Assessment of Floating Wind Turbine Foundations for North Sea Conditions

Credit: Principle Power Inc

TLB2501 – RP01-A5

Final Report

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Commissioned by:

technology leadership board

Contents

1. Executive Summary

OpenWater Renewables Ltd (OWRL) has conducted a study for the UK Technology Leadership Board (TLB) to review hull concepts for Floating Offshore Wind (FOW), which are best suited for North Sea conditions.

The views and conclusions herein are OWRL's and are based on the limited and qualitative scope of work which they were asked to complete.

Analyses of the available FOW concepts are typically conducted by wind farm developers and other interested parties; however, the results have generally not been made public. The TLB's intent in commissioning this study is to widely share the key factors relevant to FOW foundation selection and, through a generic analysis, illustrate how they might influence end users' choice of FOW foundations to be considered for their projects.

The study considered a fictional 750 MW capacity wind farm located in 100 to 150m water depth offshore Scotland, using 15 MW turbines, operational by 2030-2035

Data for the study was obtained from OWRL's FOW database, which contained details of 107 FOW concepts, as of the cutoff date for the study on 31st March 2025. New concepts launched after that date are not included. Hulls in the database are predominantly barges, semi-submersibles, SPARs and Tension Leg Platforms (TLPs), and are fabricated from steel, concrete, or a hybrid combination of both materials.

Determination of the most appropriate FOW hulls was performed using "FOW_RANK", a proprietary concept ranking tool developed by OWRL. The tool scores concepts against 38 criteria across a range of technical, commercial and project execution characteristics. Each score is weighted to reflect the influence of the criterion on the Levelised Cost of Energy (LCOE) and the project risk profile. Further Project Weighting Factors (PWF) are then applied to selected criteria to account for the specific challenges of a site or project strategy. For the North Sea, 15 criteria were selected for the application of PWF, covering the critical areas of installation, accessibility, performance and risk.

Technical maturity is a key factor in assessing the risk of selecting a concept, and consequently, for large-scale commercial wind farms, OWRL recommend only selecting concepts (at FID stage) that have had a suitable prototype in operation offshore for at least 3 years. This corresponds to Technology Readiness Level 7 (TRL 7) on a scale running from 1 to 9 (see section 4.2). Adoption of an Industry-Standard definition of TRL for FOW would simplify future comparisons of the technical maturity of different hull concepts, and a TRL scale is proposed in the report.

Fourteen concepts were identified that have either reached TRL 7 or TRL 6, i.e. have a prototype in operation and are expected to reach TRL 7 within the next 3 years. However, 9 of these concepts are either not suitable or not available for North Sea projects, reducing the number of candidates to 5.

To widen the pool of potential candidates, concepts at TRL 5 or lower were also ranked for the fictitious North Sea projects, although these would require accelerated development to reach TRL 7 within the project timeframe. The 15 most highly ranked concepts, irrespective of TRL, are summarised in the table below, together with the pros and cons of the generic concepts.

	CAPEX *	OPEX	LCOE	Ease of WTG Integration	Ease of Installation	Ease of O&M	Reliability	Performance	Ease of Major Repair	TRL/Risk	Examples (TRL)
Barge in Concrete	100%	Good	Good	Good	Intermediate	Good	Good	Intermediate	Intermediate	Intermediate / Good	BW Ideol Damping Pool (7), Sevan SWACH (5)
Barge in Hybrid Steel & Concrete	110%	Intermediate	Intermediate	Good	Good	Intermediate	Intermediate	Intermediate	Good	Intermediate	Saitec SATH (6)
Semi-Sub in Steel	105% to 115%	Intermediate	Intermediate	Good	Intermediate	Intermediate	Good	Intermediate / Good	Intermediate	Intermediate / Good	PPI WindFloat-T (7), PPI WindFloat F/FC/TC (5), Saipem Star-1 (5), Gusto TriFloat (5), Equinor WindSemi (5), Odfjell Deepsea Star (5), Steisdal TetraSub (5), Ekwil INOC (5)
Semi-Sub in Concrete	100%	Good	Good	Good	Intermediate	Good	Good	Intermediate	Intermediate	Intermediate	Bouygues OO-Star (5)
TLP in Steel	115%	Intermediate	Intermediate	Intermediate	Poor	Intermediate	Good	Good	Poor	Good	SBM Float4Wind (6)

* Ball Park total project CAPEX compared to the Concrete Barge case.

Key: Good | Intermediate | Poor

Figure 1-1: Generic Concept Pros and Cons

The two highest-ranked concepts in the pool of 15 are both concrete (1 barge and1 semi-sub), reflecting the material's durability and low maintenance requirement, lowest capital expenditure (CAPEX), and suitability for UK construction, contributing to the 50% UK content target. A further concrete barge is also included in the shortlist.

Ten steel Semi-subs are also shortlisted. Steel Semi-subs are the most numerous in the FOW development pipeline, but are likely to be more expensive and require more maintenance than concrete hulls as the structures age.

The remaining concepts include a hybrid steel and concrete barge moored by a single point mooring (SPM). This novel concept brings some of the durability benefits of concrete, but the steel elements will require similar maintenance to the steel semi-subs. In addition, while the SPM simplifies integration of a quick connect/disconnect (QCDC) mooring system, it adds critical mechanical components which will require maintenance and may adversely affect reliability.

One steel TLP is also included in the pool. TLPs are lightweight and have good motion characteristics, which may have a positive impact on energy production. However, the complexity of their installation and disconnection in North Sea Conditions resulted in low rankings for most TLP concepts.

