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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

DC02 - SUBSEA VS FLOATING SUBSTATIONS

PUBLIC REPORT



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EXECUTIVE SUMMARY

The offshore wind sector is transitioning from fixed to floating wind farms at a GW scale, necessitating an understanding of substation selection's technical and economic implications. This study aims to inform developers on supply chain engagement and substation delivery, focusing on HVAC floating and subsea substations. Inter-array and export cables are outside the scope of this study but have been considered at a high level when required.

Subsea Substations

The greatest benefit of the subsea substation is the lack of requirement for dynamic export cables and the standardisation of the design, enabling an almost cookie-cutter approach. Transformer size impacts the cable's architecture, export cable quantity, and cross-sectional area (CSA). Subsea substations require less maintenance due to their inherently reliable design but can be challenging to repair due to inaccessibility.

Subsea substations have the lowest OPEX due to minimal maintenance and high reliability but higher CAPEX as a result of the technology and low volume installed. Transformer capacity variations (150 MVA, 250 MVA, 450 MVA) show no significant CAPEX impact, suggesting site-specific selection. However, transformer capacity does impact export cable CSA and quantity, which is outside the scope of this study. Although the CAPEX is higher, as the deployment of subsea substations increases, the manufacturing capacity for components and vendor competition will likely increase, thus reducing costs over time. Additionally, there may be an opportunity to reduce components further by removing expensive switchgear in favour of 'passive systems', which is being actively pursued by an undisclosed major developer.

The risk and reliability study identified that subsea substations have significantly fewer safety and environmental risks than floating equivalents. In addition, the subsea substation is inherently reliable through design, reducing the likelihood and impact should a failure occur. However, costly vessels and equipment are needed for remedial work, leading to longer intervention times and increased loss of generating availability.

Floating Substations

Floating substation substructure designs are based on proven marine and Oil and Gas (O&G) industry designs (Technology Readiness Level (TRL) = 9), thus facing no expected issues in design, fabrication, installation, or performance. The electrical transmission equipment is analogous to fixed substations. However, there are outstanding concerns with electrical equipment fatigue uncertainties, which are anticipated to be overcome through learnings from O&G floating facilities. Expected voltages are 66-132 kV for inter-array and up to 275 kV for export. Dynamic cabling technology gaps must be addressed for commercialisation by 2030, outside the scope of this study. Post-2030, deeper waters will require larger capacities and HVDC technologies.

ORE Catapult partners chose the Advanced SPAR and semi-sub concepts for development. Both use the same topside equipment but differ in deck configuration and suitability for shallow waters. Both have comparable weights and motion performance within manufacturer limits during a 100-year storm.

Cost modelling shows that floating substations have lower CAPEX compared to subsea substations due to the extensive install basis for substructure, higher TRLs, and similar topsides to fixed substations. The OPEX for floating substations is higher than subsea substations due to the increased maintenance

and lower reliability. Lowering inter-array voltage from 132 kV to 66 kV had minimal impact on overall CAPEX.

The risk and reliability study highlighted that floating substations present higher safety and environmental risks compared to subsea substations, with lower operational reliability and more in-service interventions. However, access to the substation for remedial work was quicker and lower cost than the subsea substations. Dynamic export cables, a technology gap for floating substations, were outside the scope of this study.

Summary

In summary, the selection of subsea or floating substations goes beyond an economic consideration. Although Floating Offshore Substations (FOSSs) provide a lower CAPEX solution, wind farm developers are proposing subsea substations [1]. The increasing mass market adoption of subsea substations has the potential to drive costs down, while the reduction in key risk areas, such as dynamic export cables, provides a significant benefit for subsea substations. Accordingly, the selection of substation type will remain a project decision, as it is impacted by a multitude of factors, including but not limited to developers' experience of floating/subsea systems, local content requirements, valuing of risk mitigation, progress of key technology qualification (i.e. dynamic export cable), OPEX vs CAPEX balance.

Further work

Subsea Substations:

- Form specialised working groups to advance the development of high-voltage (HV) subsea equipment, particularly focusing on connectors and switchgear.
- Compare capital expenditures (CAPEX) across various water depths for fixed, floating, and subsea substations to determine the “tipping point” for selecting each technology.
- Address the subsea switchgear busbar capacity limitation, necessitating more switchboards that will increase CAPEX accordingly. Further investigation is required to understand whether increasing the capacity provides a CAPEX saving.

