j-tube repairs, etc.
Cables	Termination defect, cable fault finding, over trawl investigation, rock dumping/ mattressing, cable reburial, cable repair with subsea joint, cable protection system repair or replacement, etc.



8.2 OPEX and Availability Modelling

8.2.1 Approach & Methodology

To complete the OPEX and availability modelling, the Vekta Group in-house O&M model was used. This model allows for bottom-up cost and availability estimates to be created for numerous scenarios. Figure shows an overview of the modelling process.

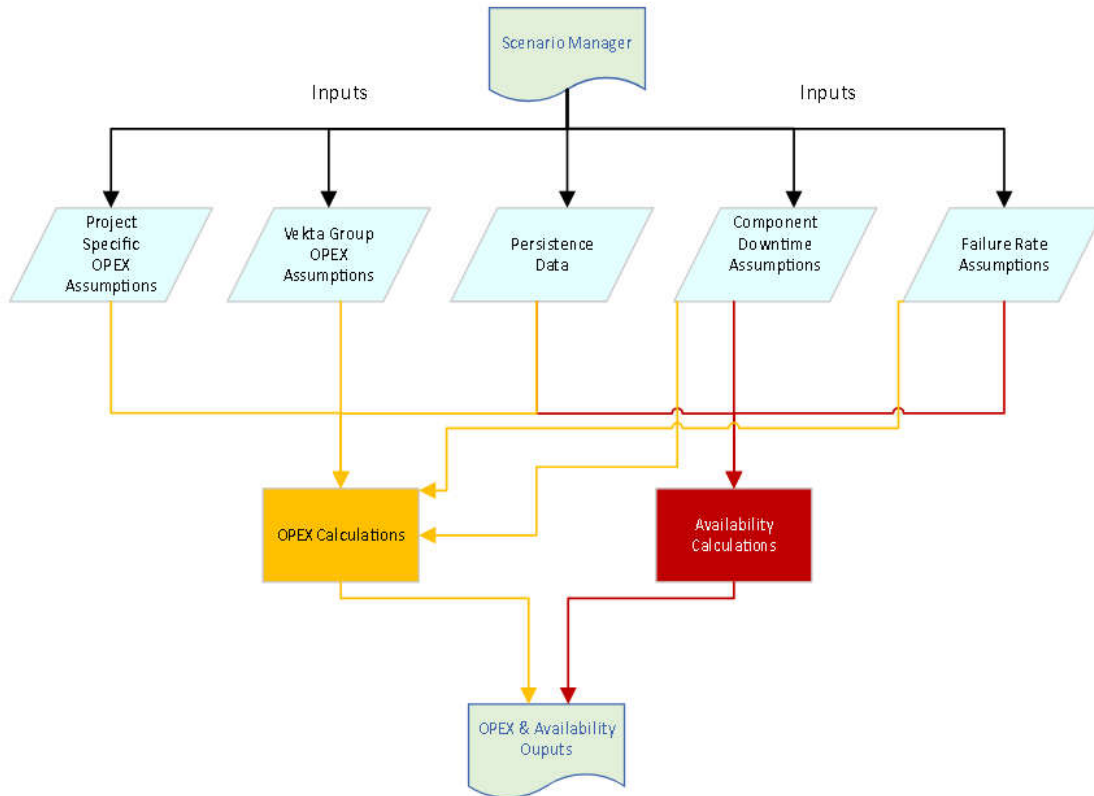


Figure 35 - Vekta Group O&M Modelling Approach

It should be noted that the O&M model uses a stochastic method to determine in which month component reactive maintenance and major component failures will occur. These then feed into both the availability and OPEX calculations to ensure that the persistence data is applied accurately within the model. This also explains why similar scenarios may have variations in their availability percentages.

Availability calculations within the model are done on a production-based calculation. The following formula is used to determine the production-based availability of the MOS platform & export cable:

$$Availability = \frac{Total\ MWh\ system\ is\ capable\ of\ delivering - MWh\ unavailable}{Total\ MWh\ system\ is\ capable\ of\ delivering} \times 100\%$$

Three scenarios were modelled to provide a range of possible availabilities of the MOS transmission system. The following scenarios were modelled:

- 1 A worst-case scenario where all transmission capability of the system is lost per maintenance event;
- 2 A scenario where 50% of the systems transmission capability is lost per maintenance event; and
- 3 A scenario where transmission capability of one of the systems export cables is lost per maintenance event.



The availability modelling has been done assuming a N-1 grid connection at Pembroke, which means the grid shall be capable of experiencing an outage without causing loss in electricity supply. It should be noted that this assumption may not reflect the grid connection that is offered to the project and it is recommended that further studies are carried out to the transmission availability for alternative connection arrangements, such as, N-2.

A base case scenario (scenario 1) was built in the model, which for the purpose of modelling was chosen to be the 220kV Aluminium single circuit connection at Freshwater West. Additional variations to include the Greenala Point landing as well as 2x 220kV circuits. The inputs used to build up this scenario were based on the outputs from the access & egress study, as well as the maintenance requirements study.

In the O&M model the assumptions for each of the above scenarios were amended to reflect the number & size of HV equipment, based on the system design as per the scenario SLD.

8.2.2 Assumptions

From , above, several assumptions are utilised within the O&M model. An overview of the basis for each is provided below:

- Project Specific OPEX Assumptions – these assumptions are cost inputs that would be specific to each scenario, i.e., OPEX allowance for general spare components, cable storage costs, O&M base OPEX.
- Vekta Group OPEX Assumptions – these assumptions are for costs that would be considered “generic” to all scenarios and are based on quotes received by Vekta Group for these services (such as provision of marine coordination, vessel charter) or from Vekta Group’s benchmarks for these activities (such as MOS platform HV servicing contract, SAP day rate, CTV day rate).
- Persistence Data – the persistence data in the model is used to determine the percentage accessibility to the assets for each month during the operational phase of the project. The persistence data was calculated, using Vekta Group’s Persistence Calculator. The hindcast data provided by CSP for the PDZ area (ref: “*ERA5 Dataset*”) was used to calculate the persistence data. P50 data was used for all scenarios.
- Component Downtime Assumptions – for non-major components corrective/ reactive maintenance downtime assumptions have been applied based on benchmarks following review of OFTO asset downtimes for offshore wind, as published by NGENSO. For annual servicing benchmark servicing times for OFTO assets has also been used.
- Failure Rate Assumptions – for main components (transformers, switchgears, shunt reactors, and export cables specific failure rates have been calculated based on the outputs of the ARM study. The system failure rates vary for each scenario based on number of components and length of export cable.

The following key assumption were made for all scenarios modelled:



Table 30 - O&M Model Key Assumptions

Parameter	Assumption	Justification
COD	Q2 2028	As per Basis of Design [1]
Operating Life	30 years	As per Basis of Design [1]
Logistics Concept	1x 12 PAX CTV (1.5m Hs transfer capability) BLS & Davit Crane for access/ egress	Based on the outcome of the logistics concept cost-benefit assessment [22]. Additionally, a risk averse approach was taken to avoid using novel systems as part of the project logistics strategy.
O&M Port	Milford Haven	This port was selected due to its proximity to site (c. 40km), ambition to support offshore renewables project in the Celtic Sea, and with Welsh local content being a key focus for the MOS project.

8.2.3 Results

From Table 31 below, it can be seen that there is minimal difference between the different scenarios from an OPEX point of view. This is mainly due to the minimal difference in electrical equipment required and the relatively short export cable, which is normally a main cause of OPEX expenditure when a failure occurs. It should also be noted that the jump up to 275kV from a 220kV system will have minimal impact from an OPEX perspective.

Table 31 - OPEX Results

O&M Model Scenario	1	2	3	4
Description	400MW Single Platform Freshwater-LP 220kV AI	400MW Single Platform Freshwater-LP 2x220kV AI	400MW Single Platform Greenala-LP 2x220kV AI	400MW Single Platform Greenala-LP 220kV AI
Connected Capacity (MW)	400	400	400	400
Total OPEX (£'000):	112,682	112,994	112,994	113,531
Ave. OPEX pa. (£'000):	3,756	3,766	3,766	3,784
Total OPEX /MW (£'000):	281.70	282.48	282.48	283.83
Ave. OPEX /MW pa. (£'000):	9.39	9.42	9.42	9.46
Ave. Export Cable Availability	99.73%	99.97%	99.97%	99.73%
Ave. Total Availability	98.5%	98.7%	98.7%	98.5%

The jump to 275kV from 220kV is not likely to have any significant impact on the availability, but with condition monitoring and cable repair frameworks in place, a single circuit 275kV solution would similarly be over the 98.5% availability target.

There is an improvement to the availability through using two export circuits. For this it was assumed that the capacity factor of the site will be 56%, which is typical for a wind farm in this area. Therefore if just one of the export cables fails then on an average day, there will only be a drop in export capability of 6%, hence the high export cable availabilities for the two circuit systems.



It is also important to note that there will be a warranted availability of 98% imposed as part of the OFTO agreement. This means that the OFTO agrees to keep the availability above this level for any given year, and if it fails to do so, a mechanism will reimburse the owners through liquidated damages. However, the target availability figure should be higher than this. The last two years of OFTO availability reporting has seen an average availability of 99.3%. The majority of downtime is associated with cable failures, with cable failures accounting for 75-80% of the industries cost of insurance claims. Of these, the failures are predominantly due to faulty installation, a full breakdown is given in Figure 36.