Deep draft SPARs were excluded from the concepts ranked for North Sea applications due to a lack of deep-water port facilities in the UK.

No UK-based concepts have been shortlisted for this fictitious North Sea project, with their ranking impacted by low technical maturity, weak balance sheet of the concept developers, and limited EPCI experience of these companies. However, some of these could be candidates for accelerated development. The highest ranked UK concepts for North Sea conditions in FOW_RANK include the OSI UK FTLP (a bottom fixed TLP) and the Trivane hybrid steel/concrete barge.

A detailed ranking of UK-based concepts, including their score across the different ranking categories, could provide a sound basis for focused development of a UK FOW hull.

The approach used by OWRL in this study, along with the weighting factors applied in their ranking tool, forms the basis of the reported findings. Varying these weightings according to real, project-specific conditions may deliver a different pool of short-listed concepts.

FOW foundation concepts which do not appear in the short-listed pool for this fictional project may still be worthy of consideration by wind farm developers for North Sea deployment, and they should carry out their own analysis prior to short-listing concepts for their projects based upon their specific project priorities.

Three main recommendations are made:

- Develop an Industry Standard definition of TRL for FOW projects
- Accelerate the TRL progress of the shortlisted concepts currently qualified as TRL 5.
- Study the leading UK-based concepts to examine their ranking and determine the scope and potential timeline to optimise their development paths for selection for North Sea projects.

2. Introduction

2.1 Objectives

The Technology Leadership Board (TLB) is one of the North Sea Transition Forum task forces set by Industry and Government to provide industry leadership for the offshore oil and gas industry. https://www.nstauthority.co.uk/about-us/north-sea-transition-forum-and-task-forces/

The TLB includes a workstream focusing on technology enablers for the North Sea Energy Transition, and this report is part of the work to investigate which of the many Floating Offshore Wind (FOW) foundation concepts available today could be best suited to North Sea conditions. https://www.the-tlb.com/

OpenWater Renewables Ltd (OWRL) is an independent UK-based consulting company with expertise in floating structures and offshore renewable energy and has developed a proprietary process for ranking FOW concepts.

TLB has engaged OWRL to conduct a study into the FOW foundations (hulls) best suited for the North Sea. The goal is to evaluate all available FOW concepts and identify a shortlist of those most likely to achieve a competitive LCOE with an acceptable risk profile for North Sea conditions.

This report presents the results of that study.

2.2 Scope of Work

The scope of work of the study is described below.

a) Agree with TLB a Basis of Design for the study, including the wind farm capacity and turbine size, water depth and metocean conditions.
b) Agree with TLB a preferred Project Execution Plan, including the target project schedule and UK content requirements.
c) Prepare a brief analysis of all FOW projects to date, sized >1MW, including project execution and operations & maintenance experience, where available.
d) Identify the “ideal characteristics” for a FOW foundation to suit the BOD and PEP requirements. Review the proposed characteristics in a joint workshop with TLB. The characteristics should include Technical, Execution and Commercial requirements, as applicable.
e) Based on the above, define a set of Project Weighting Factors to apply in the OWRL ranking tool (FOW_RANK). Where relevant, some weighting factors will be proposed as a range to allow sensitivity analyses to be run.
f) Agree on a cut-off criterion to be applied to screen out the most immature concepts. For example, exclude any that have not yet been comprehensively and successfully model tested.
g) Run the base case Ranking and any sensitivity cases to identify the concepts that come closest to the “Ideal” requirements.

h) Identify the top concepts in the base case and the sensitivity cases and present the relative scoring for each of these concepts.
i) Explain the results and the reason for the difference in scoring.
j) Present the study and its conclusions in a concise report.
k) Hold a workshop in London with TLB to present and discuss the preliminary results, before finalising the report.

2.3 Cut-off Date

This report has been prepared based on the FOW concepts available in the market as of the 31st of March 2025. New concepts launched after that date are not included.

3. Methodology

3.1 Basis of Design

A Basis of Design for the study was prepared after discussion with the TLB NST workstream, and the agreed-upon details are provided in the Datasheet in Appendix A.

The study is based on a fictional wind farm offshore Scotland, using some typical information from projects like ScotWind. However, it is not based on, nor directly related to, any specific ScotWind project.

The key parameters used for the study are.

- Capacity 750 MW
- Turbine Size 15 MW
- Water Depth 100 to 150 m
- Distance from shore 80 to 120 km
- Start of Operations 2030 to 2035

The project development plan for the FOW should enable the project to meet the UK Content targets [1], taking into account a range of supply chain assumptions for wind turbines, cables, and substations.

3.2 Process

The method for ranking FOW technologies is based on a comprehensive database of the characteristics of 107 FOW concepts being tracked by OWRL. These characteristics have been validated with many of the leading technology providers. Using this data in OWRL's proprietary tool FOW_RANK [18], each concept has been scored against criteria grouped into seven categories. These categories cover a wide range of technical, commercial and project execution details. A weighting is applied to each of these criteria based on a criticality assessment specific to the FOW industry, taking into account the entire project life cycle.

The default weighting factors can be supplemented by project weighting factors to address site or project-specific requirements. Section 5.1 of this report discusses the project weighting factors employed for this North Sea study.

Radar plots and stacked histograms are used to compare the concept scores across the seven categories of criteria. The total score from all criteria is used to rank the concepts.

The ranking process used is shown schematically in Figure 3-1 below.