Floating Substations:

- Investigate dynamic cable interfaces with FOSS to reduce fatigue loads, although this is beyond the study's scope.
- Conduct installation studies for FOSS to determine vessel requirements and encourage early industry engagement to promote investment.
- Combine this cost model for OPEX and CAPEX with the ORE Catapult's cost model to provide a complete model from inter-array cabling to onshore connections, considering risks like high-voltage dynamic cables and export cable quantity. This will provide a holistic comparison between FOSS and subsea substations.

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ABBREVIATIONS LIST

Acronym	Description
BoD	Basis of Design
CAPEX	Capital Expenditure
CEC	Crondall Energy Consultants
CSA	Cross-Sectional Area
FEED	Front End Engineering Design
FOC	Fibre Optic Cable
FOSS	Floating Offshore Substation
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
GIS	Gas Insulated Switchgear
HV	High Voltage
HVAC	High voltage alternating current
HVDC	High Voltage Direct Current
MV	Medium Voltage
O&G	Oil and Gas
O&M	Operations and Maintenance
OPEX	Operational Expenditure
ORE	Offshore Renewable Energy
OSS	Offshore Substation
ROV	Remotely Operated Vehicle
TRL	Technology Readiness Level
WT	Wind Turbine

SYMBOLS AND UNITS

Unit	Description
°C	Degree Celsius
A	Amperes (Amps)
Al	Aluminium
Cu	Copper
g	Maximum Acceleration
GM	Metacentric Height
GW	Giga-Watt
Hs	Significant Wave Height
Hz	Frequency in Hertz
kA	Short Circuit Withstand Capacity in Kilo-Amps
Kg	Kilograms
km	Kilometer
kN	KiloNewton
kV	KiloVolts
L	Inductance
m	Meter
mm	Millimeter
m/s	Meters per Second
MVA	Apparent Power in Megavolt-Amps
MVA _r	Reactive Power in Megavolt-Amps Reactive
MW	Mega-Watt
MWe	Mega-Watt Electric
PF	Power Factor
ph	Phase
s	Seconds
T	Temperature
Te	Tonne Equivalent
T _p	Peak Wave Time Period
R	Resistance
U _m	Maximum RMS Voltage
Y	Admittance

VA _r	Reactive Power in Volt-Amps Reactive
V _{current}	Current Velocity
V _{wind}	Wind Velocity
YRP	Year Return Period

1 INTRODUCTION

This project (Subsea vs Floating Substations – Technoeconomic Comparison) is part of the Dynamic Cables Strategic Programme, which has been established to accelerate technology development for identified technology gaps, qualify technology for application in floating offshore wind (FOW), reduce technology risk, optimise technology applications and system architectures, and support new supply chain organisations to enter the market, boosting capacity and competition.

As FOW projects increase in power capacity and scale, they will require the introduction of an offshore substation (OSS). Similarly, with the introduction of floating offshore wind turbines (FOWTs), the traditional fixed-bottom substation platforms will no longer be a viable option on many planned large-scale FOW sites due to the increase in water depth at project sites. Attention then turns to the prospect of floating offshore substations (FOSSs) or subsea substations (SS).

There are three potential substation types that could be used in floating wind: bottom-fixed (assuming a suitably shallow site is available), floating, or subsea. Currently, it is not understood which scenario is the most technologically and economically viable. There are reservations towards floating substations due to the requirement of high voltage (HV) dynamic export cables which are not yet available, while subsea substations require subsea connectors. There is a need to understand how the different options compare and at what water depths the solutions are competitive. The findings will help developers inform their supply chain engagement and project Front End Engineering Design (FEED) scoping. This study can take many of the learnings from floating oil and gas (O&G) assets but will also highlight the knowledge gaps for the application of floating wind.

This project aims to answer the following questions:

- What would a 1 GW (or multiple smaller) floating and subsea High Voltage Alternating Current (HVAC) substations look like?
- What are the key technology and knowledge gaps for each system? How can these gaps be bridged to bring the technology to commercial readiness at an acceptable risk?
- What are the Operations and Maintenance (O&M), as well as transportation and installation (T&I) requirements for repair/replacement and maintenance for both floating and subsea substations?
- How do through-life costs compare for floating and subsea substations?