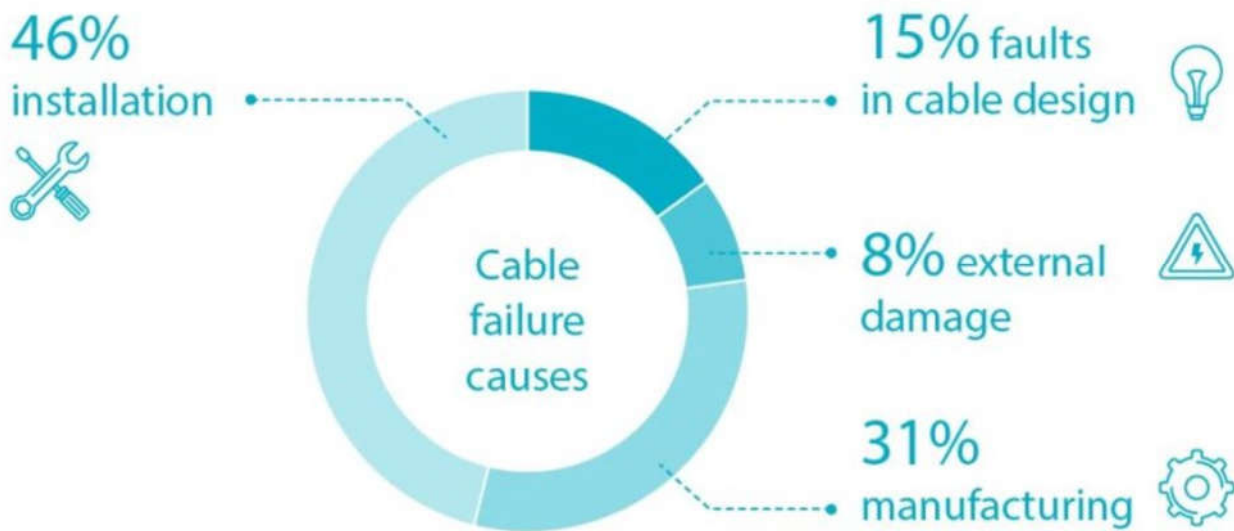


Figure 36 - Cable Failure Root Cause Analysis Breakdown

If this project wants to achieve an availability like such as the OFTO average or greater a thorough preventative maintenance schedule should be put in place. Preventative maintenance for the export cables this should include regular Distributed Temperature Sensing and Distributed Acoustic Sensing to measure the internal health of the cable. Similarly regular cable route surveys should be done along the length of the cable(s) to check for any free-spanning sections or potential exposure. For the transformer, online dissolved gas analysis can be used to continuously monitor the health of a transformer by monitoring the transformer oil, with the rate of change of gas indicating the severity of any faults.

8.3 Generator Maintenance Requirements

Below is a high-level overview of the maintenance requirements for generators that could potentially connect into the MOS platform.

8.3.1 Floating Offshore Wind Farm

- **Scheduled Maintenance:** annual maintenance/ pre-planned maintenance campaigns, usually conducted over the summer/ low wind months. These tasks are usually carried out in accordance with the WTG Equipment Manufacturers (OEM's) O&M manual.
- **Statutory Inspections:** inspections of lifting, anchor points, fall-arrest systems, etc. undertaken by a qualified engineer who will provide an inspection certificate. These inspections tend to be conducted on a 6 monthly or annual basis.



- **Preventative Maintenance:** maintenance tasks performed at routine intervals or based on analysis of condition monitoring data. Preventative maintenance checks can be completed as specified by the OEM or on an ad-hoc basis.
- **Reactive Maintenance:** performing maintenance tasks to troubleshoot & remedy issues on the WTG as and when they occur. This could be due to failure of blade pitch system, failure of hydraulic system, investigation of alarm, attending the WTG as 3 remote resets have had to be performed within an agreed period of time.
- **Major Corrective Works:** performing large component exchanges, such as, blades, generators, gearboxes, mooring line repair/ replacement etc. These campaigns for floating wind either require the asset to be towed-to-shore or a specialist lifting vessel be deployed to site to complete the task.
- **Retrofit/ Upgrade campaigns:** completion of hardware retrofit or upgrades, or SCADA system updates that are intended to improve safety, performance, and/ or servicing requirements of the WTGs.

8.3.2 Floating Solar

- **Scheduled Maintenance:** key aspects of scheduled maintenance for solar farms are cleaning the panels and annual servicing. The frequency of cleaning is dependent on-site conditions, such as, precipitation, humidity, wind velocity, particle type and source of particles. Annual servicing includes tasks, such as, inspection of photovoltaic (PV) modules, mountings, inverters, electric boards, transformer, medium voltage & HV facilities, and monitoring systems.
- **Preventative Maintenance:** as per WTG preventative maintenance requirements. The majority of preventative maintenance tasks are associated with inverters. General preventative maintenance tasks include inspections, cleaning, repairs, adjustments & replacement of parts, testing of electrical connections.
- **Reactive Maintenance:** similarly, to wind farms these tasks involve troubleshooting and remedying defects. These events can be caused by SCADA alarms, overheating of components (leading to damage), damage to wiring, repair to or replacement of a component on transformer, inverter, etc.
- **Major corrective works:** compared to wind energy, solar has less onerous major corrective work requirements, however, examples of these sort of maintenance tasks would be complete replacement of a panel or inverter system. These campaigns would also have lesser logistical requirements. Mooring line repair/ replacement would be similar to the requirements for a floating wind farm.
- **Retrofit/ Upgrade campaigns:** completion of hardware retrofit or upgrades, or SCADA system updates that are intended to improve safety, performance, and/ or servicing requirements of the solar panels.

8.3.3 Tidal Turbines

- **Scheduled Maintenance:** depending on whether the tidal turbine is fully or partially submerged dictates how frequently scheduled maintenance occurs. This tends to be annually for fully submerged devices and semi-annually for partially submerged devices. Tasks include inspection of electrical components, corrosion protection systems, turbines, blades, critical installations, cleaning of device (incl. removal of marine growth), checking oil levels , etc.
- **Preventative Maintenance:** as per WTG preventative maintenance requirements. Tasks include, maintenance of electronics, pumps, valves, piping, etc. Additionally, overhaul campaigns may be carried out at pre-defined intervals, exchange of brake discs, bearings, sealings, corrosion protection, etc.
- **Reactive Maintenance:** troubleshooting and rectification works that are required for tidal turbines include, investigating alarms from SCADA/ condition monitoring system (CMS), failure of hydraulic system, pitch systems, etc, replacements of bearings, sensors, etc.



- **Major Corrective Works:** major corrective works for tidal turbines include activities such as, blade exchanges, gearbox exchange, generator replacement, mooring line section repairs/ replacement. For these campaigns the turbine tends to be disconnected from the array and towed to a sheltered area to complete the task.
- **Retrofit/ Upgrade campaigns:** completion of hardware retrofit or upgrades, or SCADA system updates that are intended to improve safety, performance, and/ or servicing requirements of the tidal turbines.

8.3.4 Wave Energy Converters

- **Scheduled Maintenance:** as with the other devices, wave energy converters will require scheduled maintenance to be completed on a periodic basis. This tends to be done on an annual basis and includes inspection of the asset, i.e., wave energy converter, mooring line, umbilicals, etc. and exchange of components as per the OEM guidance.
- **Preventative Maintenance:** similarly, to the other devices described above preventative maintenance may be carried out on wave energy converters at pre-determined intervals or based on data received for the devices condition monitoring system.
- **Reactive Maintenance:** troubleshooting and rectification works may include tasks, such as, repair of hydraulic, cooling or lubrication systems, investigating SCADA alarms, etc.
- **Major Corrective Works:** for a wave energy converter these include campaigns to repair or replace sections of mooring line, gearbox replacement, flywheel, generator, etc.
- **Retrofit/ Upgrade campaigns:** completion of hardware retrofit or upgrades, or SCADA system updates that are intended to improve safety, performance, and/ or servicing requirements of the tidal turbines.



9 CAPEX Estimates

To assist with a techno-commercial evaluation of the scenarios considered as part of this concept study, CAPEX estimates have been prepared based on each of the scenarios and the costs are broken down into the following sub-sections:

- Landfall point
- Cable supply
- Cable installation
- SCADA design and supply
- Onshore Substation
- Offshore Substation Topside
- Offshore Substation Structure
- Spares and mandatory options.



9.1 CAPEX estimate – Cable routes

The following table shows difference in export cable CAPEX (cable material, installation, and reactors) for the two landfall options:

Table 32 Export cable CAPEX relative to landfall options

Case Cable Size, Conductor Material and Voltage	Landing Point name	Freshwater West	Greenala Point
	Onshore route, km	7.28	9.71
	Offshore route, km	32.01	38.07
	Total, km	39.30	47.78
2 x 400 Al 220kV	Cable material cost, £	£34,520,834	£41,974,029
	Cable installation cost, £	£13,459,566	£14,449,044
	Reactors, cost, £	£1,813,763	£1,912,318
	Export system CAPEX, £	£49,794,163	£58,335,390
1400 Al 220kV	Cable material cost, £	£27,330,682	£33,183,611
	Cable installation cost, £	£11,221,337	£11,071,607
	Reactors, cost, £	£986,159	£1,046,767
	Export system CAPEX, £	£39,538,178	£45,301,985
1000 Cu 220kV	Cable material cost, £	£37,724,699	£45,803,532
	Cable installation cost, £	£11,221,337	£11,071,607
	Reactors, cost, £	£956,159	£1,011,507
	Export system CAPEX, £	£49,902,195	£57,886,645
800 Al 275kV	Cable material cost, £	£22,260,977	£27,028,217
	Cable installation cost, £	£11,221,337	£11,071,607
	Reactors, cost, £	£990,203	£1,061,410
	Export system CAPEX, £	£34,472,517	£39,161,234
500Cu 275kV	Cable material cost, £	£26,694,362	£32,411,021
	Cable installation cost, £	£11,221,337	£11,071,607
	Reactors, cost, £	£906,882	£982,059
	Export system CAPEX, £	£38,822,580	£44,464,687



9.2 Offshore Cable Installation – Programme Schedule

This section sets out the estimated project schedule for the installation of the export cables, for this the 2x 400AI 220kV case and the 1400AI case were both simulated with a landfall at Freshwater West. For these simulations, Vekta Group’s in-house cable construction planning tool was used to determine the durations and weather downtime for activities based on ERA5 data at the nearest datapoint to the activity site.

Figure 37 below shows the expected installation duration for the 2x 400AI 220kV case. The activities in installing an export cable such as this with just a single cable laying vessel require that most activities need to be carried out sequentially. It is assumed that the installation would begin on the 1st of April and be concluded on the 17th of May, making the total duration 46 days. This is subject to change however based on the starting date, with the summer months being more likely to have significant windows of good weather which would decrease the expected duration, and visa-versa, construction during the winter months would extend the duration.