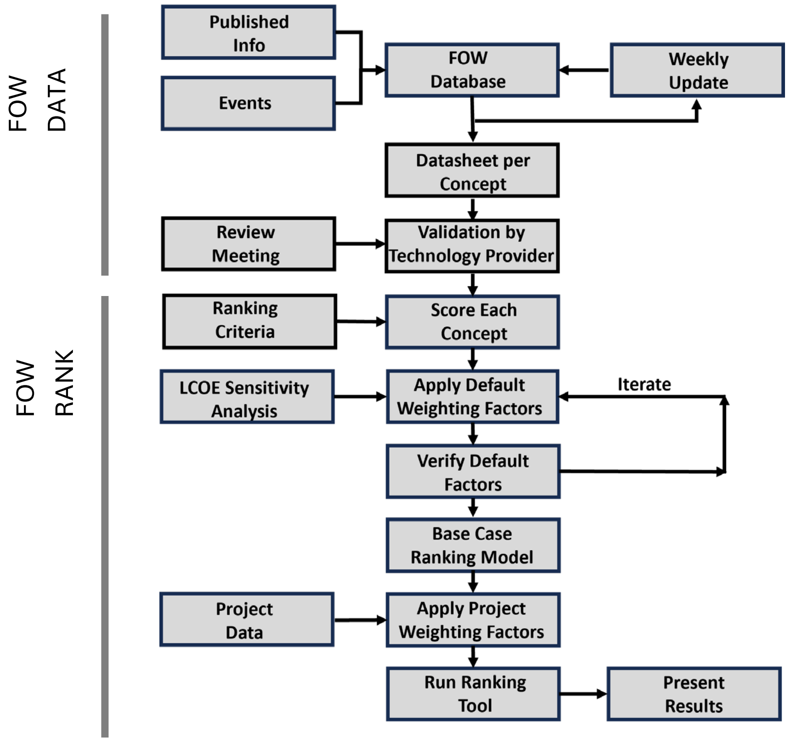

Figure 3-1: FOW Ranking Process Flowchart

3.3 Description of the FOW_RANK Tool

Using the data for each concept contained in the FOW database, 38 criteria for each concept have been systematically scored to create a concept profile in FOW_RANK. These criteria were developed through workshops led by an experienced team covering design, construction, installation, operations and maintenance, project management, and risk.

The criteria are grouped into 7 categories:

1. CAPEX (including materials of construction, ease of fabrication, transportation, ease of assembly, mooring system configuration, local content opportunity, etc.)
2. OPEX (including the need for ballast systems, reliance on large mechanical components, surface coatings, accessibility for inspection and maintenance teams, etc.)
3. Ease of installation (including towing requirements, the need for temporary equipment, offshore heavy lift requirements, etc.)
4. Ease of Major Repair (including disconnection, reconnection, stability and towing requirements)
5. Performance (including the level of nacelle motions, provision for trim and yaw control, etc.)
6. Risk (including TRL, CRL, financial strength of technology provider, etc.)
7. EPCI (including execution experience and strength of the technology provider, yard partnerships in place, schedule constraints, etc.)

Each criterion has a different level of impact on the project's LCOE or risk profile. To reflect this, weighting factors are applied to each score before they are added to determine the total score for each concept.

FOW_RANK uses two sets of weighting factors: Default Weighting Factors and Project Weighting Factors (PWF), which are described below.

a) Default Weighting Factors

A Default Weighting Factor is applied to each of the criteria, based primarily on a sensitivity analysis of their impact on LCOE and on the risk profile. Additionally, the overall weighting factor for each category has been adjusted to balance the relative contributions of each category. Default weighting factors remain constant for all ranking studies performed by OWRL.

b) Project Weighting Factors (PWF)

The default weighting factors can be supplemented with Project Weighting Factors (PWF) reflecting the specific challenges of a site or the particular concerns of the project developer. For the North Sea study, PWFs were determined through a workshop with OWRL and the TLB NST workstream, and these are detailed in Section 5.1 of this report. Additionally, a study was conducted to assess how sensitive the results are to variations in the selected project weighting factors, and this is reported in Section 5.3 and Appendix D.

More information on FOW_RANK can be found in a paper presented at the 2025 OTC conference [18].

4. Status of the FOW Market

4.1 A Historical Review of Installed FOW Units

A review of the current worldwide fleet of FOW units with a capacity of at least 1 MW was prepared and is included in Appendix B. The key points are summarised below.

A total of 41 units were identified, with a combined capacity of 281MW, of which 38 are still in operation. Norway and the UK (specifically Scotland) dominate the market, accounting for 62% of the installed capacity.

SPARs make up the most significant number of units, with 20 installed against 15 Semi-subs. Together, these account for around 90% of the installed capacity. Steel floaters are the most common, with 27 against 13 concrete hulls and 1 hybrid, although there is some evidence that concrete is gaining in popularity.

Technologies from Equinor and Principle Power Inc. (PPI) have been deployed most widely, accounting for 63% of the global fleet and over 70% of the accumulated worldwide FOW operating experience. The remaining 37% of the fleet, and 30% of the experience, is shared between 12 different technology providers, many of whom have only deployed a single pilot or demonstrator unit.

Siemens Gamesa and Vestas dominate the wind turbine market on floaters, accounting for over 80% of the accumulated experience, with 6 others making up the balance.

Capacity Factors (the ratio of average power generated to peak capacity) reported for FOW projects in Scotland and Norway are significantly higher than those achieved by UK fixed wind turbines, due to a combination of factors. However, there is insufficient data available today to identify any impact of FOW foundation type on the Capacity Factors.