1.1 Objectives

The main objectives of this project are as follows:

- Determine the current state-of-the-art equipment, components and structures for subsea and floating substation technology for power transfer of up to 1 GW HVAC.
- Identify the key technical challenges, as well as the non-technical risks and uncertainties for both options and lay out a roadmap to enable commercial deployment by 2025 to 2030.
- Make recommendations as to when each approach might be a viable option considering cost and risk and highlight the sensitivity to project and technology specific assumptions.
- Recommend where future R&D and qualification efforts would be best focused, including current supply chain capability in these areas.

1.2 Scope

The scope of this report is to deliver the following:

- Collate findings of the overarching project deliverables into a public report.
- Draw upon conclusions from the individual project deliverables to develop overarching conclusions and recommendations for this project.

1.3 Boundaries of this Project

The following project scope boundaries are identified:

- Further detailed investigations are required into dynamic export cables and their potential cost implications for floating substations.
- Design of the transmission cable routing and onshore infrastructure will not be considered.
- The ORE Catapult Floating Offshore Wind Centre of Excellence (FOW CoE), DCO6 'Cable topology comparison: cost and opportunity' study will provide the wind farm layout.
- Investigations into High Voltage Direct Current (HVDC) substations will be limited to recommendations and future considerations.

2 SUBSEA SUBSTATIONS

A subsea substation includes a foundation, protection structure, and transformer with inter-array and export connections. Figure 1 presents at a high level the fundamental components of a subsea substation system. It has fewer components and auxiliary equipment than traditional substations due to its remote location and inaccessibility. Depending on system requirements, it may only have a transformer with communication and monitoring, or it could include additional equipment like reactive compensation and switchgear for enhanced functionality.

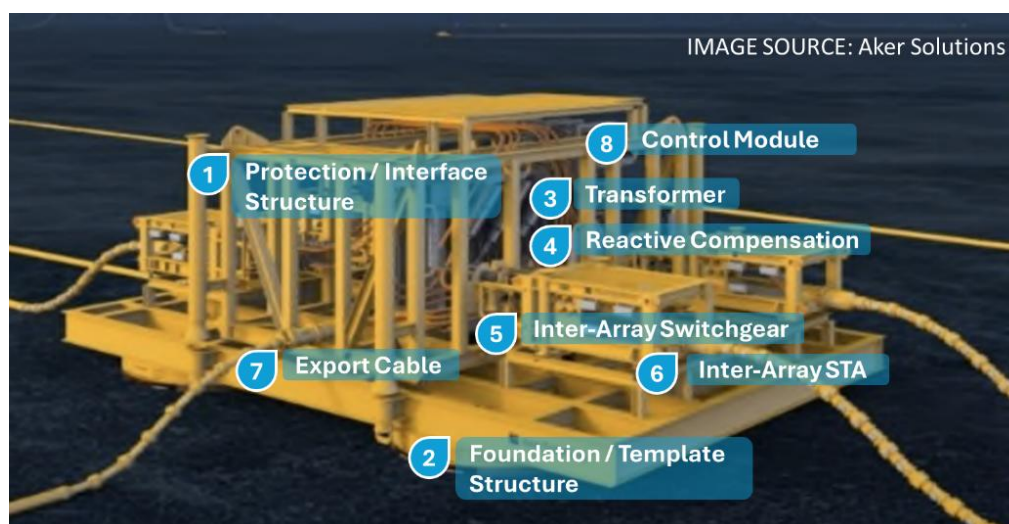


Figure 1 Subsea Substation Component Overview

2.1 State of the Art Review

The technology state-of-the-art review included an initial literature review followed by engagement with the leading subsea and floating substation vendors/EPCI contractors. The state-of-the-art review focused on substation development within the near term. Longer-term technology roadmaps are also discussed. All Technology Readiness Levels (TRLs) mentioned throughout this report align with the ORE Catapult's TRL scale. For a clarification on the TRLs, see Appendix 1

Subsea substation technology is currently (Q2, 2024) at TRL-6/TRL-7 and is expected to reach TRL-8 by Q4 2025, delivering up to 500 MVA transformers with inter-array voltages up to 66 kV and export voltages up to 220 kV. The systems are based on lower voltage components used from 2000-2015 but face challenges in qualifying wet-mate connections and supply chain constraints for transformers. Utilising star design topologies for subsea power collectors offers benefits but may not be economical. Higher-rated systems (132 kV inter-array, 400 kV export) are expected between 2030-2035, however, future advancements will be dependent on the adoption of 66kV/220kV.