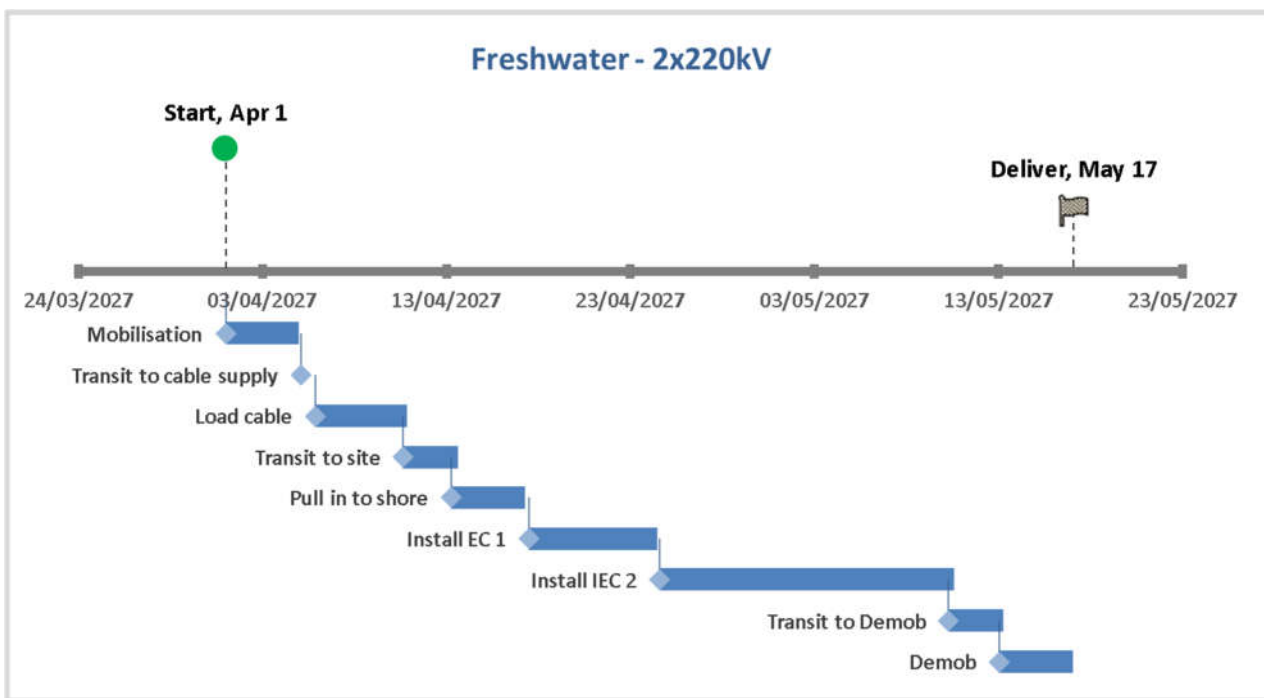


Figure 37 - Installation schedule for the 2x 400AI 220kV export cables

A breakdown of the impact of weather on these activities is given in Figure 38, here it can be seen that the installation of the cable is the most susceptible to bad weather. This cable installation activity includes the pull in to the HDD termination, launching and retrieving the cable plough, and installing the cable (simultaneous lay and bury is assumed)

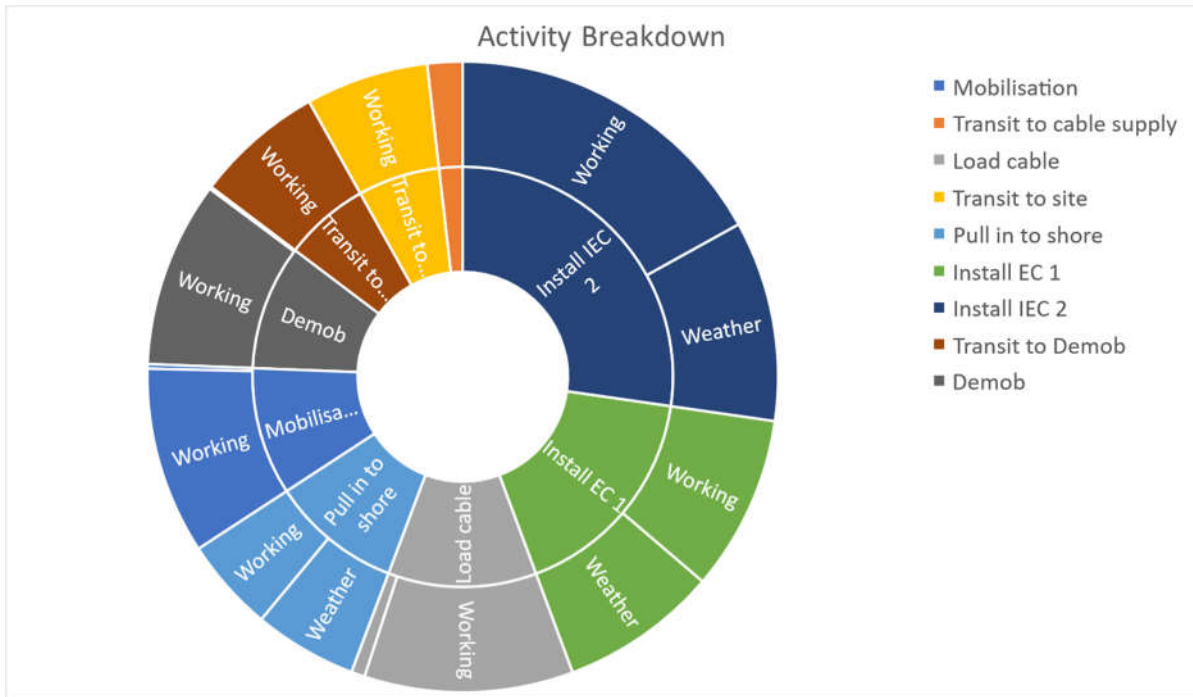


Figure 38 - Activity breakdown for 2x 400AI 220kV offshore cable installation

The next set of figures show the same results for a single cable scenario, in this case that is for the 1400AI 220kV export cable with the programme schedule shown in Figure 39.

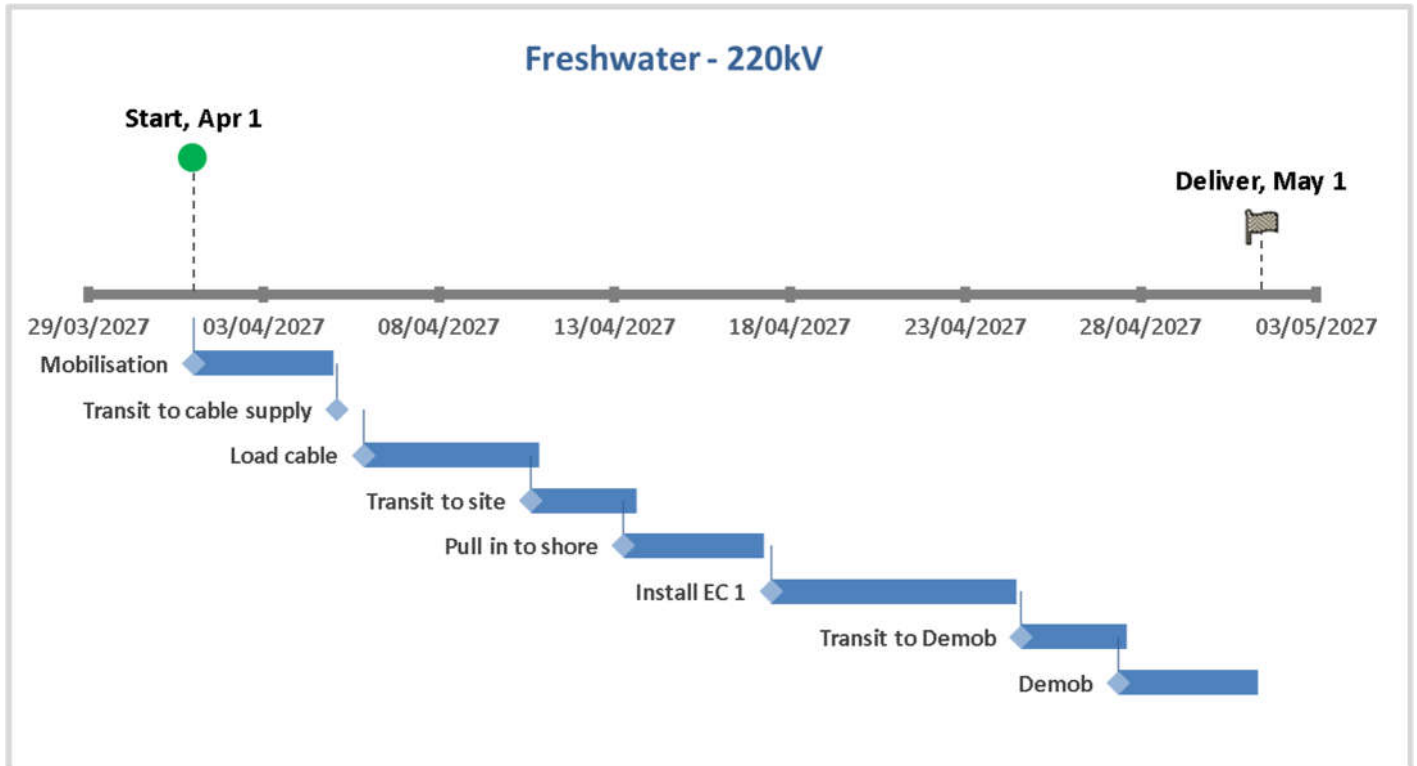


Figure 39 - Installation schedule for the 1400AI 220kV export cable



9.3 CAPEX estimate – Primary Costs

The CAPEX estimates for each scenario based on the primary components are displayed in Table 33. Cable material cost is calculated based on the cable composition, labour cost, and energy intensity for manufacturing cost. This is then correlated against recent vendor quotes for similar cables (tuning for profit margins). The cable installation costs was based on Vekta Group’s internal construction tool. This tool accounts for the total cable that can be loaded onto the cable laying vessel and, the vessel mobilisation, loadout, transit, installation and localised weather downtime based on P50 hindcast data. For this, it was assumed that a suitable multi-purpose vessel was used in a simultaneous lay and bury process, with our calculations showing that all the cable for each loadout can be done with a single loadout. The SCADA design, onshore & offshore substation, and the spares & mandatory options costs were all estimated based on quotation from OEMs for similar sized projects.