Conversely, the reported availability of FOW units is lower than that of fixed wind, and there is some concern about a possible link between FOW motions and turbine reliability, although this is not yet well documented in the public domain.

Some issues with wind turbines on two test and demonstration FOW projects (Kincardine and Hywind Scotland) have required several units to be returned to port for major component replacement, and although one 6 MW generator has been exchanged in situ offshore, OWRL consider it likely that 'Return to Port' (R2P) will become the default strategy for major repair. The key uncertainty is around how frequently this will be needed.

Asset Integrity of FOW hulls is a relatively new area. Although the oldest unit (Hywind Demonstrator steel SPAR) has been in operation for 16 years, most of the worldwide fleet is still relatively young. Experience from Oil & Gas floaters shows that beyond 15 years offshore, the Asset Integrity of steel hulls can become challenging. We expect to see growing interest in concrete hulls as Asset Integrity issues and long-term OPEX for FOW hulls become better understood.

Feedback from some North Sea FOW units indicates that accessibility is critical, and there may be a need for helicopter access in adverse weather conditions. The ability to add a small helideck is seen as an important feature for harsh environments, enabling preventive maintenance to continue year-round.

4.2 Current Status of FOW Technology

OWRL is currently tracking over 100 FOW hull concepts that may be available to project developers. Approximately 60% of these concepts are currently being actively developed and marketed, while the remaining 40% have seen little to no development in recent years.

Some of these concepts are available in either steel or concrete, which brings the total to 107 hull solutions in the OWRL database at the cut-off date. Of these, 74 are based on steel hulls, with steel Semi-subs being the most common (50 concepts). There are 26 concrete-hulled concepts, with Semi-subs again being the most prevalent (10 concepts). Additionally, 7 concepts feature a hybrid design that combines both steel and concrete.

This is summarised in Figure 4-1 below.

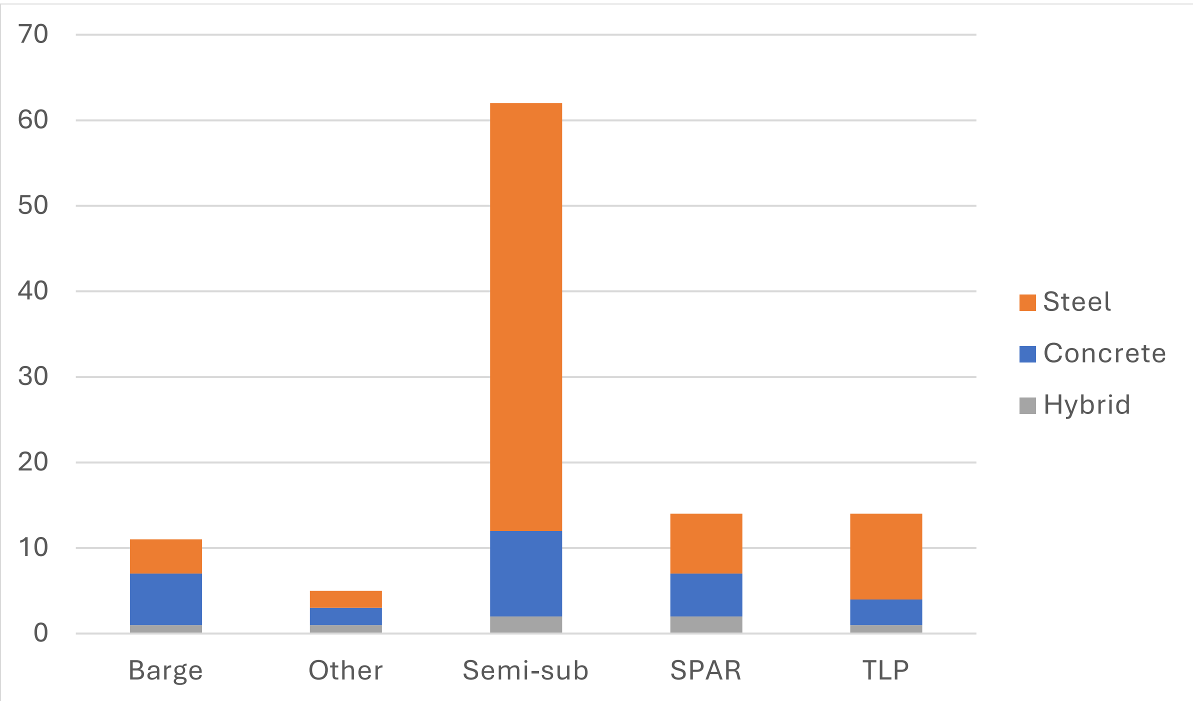

Figure 4-1: Material per hull type

The foundation concepts also vary widely in technical maturity. Using the Technology Readiness Level (TRL) process with a scale of 1 to 9 derived from DNV [2], NASA [3], ISO 16290[4], and Carbon Trust [21], OWRL has estimated the maturity of each technology.

Unfortunately, there is currently no accepted industry-standard definition of TRL for FOW. Moreover, none of the TRL processes in use are well-suited to FOW technology development. Hence, OWRL has developed and applied the following scale, which is derived from the tools available in the industry:

- TRL3 – Numerical Testing complete.
- TRL4 – Basin Testing of scale model complete.
- TRL5 – Detailed design of demonstrator completed for target offshore environment and turbine capacity ≥ 1 MW
- TRL6 – Pre-commercial unit (Demo/Pilot ≥1 MW) installed and operating.
- TRL7– Pre-commercial unit (Demo/Pilot ≥ 1 MW) successfully completed 3 years of operation.
- TRL8 – Commercial Farm (≥100 MW) installed and operating.
- TRL9 – Commercial Farm (≥100 MW) successfully completed 3 years of operation.