2.2 Development Roadmap

Current subsea substations (66/72.5 kV inter-array and 220/245 kV export) are expected to be commercialised by 2025-2030. Equipment at TRL-7 will be ready by 2025, but industry standards for higher voltages are needed. Supply chain improvements are crucial due to limited factories for large transformers and wet-mate connectors, which could lead to long lead times. Understanding maintenance logistics and costs is key for developer buy-in. At the time of writing, Renexia has announced a contract with Aker Solutions for SSs (eight (8) modules) in their 2.8 GW Med Wind FOW

project, with completion by 2030/2031 [1]. Technology vendors are aiming for 132 kV inter-array and up to 400 kV export voltages by the early-mid 2030s. No HVDC subsea equipment is planned and systems will remain HVAC.

2.3 Basis of Design

The high-level BoD for the electrical design for the subsea substation case studies can be seen in Table 1.

Table 1 Electrical Key Design Parameters for the Subsea Substation

Parameter	Subsea Substation
Wind Turbine Capacity (MWe)	15
FOW Array Size (MW)	810
FOW Configuration	Star - 12 Strings
Substation Configuration	6 x 135 MW
Inter-Array Voltage (kV)	66
Inter-Array Cable CSA (mm ²)	800
Export Voltage (kV)	220
Export Cable CSA (mm ²)	630
Distribution/Transmission	HVAC
Number of Export Cables	6

2.4 Case Studies & Reliability Assessment

The subsea substation's standardised design allows for a consistent approach, using two 405MW substations (consisting of three identical transformer modules per substation) per location to transmit power from the wind farm to shore. Due to the 66 kV switchgear's limited busbar capacity, multiple transformer modules were used, resulting in more export cables compared to floating equivalents. However, this can be optimised to utilise the same number of export cables as floating. Subsea substations require less maintenance post-installation but are difficult to repair due to inaccessibility. The foundations for the substations use suction piles for the transformer module and mudmats for the collectors.

The risk and reliability study identified that subsea substations have significantly fewer safety and environmental risks than floating equivalents. In addition, the subsea substation is inherently reliable through design, reducing the likelihood and impact should a failure occur. However, costly vessels and equipment are needed for remedial work, leading to longer intervention times and increased loss of generating availability.

3 FLOATING SUBSTATIONS

3.1 State of the Art Review

Floating substructure designs for offshore wind turbines are based on proven designs from the marine and oil and gas (O&G) industries (TRL-9). No major issues are expected with their design, fabrication, installation, or performance. The main challenges are making these designs cost-competitive and ensuring they provide the necessary motion performance for onboard electrical equipment. These challenges are being addressed through industry collaboration with the key electrical equipment vendors (ABB, Siemens and Hitachi Energy) and hull designers (Saipem, BPT, SNC-Lavalin and BW Ideol). For example, Siemens Energy has signed an MoU (Memorandum of Understanding) with Saipem (2022) [2] to develop FOSSs, as well as collaborating with BPT to explore the use of an Advanced SPAR (2021) [3]

Alternative floating substructure designs are being developed using established serial manufacturing processes, such as BW Ideol [4] and Saipem Star [5]. However, these designs are at an earlier stage of development (TRL-3/TRL-4) and there are concerns about their motion performance and topsides capacity.

Offshore electrical equipment is expected to be suitable for these applications, with power capacities up to 500 MVA and various voltage levels. However, since this equipment has not yet been deployed commercially for FOSSs, there are uncertainties about fatigue under motion. Manufacturers are leveraging experience from floating O&G and fixed wind assets to meet performance requirements, with the technology readiness level estimated at TRL-8.