Table 33 CAPEX estimate based on primary components

Case Name	Cable Material Cost (£)	Cable Installation Cost (£)	SCADA, Design, etc (£)	Onshore Substation (£)	Offshore Substation (£)	Offshore Substation Structure (£)	Spares & Mandatory Options (£)	Total CAPEX (£)	Total CAPEX (£/MW)
400MW MOS Freshwater-LP 2x220kV Al	34,520,834	13,459,566	4,132,342	45,400,000	44,563,615	20,867,536	5,360,252	168,304,145	420,760
400MW MOS Freshwater-LP 220kV Al	27,330,682	11,221,337	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	158,075,764	395,189
400MW MOS Freshwater-LP 220kV Cu	37,724,699	11,221,337	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	168,469,781	421,174
400MW MOS Freshwater-LP 275kV Al	22,260,977	11,221,337	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	153,006,058	382,515
400MW MOS Freshwater-LP 275kV Cu	26,694,362	11,221,337	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	157,439,444	393,599
400MW MOS Greenala-LP 2x220kV Al	41,974,029	14,449,044	4,132,342	45,400,000	44,563,615	20,867,536	5,360,252	176,746,817	441,867
400MW MOS Greenala-LP 220kV Al	33,183,611	11,071,607	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	163,778,963	409,447
400MW MOS Greenala-LP 220kV Cu	45,803,532	11,071,607	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	176,398,883	440,997
400MW MOS Greenala-LP 275kV Al	27,028,217	11,071,607	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	157,623,568	394,059
400MW MOS Greenala-LP 275kV Cu	32,411,021	11,071,607	4,132,342	45,000,000	44,163,615	20,867,536	5,360,252	163,006,373	407,516



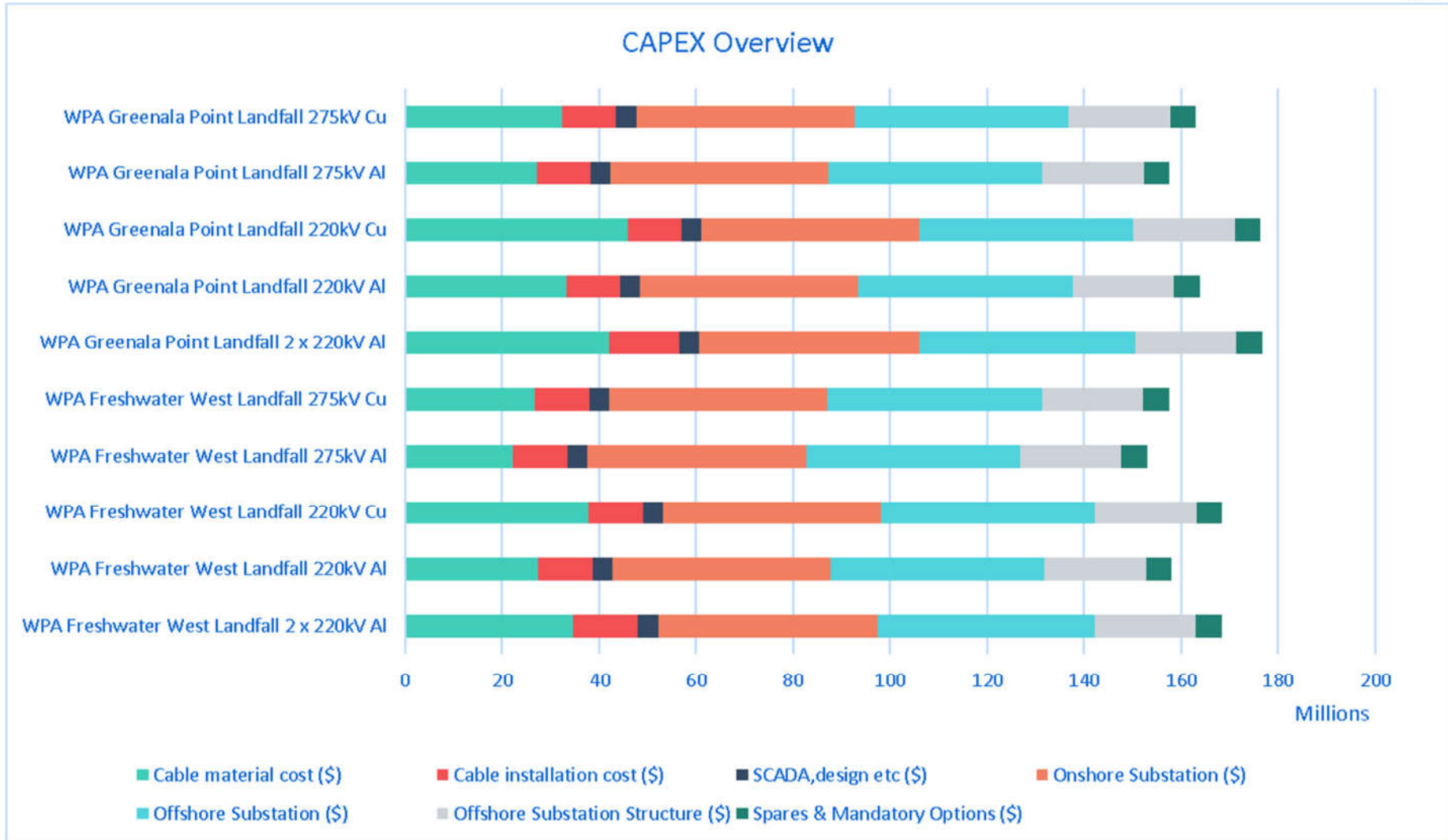


Figure 41 – CAPEX Overview – All Scenarios



10 Project life costs (CAPEX & OPEX)

Table 34 presents the lifetime costs for the project, including the CAPEX and OPEX. This allows for a full comparison between different operating voltages and circuit numbers. The highlighted row indicates the lowest total whole life costs scenario.

Table 34 Summary lifetime costs for all scenarios

Case Name	Total CAPEX (£)	Total CAPEX (£/MW)	Total OPEX for 30-year life (£)	Total average OPEX pa. (£/year)	Total whole life cost (£)	Lifetime cost/MW (£/MW)	Availability (%)
400MW MOS Freshwater-LP 2x220kV Al	167,504,145	418,760	112,994,000	3,766,000	280,498,145	701,245	98.7
400MW MOS Freshwater-LP 220kV Al	158,075,764	395,189	112,682,000	3,756,000	270,757,764	676,894	98.5
400MW MOS Freshwater-LP 220kV Cu	168,469,781	421,176	112,682,000	3,756,000	281,151,781	702,879	98.5
400MW MOS Freshwater-LP 275kV Al	153,006,059	382,515	112,682,000	3,756,000	265,688,059	664,220	98.5
400MW MOS Freshwater-LP 275kV Cu	157,439,444	393,599	112,682,000	3,756,000	270,121,444	675,304	98.5
400MW MOS Greenala-LP 2x220kV Al	175,946,818	439,867	112,994,000	3,766,000	288,940,818	722,352	98.7
400MW MOS Greenala-LP 220kV Al	163,778,963	409,447	113,531,000	3,784,000	277,309,963	693,275	98.5
400MW MOS Greenala-LP 220kV Cu	176,398,884	440,997	113,531,000	3,784,000	289,929,884	724,825	98.5
400MW MOS Greenala-LP 275kV Al	157,623,569	394,059	113,531,000	3,784,000	271,154,569	677,886	98.5
400MW MOS Greenala-LP 275kV Cu	163,006,373	407,516	113,531,000	3,784,000	276,537,373	691,343	98.5



10.1 CAPEX and OPEX summary

As can be seen from Table 34, there is a distinct indication that one export cable landing at Freshwater West has a lower whole life cost. However, it should be noted that this cost analysis does not take into consideration the availability calculation relative to potential generation profile / capacity factor for connected wind farms along with penalty charges associated with the OFTO regime. Furthermore, the redundancy profile, spare export capacity and the ability to operate the export cables dynamically along with transformers at their emergency rating could mitigate some availability loss at specific times of the year but a more detailed model is recommended during Pre-FEED stage works.

Scenario **400MW MOS Freshwater-LP 275kV AI** has the lowest whole life costs, fewer losses than the 220kV scenarios and fits the minimum availability requirements for an OFTO asset. It has therefore been used for the cost benefit analysis in the following section of this report.

11 Cost benefit analysis

Once the concept design and CAPEX model was constructed for the 400MW PDZ MOS, a second stage analysis was conducted on 4 x 100MW independent floating projects. This is to meet the project objective of comparing the costs of a stepped coordinated 400MW project (4 x 100MW) with 4 x 100MW independent generation projects. To allow a direct comparison of costs, the independent generation projects are considered within the PDZ region with either a connection being standalone to an onshore PCC or, via a single offshore connection to the MOS.

11.1 Independent radial projects

For the purpose of the Cost Benefit Analysis (CBA), the 4 x theoretical 100MW independent floating projects and the MOS have been modelled based on the technical assumptions shown in Table 35, which are also visually represented in Figure 42.