A more detailed definition of the TRL scale used by OWRL, and a comparison with other scales, is provided in Appendix C.

The OWRL definitions of TRL 8 and 9, therefore, refer to commercial farms with at least 100 MW capacity, but no FOW units have yet reached these TRLs.

Most of the tracked concepts are at TRL 3 or TRL 4, indicating they have been validated through numerical simulations or model basin testing. Nineteen concepts have progressed to TRL 5, but only 14 concepts have reached or exceeded TRL 6, which requires at least one prototype or demonstrator of ≥ 1 MW to be operational offshore. These include 7 Semi-subs, 4 SPARs, 2 barges, and 1 TLP. The remaining 93 concepts have not yet reached the stage of having a demonstrator or prototype of ≥ 1 MW at sea.

A literature review suggests that the average time to progress from a successful model test to a pilot or demonstrator unit at sea, i.e. to progress from TRL 4 to TRL 6, is about 6 years, with a range of 3 to 10 years.

The overall distribution of TRL levels for the concepts is summarised in Figure 4-2 below. Note that where a concept is available in both steel and concrete, it is counted as a single concept in this summary.

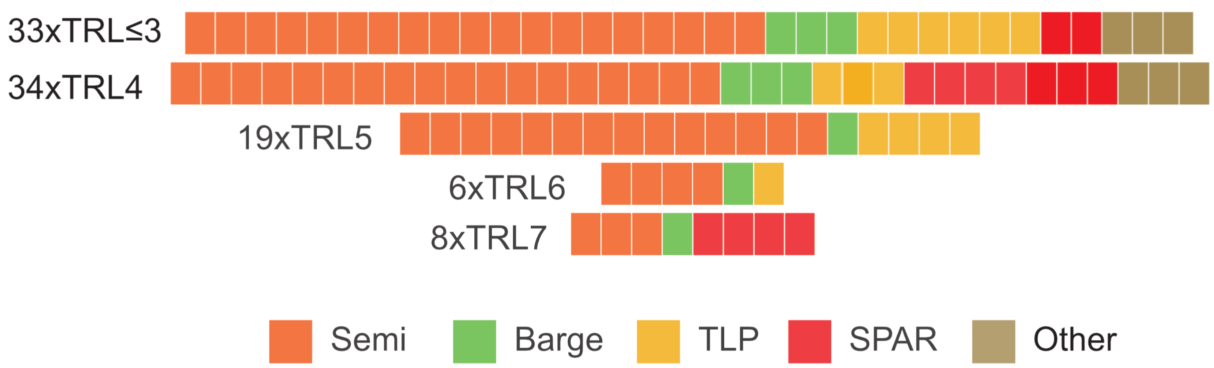

Figure 4-2: Summary of TRL levels by hull type

FOW concepts that have reached TRL 6 or 7, i.e. that have a demonstrator of at least 1 MW in operation now or previously, are discussed in Section 4.1 and Appendix B of this report.

It should be noted that, of the eight TRL 7 concepts, two projects (the JMU Advanced SPAR and the Mitsui Compact Semi-sub) from the Fukushima Forward research project have now been decommissioned and are no longer under development. Similarly, the TRL 6 MHI V-Shaped Semi, also from the Fukushima Forward research project, has been decommissioned and is not being proposed for new developments.

5. Study Results

5.1 Project Weighting Factors (PWF)

To define the Project Weighting Factors (PWF) for this project, the ideal FOW characteristics for the UK North Sea were first identified. This involved a detailed review of the 38 criteria from FOW_RANK, to define the preferred characteristics for a 15 MW North Sea FOW unit. This process was carried out in a workshop with members of the TLB NST workstream.

From that listing, the criteria that would have the most significant impact on LCOE and Project Risk for the fictional North Sea wind farm were identified and agreed upon. The selection of 15 criteria from the 38 in FOW_RANK was based on previous relevant experience for both oil and gas projects and FOW developments. PWF were then assigned to these criteria in 3 groups, depending on the perceived criticality.

The summary of the selected criteria for application of a PWF for this project is shown in Table 5-1 below, which are in addition to the Default Weighting Factors included in FOW_RANK.

Criteria Group	Criteria	PWF Group	PWF
CAPEX	Draft after Turbine Integration	A	2
	Local Content Opportunity	A	2
Installation	Ease of Installation	C	4
	Use of Temporary Buoyancy	C	4
	Use of Temporary Winches	C	4
	Offshore Vessel Requirement	C	4
	Towing Costs	C	4
OPEX	Accessibility	A	2
Performance	Nacelle Motions	A	2
Repair	Ease of Disconnection	B	3
	Laydown area	A	2
Risk	TRL	B	3
	Financial Strength of Company	B	3
EPCI	Engineering Strength	B	3
	Project Execution Strength	B	3

Table 5-1: PWF Groups

Criteria in FOW_RANK that are not included in Table 5-1 are still weighted with Default Weighting Factors, but the corresponding PWF was set to 1.

The short windows of calm weather in the North Sea mean that ease of installation is a key differentiator between concepts, hence for this study, that criteria group has been given the highest PWF.