Figure 2 Traditional hull designs

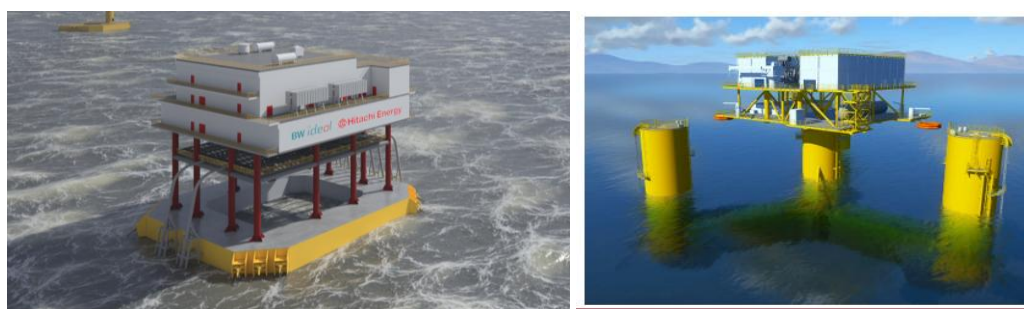


Figure 3 Alternative floating substructure designs - BW-Ideol Damping Pool FOSS and Saipem Star 1 FOSS [5] [4]

3.2 Development Roadmap

The floating substation technology is at a high Technology Readiness Level (TRL-8), with designs based on proven applications from other industries. Most components are commercially available, but further innovation is needed to improve cost and commercialisation.

HVAC technology is used, but it has limitations with losses and distance to shore. As the industry moves to deeper waters, HVDC technology, though costly and not yet commercially attractive, is expected to become more prevalent, with commercial availability anticipated post-2030.

Several floating wind farms are planned to be operational by 2030, contributing to the market for floating substations. The UK aims to have up to 5GW of floating wind capacity by 2030. Collaboration among equipment suppliers, EPC contractors, and marine designers is ongoing to make the technology commercially viable. No major obstacles have been identified, and the industry is ready for project approval and execution. Both regulators and the supply chain are pushing the technology forward, awaiting investment and developers to push the technology into project execution.

3.3 Basis of Design

The high-level BoD for the electrical design of the subsea substation can be seen in Table 2.

Table 2 Electrical Key Design Parameters for the Floating Substation

Parameter	Floating Substation
Wind Turbine Capacity (MWe)	15
FOW Array Size (MW)	810
FOW Configuration	Radial – 10 Strings
Substation Configuration	2 x 405 MW
Inter-Array Voltage (kV)	132
Inter-Array Cable CSA (mm ²)	400
Export Voltage (kV)	220
Export Cable CSA (mm ²)	630
Distribution/Transmission	HVAC
Number of Export Cables	4

3.4 Case Studies & Reliability Assessment

Two sites were selected for the base cases of the study. One site West of Orkney in the North Sea and the other, Southwest of Wales in the Celtic Sea. Table 3 presents the site parameters for Site A (North Sea) and Site B (Celtic Sea) [6]. Each site has a mixture of parameters that allowed comparison between the technologies such as water depth, distance to shore/grid connection, soil type and environmental loading.

Table 3 Site Parameters

Parameter	Site A	Site B
Water Depth (m)	50 - 150	75 – 95
Distance to Shore (km)	65	100
Distance to Grid Connection (km)	70 (Dounreay)	126 (Cornwall) 138 (Wales)
Seabed Type	Silt, Sand, Gravel or Clay	Dense Clay and Sand
Average Seabed Temperature (°C) [7]	7.0	9.0
Environment	Harsh	Moderate
Significant Wave Height; 100-year return period (Hs)	15 - 18	10 -12
Peak Current Flow (m/s) [8]	0.5 – 0.8	0.3 – 0.5
Wind Speed @40m above SL (m/s) [9]	9 - 10	9 - 10

ORE Catapult FOW COE partners have selected the Advanced SPAR and semi-sub concepts for FOSS development. Both concepts use the same topside equipment, but the semi-sub has a single deck, while the Advanced SPAR has a two-storey deck due to different hull configurations. Both are technically feasible for deployment at sites A and B.

The semi-sub is larger in area, while the Advanced SPAR is more compact but has a larger draught, which may limit mooring design and cable use in shallower waters (<90 m). The semi-sub may also face challenges in shallower depths (around 50 m). Both structures have comparable weights and motion performance, with equipment accelerations within manufacturer limits during a 100-year storm.

Electrical equipment will use proven designs from fixed substations, but further investigation is needed for the fatigue life of transmission components. The selection between Advanced SPAR and semi-sub depends on economic and project-specific factors, such as construction locations, installation methods, company experience, and the balance between CAPEX and OPEX.