Table 35 – Zone and MOS Assumptions for CBA

Zone ID	Distance to onshore PCC (km)	Distance to MOS (km)	Voltage (kV)	Independent Connection Point
1	54	19.5	66	Pembroke
2	54	9.5	66	Pembroke
3	75.6 / 80.5	35.5	66	Pembroke / Yelland
4	38	5	66	Pembroke
MOS	39	-	275kV	Pembroke

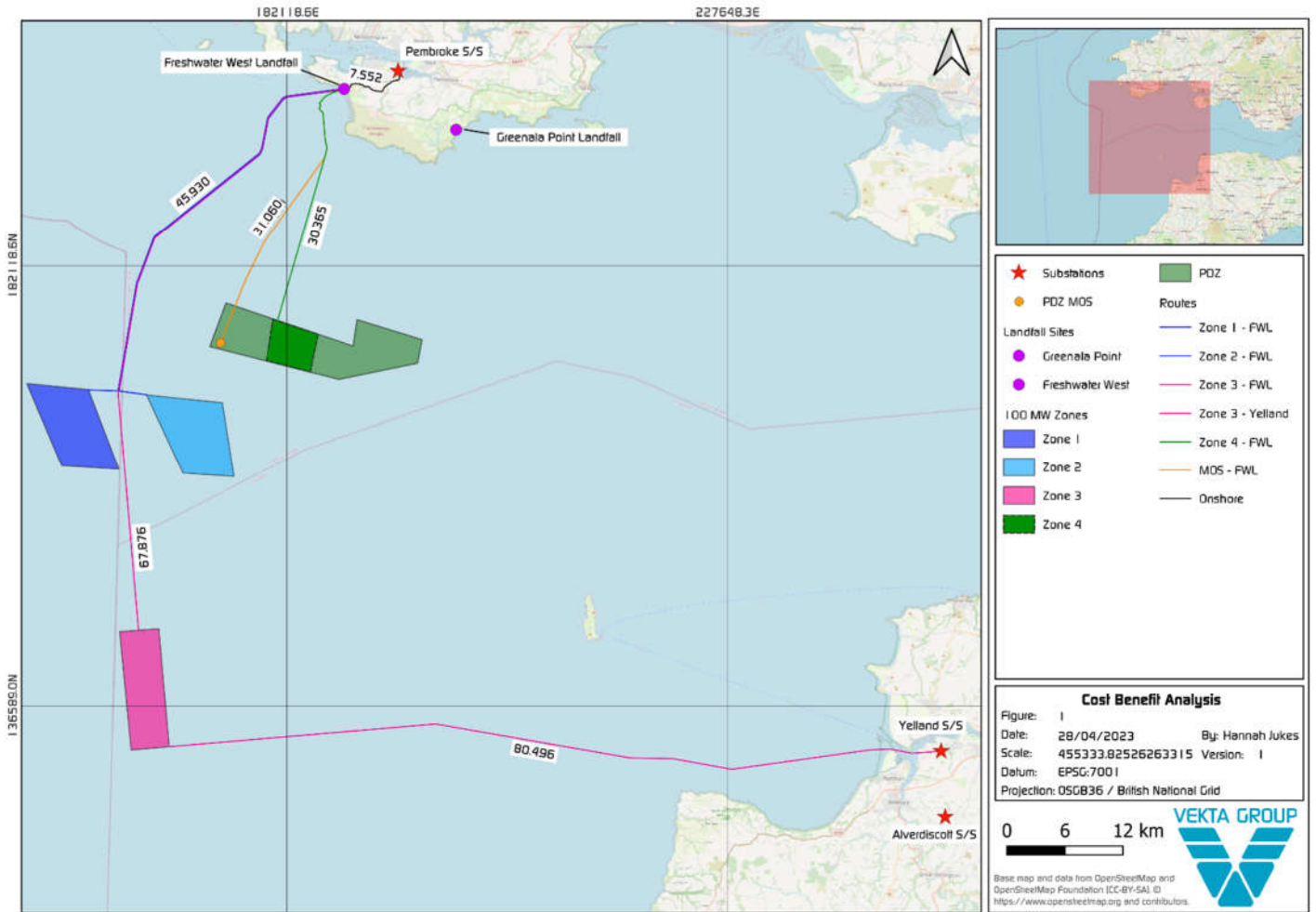


Figure 42 – Map of Zones and MOS

TNuoS charges are the same for any project connecting to Pembroke. TNuoS charges are therefore not considered to be a differentiator between each PCC at this time because the regulatory and charging mechanism related to multi-user connection to an offshore transmission system has not been defined by the regulator.



11.2 Technical assumptions

The following assumptions were made for the 4 x 100MW independent connections scenarios:

Table 36 – Assumptions for 4 x 100MW Independent Connections

Criteria	Assumptions for 4 x 100MW Independent Connections
Cable supply	1000mm ² 66kV Al export cables. Pricing from recent RFQs (2023) and using Vekta Group in-house cable pricing tool. Supplied from EU OEM.
Cable installation	Proprietary cable installation planning tool using ERA5 regional metocean data. Boskalis Ndeavour installation vessel. Using simultaneous lay and bury. Cable supply pick-up from Rotterdam. Mobilisation/demobilisation at Eemshaven. Assumes HDD cost of £2.5m for each landing.
Onshore substation	Each Zone assumed to have single-circuit 66kV/400kV substation within 2km of PCC.
Offshore substation	Not applicable.
Land rights	Land lease rights and option agreements. Total annual leasing costs for cable route and onshore substation.
Onshore consent (DEVEX)	Assumed DEVEX cost for 4 years to achieve onshore consent, based on previous experience.
Offshore consent (DEVEX)	Assumed DEVEX cost for any surveys, engineering or consenting activities relating exclusively to export cable corridor.
Connection costs (non-contestable)	Any reinforcement works or National Grid substation works in relation to the PCC.
OPEX	HV services for maintaining electrical infrastructure only. Includes 1 cable failure for Zones 1, 2 & 4 and 2 cable failures for Zone 3. Does not include WTGs or O&M Base costs.
Electrical Losses (over 30 years)	Includes electrical losses of export cables (onshore and offshore) only based on a wind farm capacity factor of 56%, using generic 4 arrays x 6 x 16MW WTGs. Onshore transformer losses are not included. Power price is £90/MWh.



The following assumptions were made for the coordinated MOS solution:

Table 37 – Assumptions for Coordinated MOS Solution

Criteria	Assumptions for Coordinated MOS Solution
Cable supply	1000mm ² Al 66kV export cable connecting each Zone to the MOS. 800mm ² Al 275kV export cable from MOS to PCC. Pricing from recent RFQs (2023) and using Vekta Group in-house cable pricing tool. Supplied from EU OEM.
Cable installation	Proprietary cable installation planning tool using ERA5 regional metocean data. Cable installation assumption costs from each Zone to MOS does not include separate mob/demob costs due to assumption that the array cable vessel for each zone would absorb the mob/demob cost for the export cable. Boskalis Ndeavour installation vessel. Using simultaneous lay and bury. Cable supply pick-up from Rotterdam. Mobilisation/demobilisation at Eemshaven. Assumes HDD cost of £2.5m for landing.
Onshore substation	MOS assumed to have single-circuit 275kV/400kV substation within 2km of PCC.
Offshore substation	Includes supply and installation of topside and foundation.
Land rights	Land lease rights and option agreements. Total annual leasing costs for cable route and onshore substation. Larger land requirement assumed for onshore substation.
Onshore consent (devex)	Assumed DEVEX cost for 4 years to achieve onshore consent, based on previous experience.
Offshore consent (devex)	Assumed DEVEX cost for any surveys, engineering or consenting activities relating exclusively to export cable corridor.
Connection costs (non-contestable)	Any reinforcement works or National Grid substation works in relation to the PCC. Assumed onshore costs are higher for MOS due to increased connection capacity. For Zones 1-4 to MOS, includes cable pull in and termination and testing.
OPEX	HV services for electrical infrastructure from each site to MOS, full OPEX for MOS to PCC. MOS is an OFTO asset and fully maintained by said OFTO.
Electrical Losses (over 30 years)	Includes electrical losses of export cables (onshore and offshore) only based on a wind farm capacity factor of 56%, using generic 4 arrays x 6 x 16MW WTGs. Onshore transformer losses are not included. Power price is £90/MWh.



11.3 Costs

Figure 43 below shows a walkthrough of the costs from the initial baseline of 4 x 100MW zones connecting independently, to utilising the 400MW PDZ MOS as a coordinated solution.

Starting at the total CAPEX cost for 4 x 100MW independent radial generation projects, the ‘decrease’ in costs represent savings by working in a coordinated approach whilst the ‘increase’ in costs represent costs directly apportioned to the PDZ MOS infrastructure.

As can be noted from Figure 43 below the overall benefit when looking collectively at 400MW of generation, is that a coordinated approach has a cost saving of £97.1M.

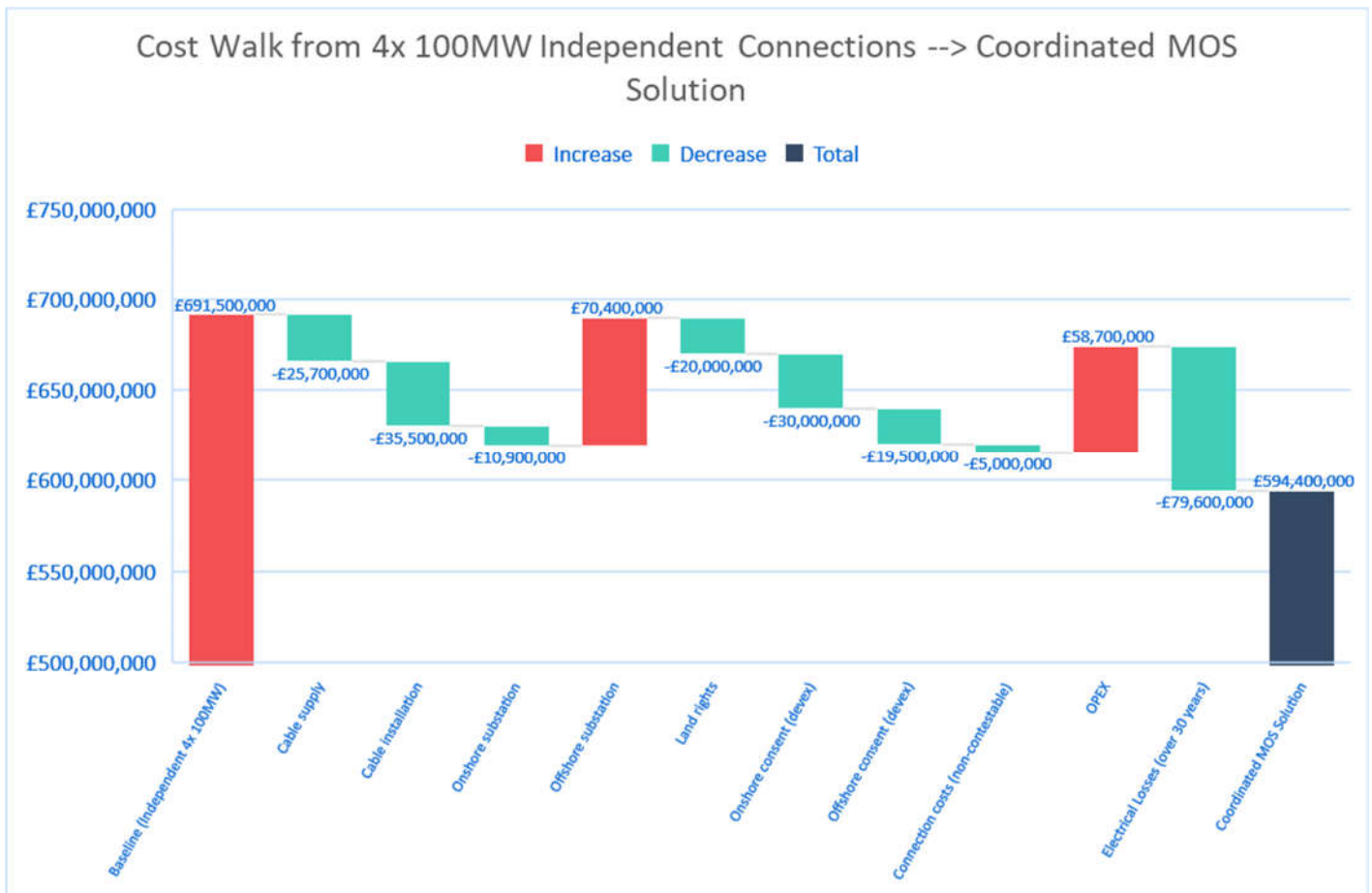


Figure 43 – Cost walk from 4 x 100MW Independent Connections to Coordinated MOS Solution



Figure 44 below shows a walkthrough of a single 100MW project (Zone 1) connecting independently through to a single 100MW project (Zone 1) connecting to the PDZ MOS as part of a coordinated approach.