The selection of PWF for a given project will depend on project conditions, the project developer's experience and preferences, and the concerns of financiers and insurers. The PWF adopted would typically be tailored for a specific FOW farm development, but for the present screening study, a sensitivity study has been conducted to assess the robustness of the base case concept rankings. This sensitivity study is reported in Section 5.3 and Appendix D of this report.

5.2 Base Case Analysis

The base case for the present study applied the PWF described in Section 5.1 to the 107 concepts contained in the FOW_RANK database. The resulting rankings were then filtered based on the following factors:

1. Concepts having achieved TRL 6 or TRL 7 and suitable for North Sea projects.
2. High-ranking concepts of any TRL suitable for North Sea projects.

The concepts with the highest overall ranking scores, based on these factors, are summarised in histograms in the following sections. These histograms also provide a breakdown of the scores of each concept in the 7 categories used in the ranking. Radar plots are provided to illustrate further the relative strengths and weaknesses of each concept within each ranking category.

Each histogram is normalised by the highest overall score of any concept, while the highest score within each specific category normalises the radar plot values.

5.2.1 TRL 6 & 7 Concepts for North Sea Projects

Before a concept is selected for a large commercial-scale project, OWRL recommends that the technology has reached at least TRL 7, i.e. a prototype should have successfully operated offshore for at least 3 years. This provides multiple benefits:

- Validation of analytical tools used to predict the performance over the life cycle,
- Reduced risk of serial failures (which may be uninsurable),
- Operational and maintenance feedback and integration of lessons learnt into the design of the commercial scale units,
- Supply chain, construction, integration and commissioning feedback into the next design,
- Lower contingency and design allowances needed for weight growth,
- Improved likelihood of obtaining project finance, and/or better rates,
- Improved terms for insurance.

Some concept developers argue that prototype or demonstrator projects are not needed to validate their concepts, and they can proceed directly from model tests to full commercial-scale deployment of multiple hulls on large commercial projects. OWRL believe that, even if the concept developer is a large and experienced offshore EPCI contractor, the risk of such a strategy could be difficult for many project developers, financiers and insurers to accept.

Of the16 concepts at TRL 6 or 7 (14 basic concepts, with 2 proposed in steel or concrete), a number were excluded from the ranking for UK North Sea projects, as identified in Table 5-2 below.

Concept	TRL	Reason for Exclusion
CTG Renewables Semi	7	Focused on Asian projects
Equinor Hywind Concrete	7	Draft too deep for UK ports
Equinor Hywind Steel	7	Draft too deep for UK ports
JMU Advanced SPAR	7	Fukushima Forward project – not offered commercially
Mitsui Compact Semi-sub	7	Fukushima Forward project – not offered commercially
Toda Hybrid SPAR	7	Draft too deep for UK ports – horizontal assembly but deep port required for repair
BW Ideol Damping Pool Steel	7	Concrete version more economic for commercial-scale development
MHI V-Shaped Semi	6	Fukushima Forward project – not offered commercially
Mingyang Ocean X	6	Twin turbines – special case (see section 6.4)
CNOOC Haiyou Guanlan	6	Focused on Asian fabrication
CSSC FuYao	6	Focused on Asian projects

Table 5-2: TRL 6 and 7 concepts excluded for consideration on North Sea projects

The ranking of the remaining 5 concepts at TRL 6 and 7 is shown in Figure 5-1. The two concepts at TRL 6 - Saitec SATH and SBM PGL (renamed Float4Wind) - are expected to reach TRL 7 by 2028. This timeline aligns with the study's requirement for operations to begin between 2030 and 2035.

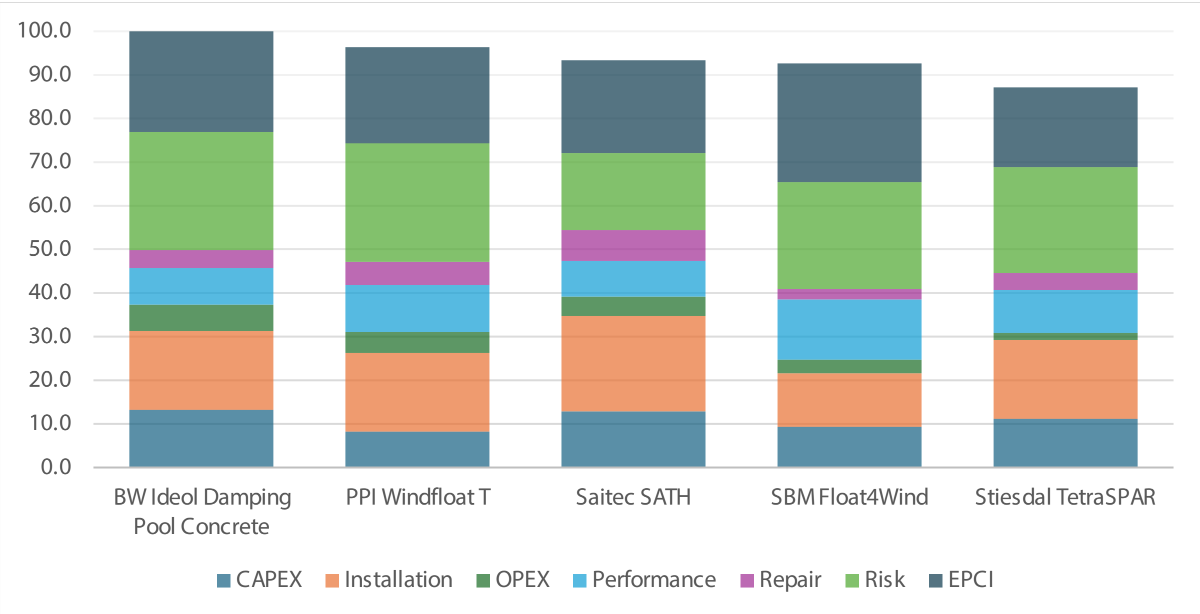

Figure 5-1: Ranking of TRL 6 & 7 concepts for North Sea projects

The overall normalised scores range from 100 to 87.2, and the relative scores of each concept in the ranking categories are shown in Figure 5-2 below. As a basis of comparison, the overall normalised score for this project of the concept ranked 100th in the OWRL FOW database is 49.