Floating substations have safety risks, like flammability from battery storage and fuel oil systems, but these are lower for an attended installation. High risks require extra safety measures, which impacts costs. Known risks include asphyxiation from CO2 systems and ‘walk to work’ hazards, with safer alternatives available.

Environmental risks include fuel oil leaks and high-GWP switchgear gases, which can be mitigated with proper design and alternatives. Economic risks include equipment failures and cyber threats, requiring robust cybersecurity measures.

FMEAs for the Floating Substation identified mostly economic risks, with seven high and two medium risks. Nine failure scenarios could lead to the most severe economic consequence: loss of power from 27 wind turbines

4 COST MODELLING

This study analysed the CAPEX and OPEX of floating and subsea substations using vendor quotes, industry factors, and Crondall data to create a cost breakdown structure. Estimates were made to an AACE class 5 level (-30% to +50%) with contingencies based on confidence intervals for level 2 cost hubs. The analysis included two floating substation types (semi-submersible and advanced spar) and three subsea variants (with switchgears, with passive collectors, and without collectors). The results of the analysis are summarised in Figure 4.

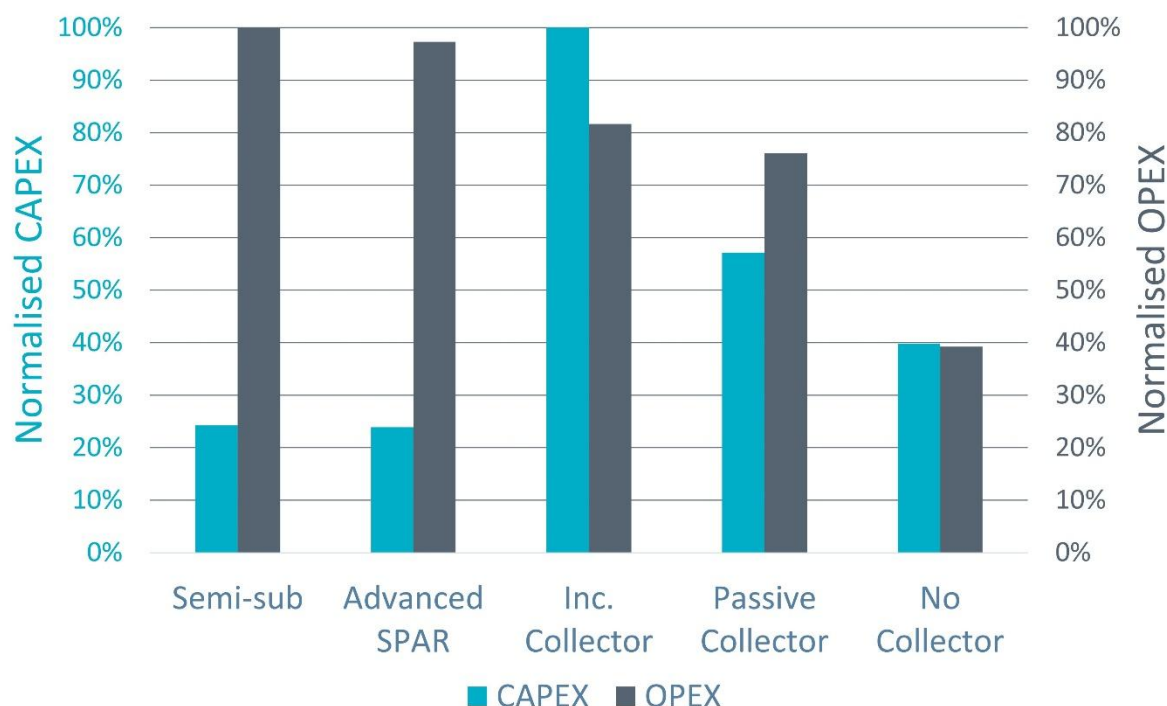


Figure 4 Normalised CAPEX and OPEX of floating and subsea substations

The study has shown that the FOSS provides the lowest CAPEX solution for the sites studied, based on topsides technology already developed for fixed deployments and fabrication (topside and substructure) infrastructure already existing in the UK. Subsea substations provide the lowest OPEX. However, it is unlikely that this will pay back the significantly higher CAPEX associated with the solutions. As subsea substations are deployed, the manufacturing capacity for components and vendor competition will likely increase, thus reducing costs over time.