Starting at the total CAPEX cost for single 100MW independent radial generation project, the ‘decrease’ in costs represent savings by connecting to the PDZ MOS.

As can be noted from Figure 44 below the overall benefit, when considering at a single 100MW generation project, is that a coordinated approach has a cost saving of £113.7m. It should be noted that this is the direct CAPEX and OPEX cost saving by the individual generation project and does not include the cost of PDZ MOS infrastructure or costs for connecting the MOS to the PCC. It is also not based on a financial model being produced for each individual project.

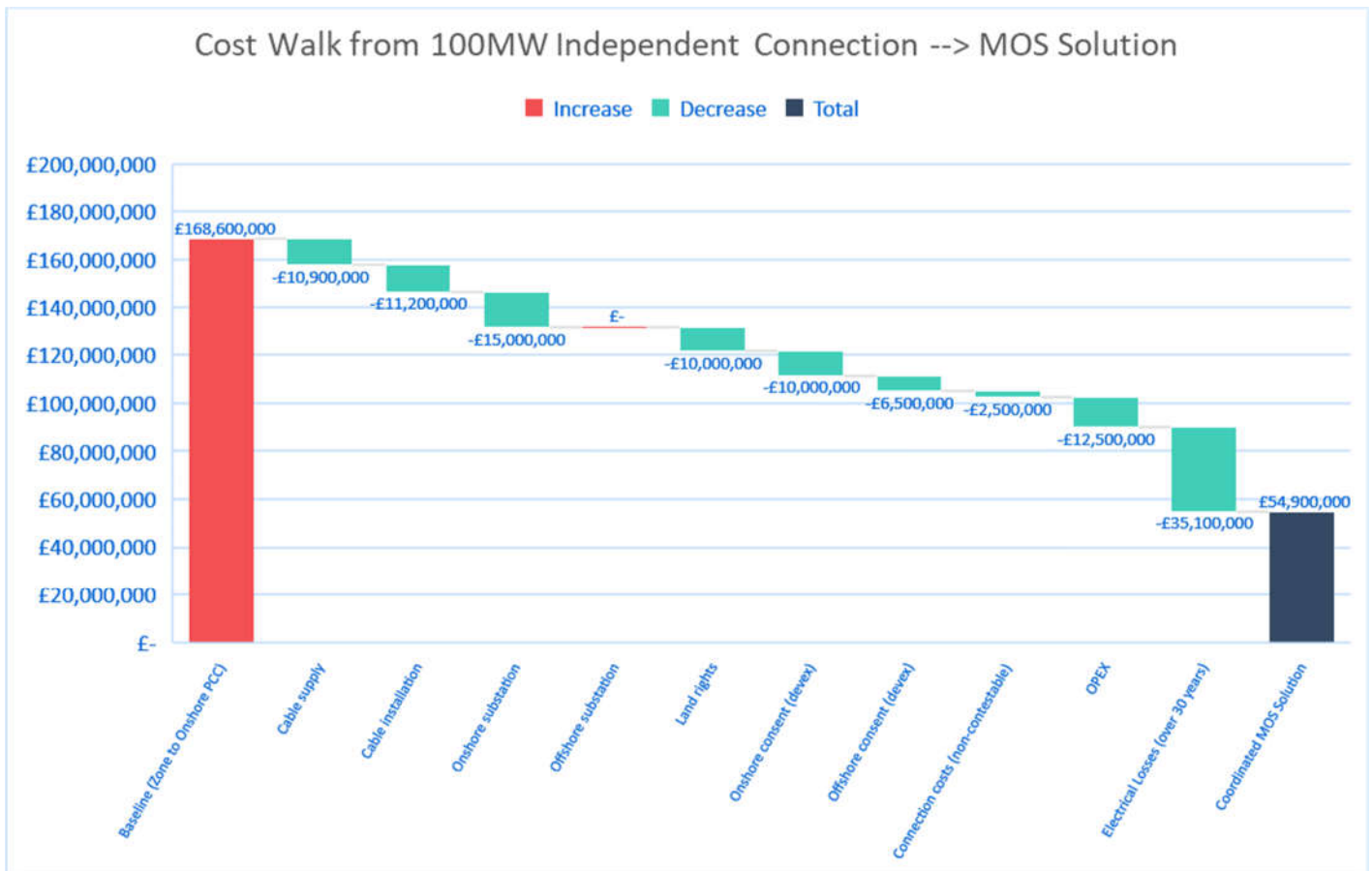


Figure 44 – Cost Walk from 100MW Independent Connection to MOS Solution



Costs in relation to connecting 4 x 100MW connections independently to respective independent onshore PCCs are detailed in Table 38 below.

Table 38 – Cost estimate for 4 x 100MW Zones to Onshore PCC

Cost Item	4 x 100MW Zones to onshore PCC (£)				
	Zone 1	Zone 2	Zone 3	Zone 4	TOTAL
Cable supply	17,100,000	17,100,000	23,900,000	12,000,000	70,100,000
Cable installation	17,300,000	17,300,000	24,000,000	12,300,000	70,900,000
Onshore substation	15,000,000	15,000,000	15,000,000	15,000,000	60,000,000
Offshore substation	-	-	-	-	-
Land rights	10,000,000	10,000,000	10,000,000	10,000,000	40,000,000
Onshore consent (DEVEX)	10,000,000	10,000,000	10,000,000	10,000,000	40,000,000
Offshore consent (DEVEX)	10,000,000	10,000,000	15,000,000	10,000,000	45,000,000
Connection costs (non-contestable)	3,500,000	3,500,000	3,500,000	3,500,000	14,000,000
OPEX	31,000,000	31,000,000	35,000,000	31,000,000	128,000,000
Electrical Losses (over 30 years)	54,700,000	54,700,000	74,500,000	39,600,000	223,500,000
TOTAL	168,600,000	168,600,000	210,900,000	143,400,000	691,500,000



Costs in relation to connection 4 x 100MW connections to the PDZ MOS and then the MOS connecting to the onshore PCC are shown in Table 39 below.

Table 39 – Cost estimate for MOS Solution

Cost Item	4 x 100MW Zones to PDZ MOS (£)				PDZ MOS	TOTAL
	Zone 1	Zone 2	Zone 3	Zone 4		
Cable supply	6,200,000	3,000,000	11,300,000	1,600,000	22,300,000	44,400,000
Cable installation	6,100,000	2,900,000	11,100,000	1,600,000	13,700,000	35,400,000
Onshore substation	-	-	-	-	49,100,000	49,100,000
Offshore substation	-	-	-	-	70,400,000	70,400,000
Land rights	-	-	-	-	20,000,000	20,000,000
Onshore consent (DEVEX)	-	-	-	-	10,000,000	10,000,000
Offshore consent (DEVEX)	3,500,000	3,500,000	5,000,000	3,500,000	10,000,000	25,500,000
Connection costs (non-contestable)	1,000,000	1,000,000	1,000,000	1,000,000	5,000,000	9,000,000
OPEX	18,500,000	18,500,000	18,500,000	18,500,000	112,700,000	186,700,000
Electrical Losses (over 30 years)	19,600,000	9,700,000	34,600,000	5,200,000	74,800,000	143,900,000
TOTAL	54,900,000	38,600,000	81,500,000	31,400,000	388,000,000	594,400,000

11.4 Conclusion

There are two key outcomes of the CBA, both of which demonstrate that the CAPEX and OPEX costs of a multi-project offshore connection are consistently lower than if each 100MW project were to connect independently to an onshore PCC:

- 1 The cost saving between a coordinated 400W PDZ MOS solution and 4 x 100MW independent projects is £97.1m.
- 2 The cost saving for each 100MW zone ranges from £110-130m, relative to DPO location. This does not include the cost of connecting the MOS to the PCC, nor the MOS infrastructure costs.

It is recommended that further investigation is conducted in Pre-FEED to obtain more detailed (higher-class) level of pricing information from the supply chain. This is to verify the cost estimates presented in this report, which are currently class 3/4, depending on the scope item (e.g. cables, substructures and substation).



12 Anticipatory investment

Following a similar approach commissioned by Ofgem, Apollo and Vekta have prepared capital expenditure (CAPEX) estimates for the independent and coordinated scenarios presented in Section 11 – based on two delivery approaches:

- Independent (Referred to as ‘Counterfactual’ by Ofgem report)
- Coordinated (Referred to as ‘Integrated’ by Ofgem report)

‘Independent’ is the current and most common approach when developing new infrastructure for offshore wind farms. This involves the development of separate single users with radial connections.

‘Coordinated’ is an approach with more than one user sharing a common offshore transmission system. Delivery models are being developed for this approach to provide greater clarity. Where collaboration is between a known and potential future user, who is entering the market at different auction rounds, Ofgem has set out the process for that to be delivered via their minded to decision on Anticipatory Investment (AI).