There is significant variation in the scores in all criteria categories, reflecting the strengths and weaknesses of the various concepts for their deployment in the North Sea.

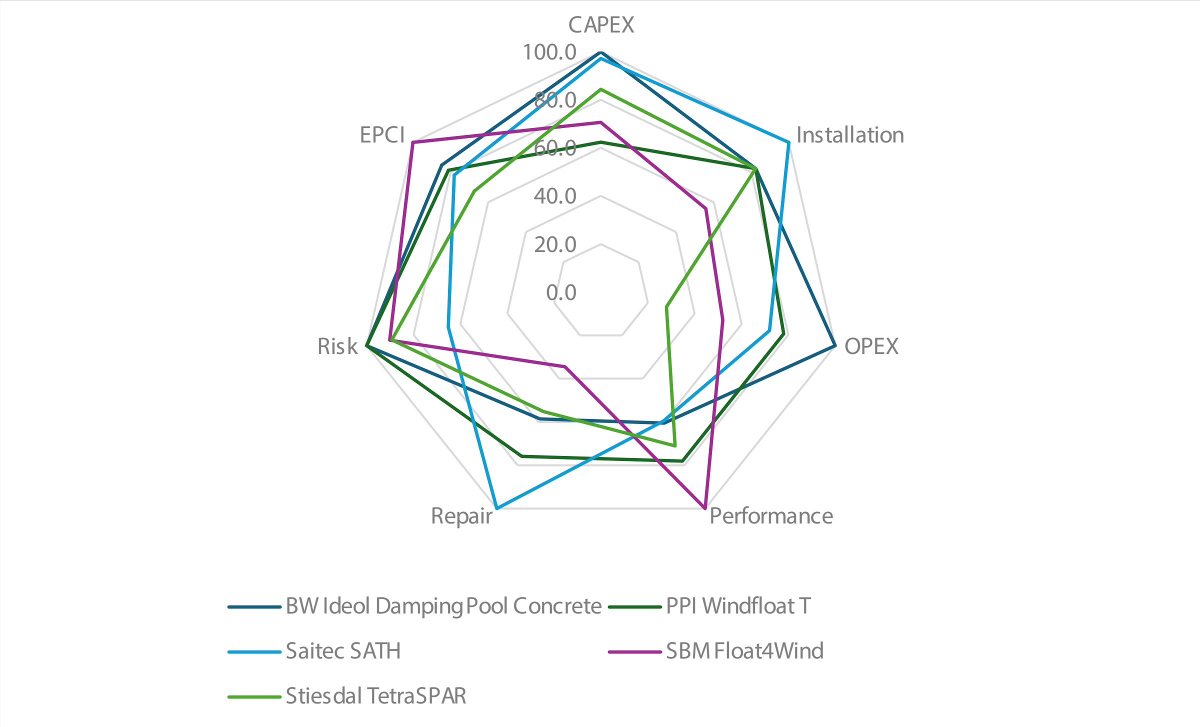

Figure 5-2: Relative score of TRL 6 & 7 concept ranking categories

The two concepts at TRL 7 (BW Ideol Damping Pool Concrete, and PPI WindFloat T) both show a favourable score for the risk category, whereas for example the SBM Float4Wind TLP scores highest for performance, and the SPM moored Saitec SATH barge has the highest scores for both installation and repair. The differences in these characteristics may influence the selection of a concept rather than overall score alone.

5.2.2 15 Highest-Ranked Concepts for North Sea Projects

Additional concepts currently at TRL 5 or lower could be considered for North Sea projects starting operation between 2030 and 2035. In this case, an accelerated development plan is recommended to qualify the technology to TRL 7 within the required timescale.

A ranking of the 15 highest-scoring concepts for North Sea projects, irrespective of their TRL, includes two concepts at TRL 7, two at TRL 6 and eleven concepts at TRL 5 (or lower). These are listed in Table 5-3 below. However, as with the TRL 6 and 7 concepts for North Sea projects discussed in Section 5.2.1, some concepts that would have featured in the 15 highest-ranked have been excluded from the ranking as being unsuitable for UK North Sea projects. These are identified in Table 5-4 below.