The study's scope was limited to substations, excluding dynamic cables, which could affect overall cost comparisons. Minimal variation in costs between UK sites suggests broad transferability. Further development of OPEX estimates and risk-based assessments is needed. Varying switchgear and transformer sizes showed minor cost impacts. The main limitation is the exclusion of inter-array and export cables, which could provide a more comprehensive cost view.

Future work should combine this cost model for OPEX and CAPEX with the ORE Catapult FOW CoE's cost model to provide a complete model from inter-array cabling to onshore connections, considering risks like high voltage dynamic cables and export cable quantity, to provide a holistic comparison between FOSS and subsea substations.

4.1 Sensitivities

The following section summarises CAPEX sensitivities performed as part of the study.

4.1.1 Floating substation inter-array voltage

The base case study for the FOSS considers the use of 132 kV switchgear for inter-array cabling, thus requiring dynamic cables connecting the substation to the wind farm array, which are rated at 132 kV. However, 132 kV dynamic cables are currently at a lower TRL than 66 kV dynamic cables, with 66 kV being the current standard for offshore wind farms. Overall, changing the 132 kV switchgear to 66 kV results in a negligible reduction in the overarching FOSS cost.

4.1.2 Subsea transformer size

Various transformer sizes are being developed by equipment manufacturers, up to 500 MVA. Therefore, an investigation into varying the transformer size to 250 MVA and 450 MVA has been conducted. This sensitivity is focused on investigating the impact on CAPEX and the quantity of export cables of varying the transformer capacity of the subsea substation.

The sensitivity highlighted the negligible differences in the subsea substation cost, for varying transformer sizes but did achieve a reduction in the quantity of export cables (outside the scope of this study). This highlights that there is flexibility to select the transformer capacity most suitable for site-specific design requirements. However, it should be noted that changing transformer sizes and/or makeup (i.e. single phase or 3-phase) may impact the configuration of the substation due to required modifications to cabling, switchgear, and shunt reactors, which could influence the cost of the substation and the complexity of installation e.g. the switchgear is installed as a separate module that needs to be connected to the transformer module on the seabed.

5 CONCLUSIONS

Bringing together the contents of the full study, outlined within this report, a comparison between subsea and FOSSs is discussed in this conclusion.

From the state-of-the-art review, FOSSs have higher maturity of design compared to subsea substations, due to the extensive track record of floating structures and fixed substations which combine for FOSS, compared to subsea substations with fewer installed at much smaller capacities. However, subsea substation technology gaps are few, and those remaining are closing within the coming years, with future commercial applications accelerating this development further.

The case studies highlighted differences in the designs between subsea substations and FOSSs. The subsea substation has fewer components, with inherently higher reliability compared to the FOSS. This is further emphasised by a lower annual OPEX estimate for subsea substations, compared to the FOSS. However, subsea substations do have a higher CAPEX than FOSS. However, the CAPEX for subsea substations may reduce as the quantity of commercial applications increases. Additionally, there may be an opportunity to reduce components further by removing expensive switchgear in favour of 'passive systems' due to less HSE requirements when operating electrical equipment in a subsea environment. This approach is currently being pursued by a major developer from one of the identified vendors.

The risk and reliability study demonstrated that FOSSs pose higher safety and environmental risks than subsea substations. FOSSs have a greater complexity due to the greater quantity of equipment and systems, compared to subsea substations. This indicates that FOSSs are likely less reliable and require more maintenance, highlighting the increased reliability of subsea substations.

In summary, the selection of subsea or floating substations goes beyond an economic consideration. Although FOSSs provide a lower CAPEX solution, wind farm developers are beginning to commit (FEED) to subsea substations for their projects [1]. The increasing mass market adoption of subsea substations has the potential to drive costs down, while the reduction in key risk areas, such as dynamic export cables, provides a significant benefit for subsea substations. Accordingly, the selection of substation type will remain a project decision, as it is impacted by a multitude of factors, including but not limited to developers' experience of floating/subsea systems, local content requirements, valuing of risk mitigation, progress of key technology qualification (i.e. dynamic export cable), and the OPEX vs CAPEX balance.