This approach requires the Initial User (IU) to make an anticipatory investment to develop the primary common infrastructure that will then be shared with future users to facilitate their connection. The Later User(s) (LU) will then fund the further infrastructure required for their development. The IU recovers its additional design and construction costs from the OFTO auction and ongoing liabilities, securities and risk sit with the consumer until the later user connects.

For developers who enter the same round, Ofgem are expecting them to work collaboratively on a commercial solution. However, their approach does not factor in the developing leasing round strategy to allow the delivery of floating offshore wind projects in phases. These could be subject to future regulatory amendments to enable delivery.

For this report, the assumption is that the AI cost gap and AI risk will reside with the consumer as per Ofgem’s current decision and has used the terms Initial User and Later User to describe the parties collaborating.

Figure 45 and Figure 46 below outlines the scenarios discussed in the Cost Benefit Analysis (Section 11) with the CAPEX costs only being apportioned to illustrate how an anticipatory investment case would apply.

As can be seen, based on the Initial User developing Zone 1 (refer Figure 42), the anticipatory investment is £137.4m.

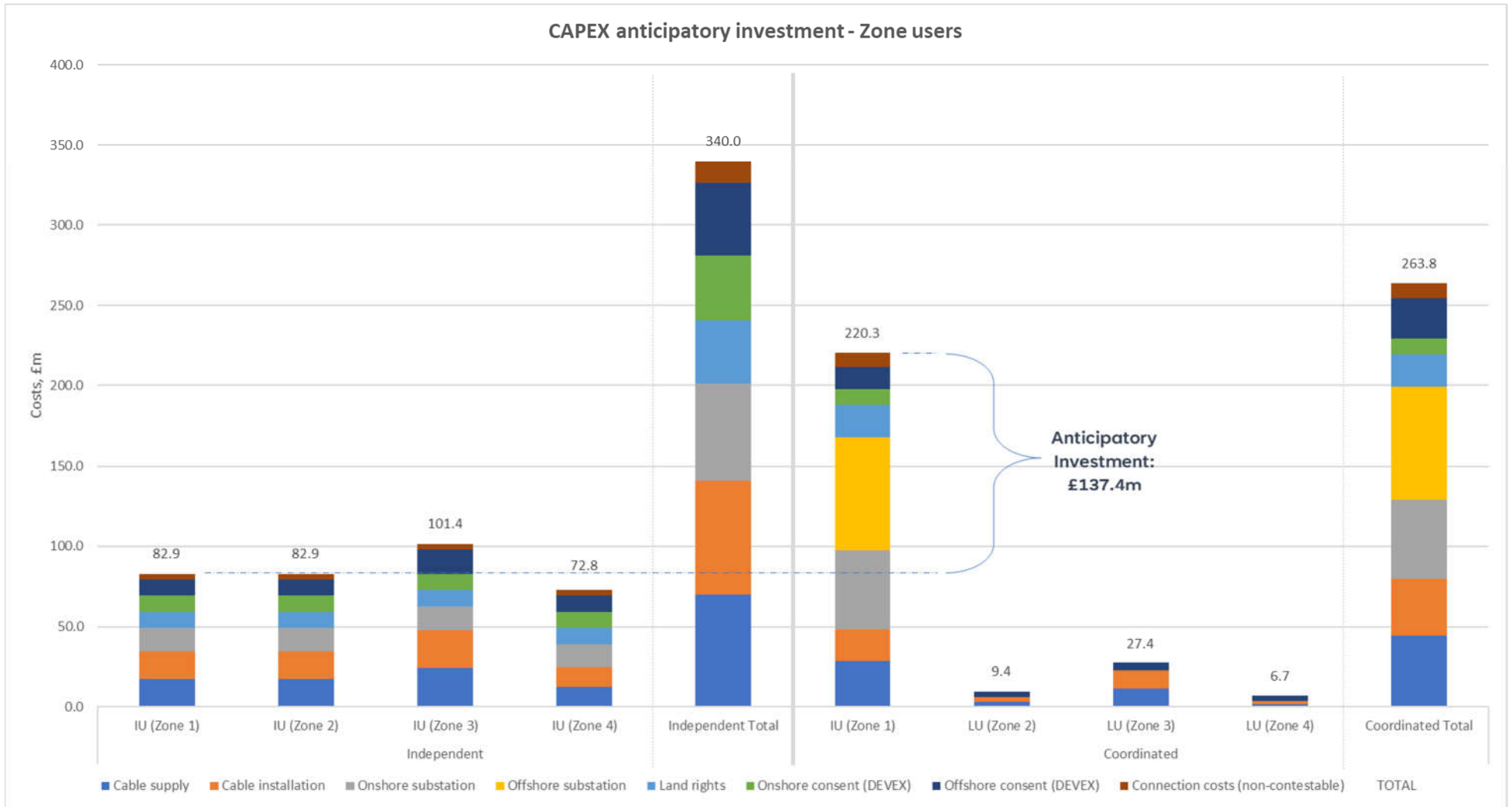


Figure 45 – Anticipatory investment by zone users



Table 40 – CAPEX estimates for anticipatory investment by zone users

CAPEX estimates	Independent					Coordinated				
	IU (Zone 1) £m	IU (Zone 2) £m	IU (Zone 3) £m	IU (Zone 4) £m	Independent Total £m	IU (Zone 1) £m	LU (Zone 2) £m	LU (Zone 3) £m	LU (Zone 4) £m	Coordinated Total £m
Cable supply	17.1	17.1	23.9	12.0	70.1	28.5	3.0	11.3	1.6	44.4
Cable installation	17.3	17.3	24.0	12.3	70.9	19.8	2.9	11.1	1.6	35.4
Onshore substation	15.0	15.0	15.0	15.0	60.0	49.1	0.0	0.0	0.0	49.1
Offshore substation	0.0	0.0	0.0	0.0	0.0	70.4	0.0	0.0	0.0	70.4
Land rights	10.0	10.0	10.0	10.0	40.0	20.0	0.0	0.0	0.0	20.0
Onshore consent (DEVEX)	10.0	10.0	10.0	10.0	40.0	10.0	0.0	0.0	0.0	10.0
Offshore consent (DEVEX)	10.0	10.0	15.0	10.0	45.0	13.5	3.5	5.0	3.5	25.5
Connection costs (non-contestable)	3.5	3.5	3.5	3.5	14.0	9.0	-	-	-	9.0
TOTAL	82.9	82.9	101.4	72.8	340.0	220.3	9.4	27.4	6.7	263.8

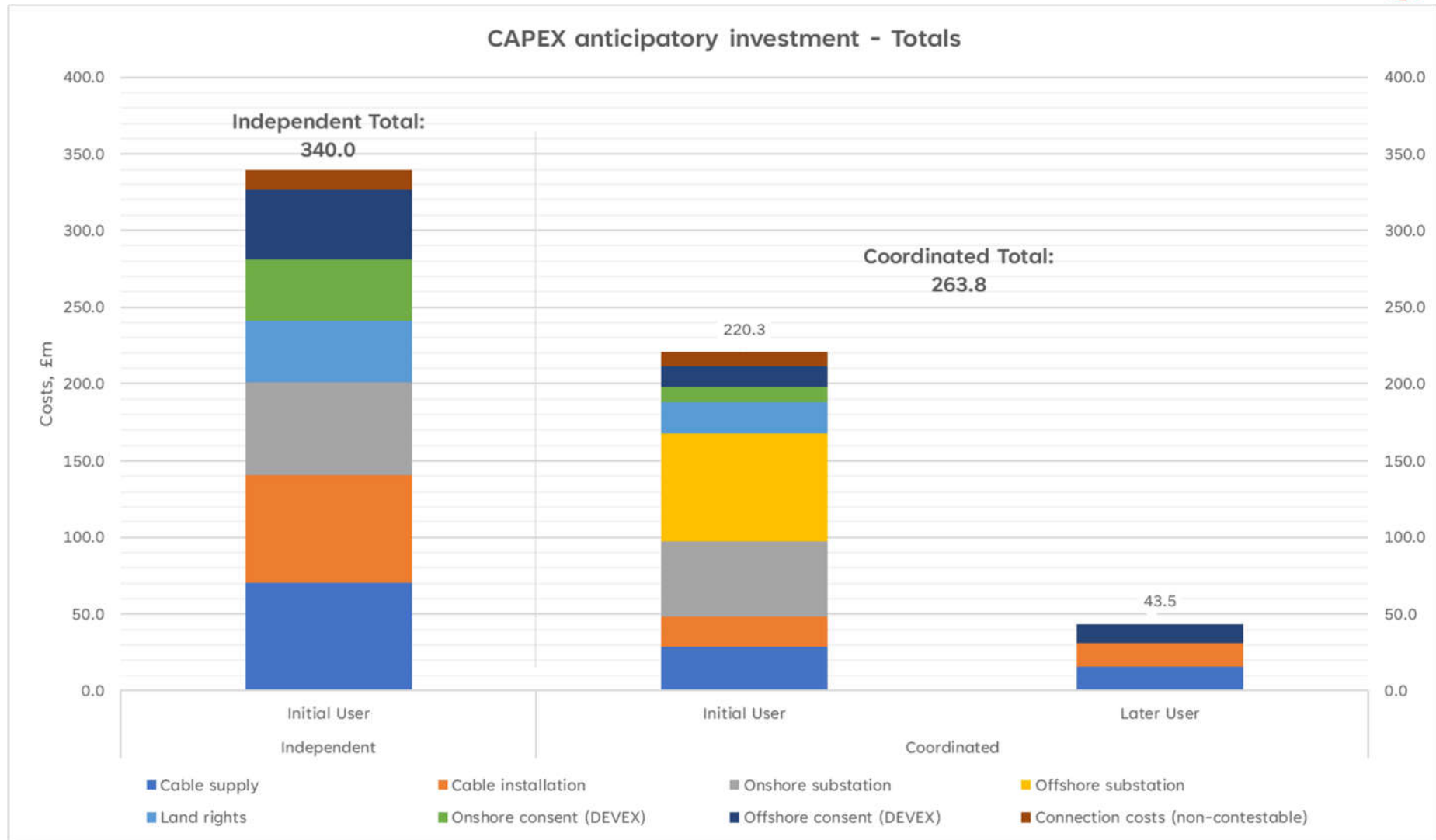


Figure 46 – Anticipatory investment by zone users



Table 41 – CAPEX estimates for anticipatory investment totals

CAPEX estimates Cost Item	Independent	Coordinated	
	Initial User, £m	Initial User, £m	Later User, £m
Cable supply	70.1	28.5	15.9
Cable installation	70.9	19.8	15.6
Onshore substation	60.0	49.1	0.0
Offshore substation	0.0	70.4	0.0
Land rights	40.0	20.0	0.0
Onshore consent (DEVEX)	40.0	10.0	0.0
Offshore consent (DEVEX)	45.0	13.5	12.0
Connection costs (non-contestable)	14.0	9.0	0.0
Subtotal, £m	340.0	220.3	43.5
Total, £m	340.0	263.8	



13 References

- [1] “ESO Offshore Coordination Celtic Sea webinar,” in *HNDFUE*, 27th October 2023.
- [2] Apollo, “395-003-GRL-BOD-0001-0 PDZ 400MW MOS Concept - Basis of Design,” 2023.
- [3] National Grid ESO, “Electricity Ten Year Statement (ETYS),” [Online]. Available: <https://www.nationalgrideso.com/research-and-publications/electricity-ten-year-statement-etys#:~:text=The%20Electricity%20Ten%20Year%20Statement,over%20the%20next%2010%20years..> [Accessed 27th March 2023].
- [4] National Grid, “The Pathway to 2030 Holistic Network Design,” [Online]. Available: <https://www.nationalgrideso.com/future-energy/pathway-2030-holistic-network-design>. [Accessed 27th March 2023].
- [5] National Grid ESO, “SQSS Code Documents,” [Online]. Available: <https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standard-sqss/sqss-code-documents>. [Accessed 3rd April 2023].
- [6] National Grid ESO, “Draft NETS Security and Quality of Supply Standards v2.6,” [Online]. Available: <https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standard-sqss/sqss-code-documents>. [Accessed 3rd April 2023].
- [7] Health and Safety Executive, “Avoiding Danger from underground services,” [Online]. Available: <https://www.hse.gov.uk/pubns/books/hsg47.htm>. [Accessed 3rd April 2023].
- [8] National Grid ESO, “GSR026: Adding Non-Standard Voltages to the SQSS,” [Online]. Available: <https://www.nationalgrideso.com/industry-information/codes/sqss/modifications/gsr026-adding-non-standard-voltages-sqss>. [Accessed 3rd April 2023].
- [9] National Grid ESO, “TEC Register,” [Online]. Available: https://data.nationalgrideso.com/connection-registers/transmission-entry-capacity-tec-register/r/tec_register. [Accessed 7th April 2023].
- [10] Vekta Group, “395-003-ELE-RPT-1002 400MW MOS Concept Cable Routing Report,” 2023.
- [11] B. G. Wind, “Erebus,” [Online]. Available: <https://www.bluegemwind.com/our-projects/erebus/>. [Accessed 11 April 2023].
- [12] Greenlink, “Greenlink Interconnector,” [Online]. Available: <https://www.greenlink.ie/>. [Accessed 11 April 2023].
- [13] ABPmer, “Awel y Môr Environmental Statement: Marine Physical Processes Chapter,” 2022.
- [14] British Geological Survey, “GeoIndex Offshore,” [Online]. Available: https://mapapps2.bgs.ac.uk/geoindex_offshore/home.html?_ga=2.175849830.516179553.1675768110-2089018831.1674564917#. [Accessed 6th April 2023].
- [15] Vekta Group, “395-003-ELE-RPT-1003 400MW MOS Concept Cost Benefit Analysis,” 2023.



- [16] Apollo, “395-001-0005RPT-0 PDZ MOS Concept Design Concept Study Report,” 2022.
- [17] DNV, *DNV-RP-0360 Subsea Power Cables in Shallow Water*, DNV AS, 2021.
- [18] Safety Regulation Group, *CAP 437 Standards for Offshore Helicopter Landing Areas*, UK Civil Aviation Authority, 2021.
- [19] DNV, *DNV-ST-0145 Offshore Substations*, 2021.
- [20] Department of Energy & Climate Change, “The Capability & Capacity of the UK Offshore Oil & Gas Fabrication Section,” Crown, 2011.
- [21] offshoreWIND, “offshoreWIND.biz,” 15 April 2020. [Online]. Available: <https://www.offshorewind.biz/2020/04/15/first-triton-knoll-offshore-substation-in-place/>.
- [22] Vekta Group, “395-003-ELE-TN-1001 400MW MOS Concept Logistics Strategy,” 2023.
- [23] Vekta Group, “395-003-ELE-TN-1002 400MW MOS Concept Platform Transfer Strategy,” 2023.
- [24] H. Stiesdal and P. H. Madsen, “Design for Reliability,” *Copenhagen Offshore Wind*, 2005.
- [25] *Pembrokeshire Demonstration Zone Pre-Concept Technical Discussion Note*, 2021.
- [26] SEACAMS 2, *Characterisation of the seabed and shallow subsurface to support the development of an MRE wave energy demonstration zone, South Wales*, 2022.
- [27] Tractebel Overdick, *Celtic Sea Power Pembrokeshire Demonstration Zone Pre-Concept Technical Discussion Note*, 2021.
- [28] SEA 8, “SEA 8 Technical Report - Hydrography,” April 2007. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/197013/SEA8_TechRep_Hydrography.pdf. [Accessed 23 February 2023].
- [29] Tractebel Overdick, “O1123-REP-10-001-01 Celtic Sea Power Pembrokeshire Demonstration Zone Pre-Concept Technical Discussion Note,” 2021.
- [30] C. C. C. S. (C3S), *ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate*, 2017.
- [31] Apollo, “395-003-STR-RPT-0005 400MW MOS Topsides Concept Design,” 2023.
- [32] Vekta Group, “395-003-ELE-RPT-1001 400MW MOS Concept Power System Study Report,” 2023.
- [33] National Grid ESO, “Network Options Assessment 2021/2022,” [Online]. Available: <https://www.nationalgrideso.com/research-and-publications/network-options-assessment-noa>. [Accessed 7th April 2023].



Appendix A Supporting documentation

Item	Description	Apollo Document Ref.
1	400MW MOS Concept Power System Study Report	395-003-ELE-RPT-1001
2	400MW MOS Cable Routing Report	395-003-ELE-RPT-1001
3	400MW MOS Concept Logistics Strategy	395-003-ELE-TN-1001
4	400MW MOS Concept Platform Transfer Strategy	395-003-ELE-TN-1001
5	400MW MOS Concept Preliminary Key Single Line Diagram	395-003-ELE-SLD-1001
6	PF 400MW MOS Freshwater-LP 2 x 220kV Al	395-003-ELE-SLD-1002
7	PF 400MW MOS Freshwater-LP 220kV Al	395-003-ELE-SLD-1003
8	PF 400MW MOS Freshwater-LP 220kV Cu	395-003-ELE-SLD-1004
9	PF 400MW MOS Freshwater-LP 275kV Al	395-003-ELE-SLD-1005
10	PF 400MW MOS Freshwater-LP 275kV Cu	395-003-ELE-SLD-1006
11	PF 400MW MOS Greenala-LP 2 x 220kV Al	395-003-ELE-SLD-1007
12	PF 400MW MOS Greenala-LP 220kV Al	395-003-ELE-SLD-1008
13	PF 400MW MOS Greenala-LP 220kV Cu	395-003-ELE-SLD-1009
14	PF 400MW MOS Greenala-LP 275kV Al	395-003-ELE-SLD-1010
15	PF 400MW MOS Greenala-LP 275kV Cu	395-003-ELE-SLD-1011
16	SC3ph 400MW MOS Freshwater-LP 2 x 220kV Al	395-003-ELE-SLD-1012
17	SC3ph 400MW MOS Freshwater-LP 220kV Al	395-003-ELE-SLD-1013
18	SC3ph 400MW MOS Freshwater-LP 220kV Cu	395-003-ELE-SLD-1014
19	SC3ph 400MW MOS Freshwater-LP 275kV Al	395-003-ELE-SLD-1015
20	SC3ph 400MW MOS Freshwater-LP 275kV Cu	395-003-ELE-SLD-1016
21	SC3ph 400MW MOS Greenala-LP 2 x 220kV Al	395-003-ELE-SLD-1017
22	SC3ph 400MW MOS Greenala-LP 220kV Al	395-003-ELE-SLD-1018
23	SC3ph 400MW MOS Greenala-LP 220kV Cu	395-003-ELE-SLD-1019
24	SC3ph 400MW MOS Greenala-LP 275kV Al	395-003-ELE-SLD-1020
25	SC3ph 400MW MOS Greenala-LP 275kV Cu	395-003-ELE-SLD-1021
26	SCphtg 400MW MOS Freshwater-LP 2 x 220kV Al	395-003-ELE-SLD-1022
27	SCphtg 400MW MOS Freshwater-LP 220kV Al	395-003-ELE-SLD-1023
28	SCphtg 400MW MOS Freshwater-LP 220kV Cu	395-003-ELE-SLD-1024
29	SCphtg 400MW MOS Freshwater-LP 275kV Al	395-003-ELE-SLD-1025
30	SCphtg 400MW MOS Freshwater-LP 275kV Cu	395-003-ELE-SLD-1026
31	SCphtg 400MW MOS Greenala-LP 2 x 220kV Al	395-003-ELE-SLD-1027
32	SCphtg 400MW MOS Greenala-LP 220kV Al	395-003-ELE-SLD-1028



Item	Description	Apollo Document Ref.
33	SCphtg 400MW MOS Greenala-LP 220kV Cu	395-003-ELE-SLD-1029
34	SCphtg 400MW MOS Greenala-LP 275kV Al	395-003-ELE-SLD-1030
35	SCphtg 400MW MOS Greenala-LP 275kV Cu	395-003-ELE-SLD-1031
36	400MW MOS Concept Substation LV Utilities Switchroom Layout	395-003-ELE-LAY-1001
37	400MW MOS Concept Jacket & Topsides Isometric	395-003-STR-SK-1001
38	400MW MOS Concept Elevation – South Face	395-003-STR-SK-1002
39	400MW MOS Concept Elevation – East Face	395-003-STR-SK-1003
40	400MW MOS Concept Cable Deck Plot Plan	395-003-STR-SK-1004
41	400MW MOS Concept Main Deck Plot Plan	395-003-STR-SK-1005



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