5.1 Further Work

5.1.1 Subsea Substations

The following recommendations on further work for subsea substations are outlined:

- Form working groups to create guidance for HV subsea equipment, focusing on higher voltage ratings for connectors and switchgear.
- Conduct detailed studies on supply chain constraints for large transformers and wet-mate connectors. To understand lead times for future substation projects.
- Investigate the maintenance and repair of complex components like wet-mate connectors and switchgear to understand the timeline and risk for repairs.
- Consideration of CAPEX case studies across a range of water depths for fixed, floating and subsea substations. This will enable a comparison between the various substation solutions by producing a graph to understand the tipping point for each technology type.

- Address FOC connection requirements for FOW, ensuring adequate equipment design. This was outside the scope of this assessment.
- The capacity of 66 kV subsea switchgear busbar (1250 A) is a limiting factor as it necessitates more switchboards that will increase CAPEX accordingly. Further investigation is required to understand whether increasing the capacity provides a CAPEX saving.
- Combine this cost model for OPEX and CAPEX with the ORE Catapults cost model to provide a complete model from inter-array cabling to onshore connections, considering risks like high voltage dynamic cables and export cable quantity. This will provide a holistic comparison between FOSS and subsea substations.

5.1.2 Floating Substations

The following recommendations on further work for floating substations are outlined:

- Even though dynamic cabling is outside the study scope, they are a critical FOSS interface. As dynamic cables are prone to fatigue failure, investigation of the cable interfaces with FOSS applications is required to understand how the fatigue loads can be minimised.
- Installation studies of FOSS are required to identify required vessels and shortages in current availability. The design and fabrication of these vessels may take up to 5 years. Thus, early engagement with the industry is recommended to encourage investment.
- Water depth and mooring system restrictions suggest that cables may also face limitations regarding water depth and FOSS draught. Further studies are recommended, particularly for shallower waters (<150 m).
- Combine this cost model for OPEX and CAPEX with the ORE Catapult cost model to provide a complete model from inter-array cabling to onshore connections, considering risks like high voltage dynamic cables and export cable quantity. This will provide a holistic comparison between FOSS and subsea substations.
- Further optimisation and development of the semi-sub and advanced spar FOSS may provide a clear difference in CAPEX and OPEX between the designs.

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APPENDIX 1 TRL CLARIFICATION

Within the offshore energy industry there is often inconsistency with the application of Technology Readiness Level (TRL) due to several standards existing e.g. API and EN-27988. Typically, in the O&G industry, where much of the technology is being transferred to FOW, an API standard is used for TRL. However, more recently (2017), the European Commission recognised that there was a lack of common understanding of TRL, specifically for renewable energy technologies. As a result, they performed a study [10] to define TRL for specific renewable technology i.e. Photovoltaics, Hydropower, Wind, Geothermal, and Wave and Tidal.

Furthermore, ORE Catapult defined TRL in a study for dynamic cable technology qualification (2022) [11]. It is noted that the TRL system adopted by ORE Catapult is more consistent with the TRL developed by the European Commission specifically for offshore and onshore wind (EN-27988, Annex 4) [12]. For consistency, and to align with other ORE Catapult documentation, where TRL level has been reported, it has been 'normalised' to the ORE Catapult TRL.

Table 4 presents the TRL comparison between API, EN and ORE Catapult.

Table 4 TRL Comparison

API TRL	ORE Catapult TRL	EN-27988 TRL	EN-27988 Description
TRL-1	TRL-2	TRL-2	Technology formulation. Concept and application have been formulated.
Proven Concept	Feasibility confirmed	Technology Concept Formulated	
TRL-2	TRL-4	TRL-4	Small scale prototype built in a lab environment ('ugly' prototype).
Validated Concept	Concept Validated	Technology Validated in Lab	
TRL-3	TRL-6	TRL-5 /6	Prototype system tested in intended environment close to expected performance.
Prototype Tested	Prototype Validated	Prototype validated/demonstrated	
TRL-4	TRL-7	TRL-7	Demonstration of system operating in operational environment at pre-commercial stage.
Environment Tested	Prototype Demonstrated	Prototype demonstrated in an operational environment.	
TRL-5	TRL-8	TRL-8	First of a kind commercial system. Manufacturing issues solved.
System Tested	System Validated	System complete and qualified	
TRL-6 / 7	TRL-9	TRL-9	Full commercial application, technology available for consumers
Operationally Proven	Operationally Proven	Operationally Proven	

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