Concept	TRL	Hull Form	Material
BW Ideol Damping Pool	7	Barge	Concrete
Bouygues OO-Star	≤5	Semi-Sub	Concrete
PPI WindFloat T	7	Semi-Sub	Steel
Saipem Star-1	≤5	Semi-Sub	Steel
Saitec SATH	6	Barge	Hybrid
PPI WindFloat FC	≤5	Semi-Sub	Steel
Gusto TriFloater	≤5	Semi-Sub	Steel
Sevan SWACH Wind	≤5	Barge	Concrete
Equinor Wind Semi	≤5	Semi-Sub	Steel
Odfjell Wind Star	≤5	Semi-Sub	Steel
PPI WindFloat F	≤5	Semi-Sub	Steel
SBM Float4Wind	6	TLP	Steel
PPI WindFloat TC	≤5	Semi-Sub	Steel
Stiesdal TetraSub	≤5	Semi-Sub	Steel
Ekwil INOC	≤5	Semi-Sub	Steel

Table 5-3: TRL of 15 highest ranked concepts for North Sea projects

Concept	Reason for Exclusion
HHI Hi-Float	Focus on Asian projects
Equinor Hywind Concrete	Draft too deep for UK ports
SHI TriStar Float	Focus on Asian projects
Toda Hybrid SPAR	Draft too deep for UK ports – horizontal assembly but deep port required for repair
Mingyang Ocean X	Twin turbines – special case (see section 6.4)
CNOOC Haiyou Guanlan	Focus on Asian fabrication
BW Ideol Damping Pool Steel	Concrete version more economic for commercial-scale development
JMU Semi-sub	Focus on FOW offshore Japan but may license the Semi-sub elsewhere

Table 5-4: Exclusions from 15 highest ranked concepts for North Sea projects

The 15 highest-ranked concepts for North Sea projects are shown in Figure 5-3 below. The variation in normalised scores ranges from 100 to 88. Due to the relatively small variation in the scores of these highest-ranked concepts, small changes in the assessment criteria may change the ranking order. Consequently, the 15 concepts identified in this work should be considered as a pool of candidates, with strengths in different categories as shown in Figures 5.3 and 5-4 below.

The concepts at TRL 6, Saitec's SATH and SBM's Float4Wind (now Ekwil), are expected to reach TRL 7 by 2028, i.e. before the projected operational date of 2030 to 2035. The 11 concepts at TRL 5 (or lower) make the highest-ranked list for North Sea projects due to their design characteristics, plus the project execution experience and financial strength of the concept developers. Of these concepts, 1 is a barge (Sevan's SWACH Wind) and the remaining 10 are Semi-subs. These concepts would require rapid progress to deploy a prototype and reach TRL 7 in time for the development of commercial-scale designs within the target timeframe, to mitigate risk.

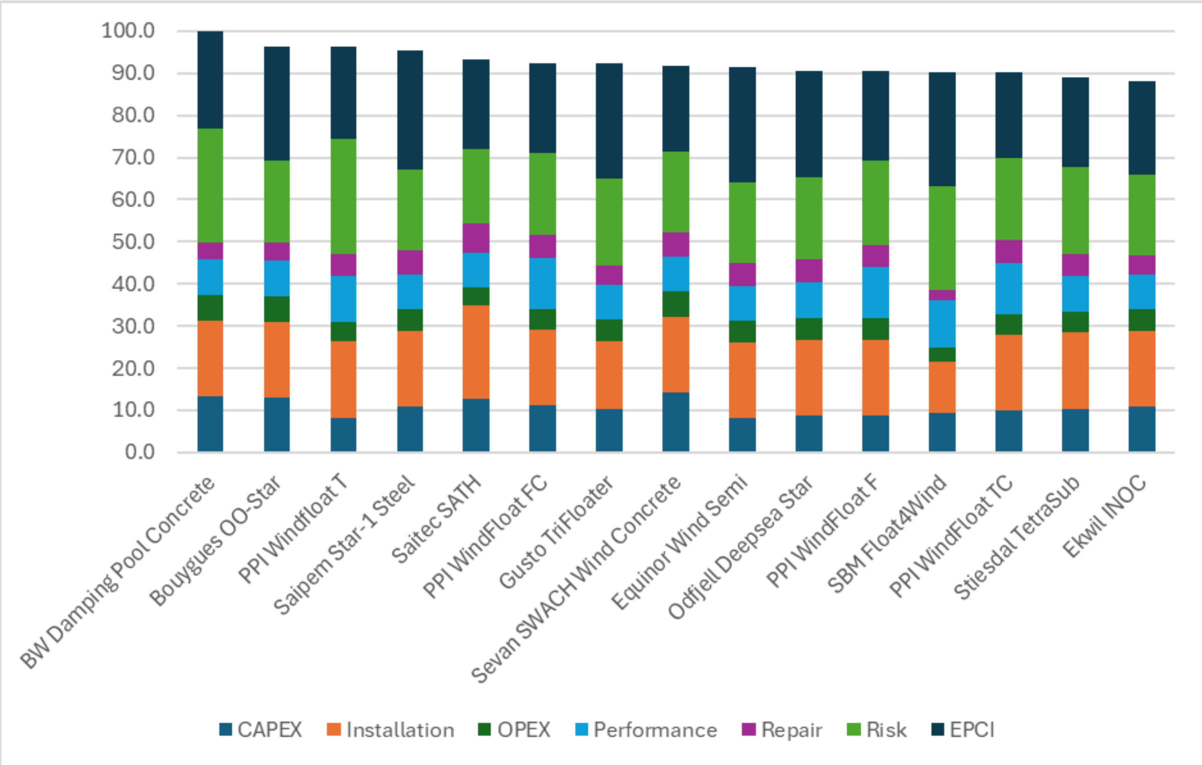

Figure 5-3: Scoring of the 15 highest-ranked concepts for North Sea projects

Figure 5-4 below illustrates the relative strengths and weaknesses of these concepts, with those at TRL 5 or lower exhibiting low scores in Risk due to their relatively low technical maturity. However, strengths in other categories, such as OPEX for the concrete Bouygues OO-Star and Sevan SWACH Wind, may encourage project developers to accelerate the deployment of a prototype, thereby increasing a concept's technical maturity.

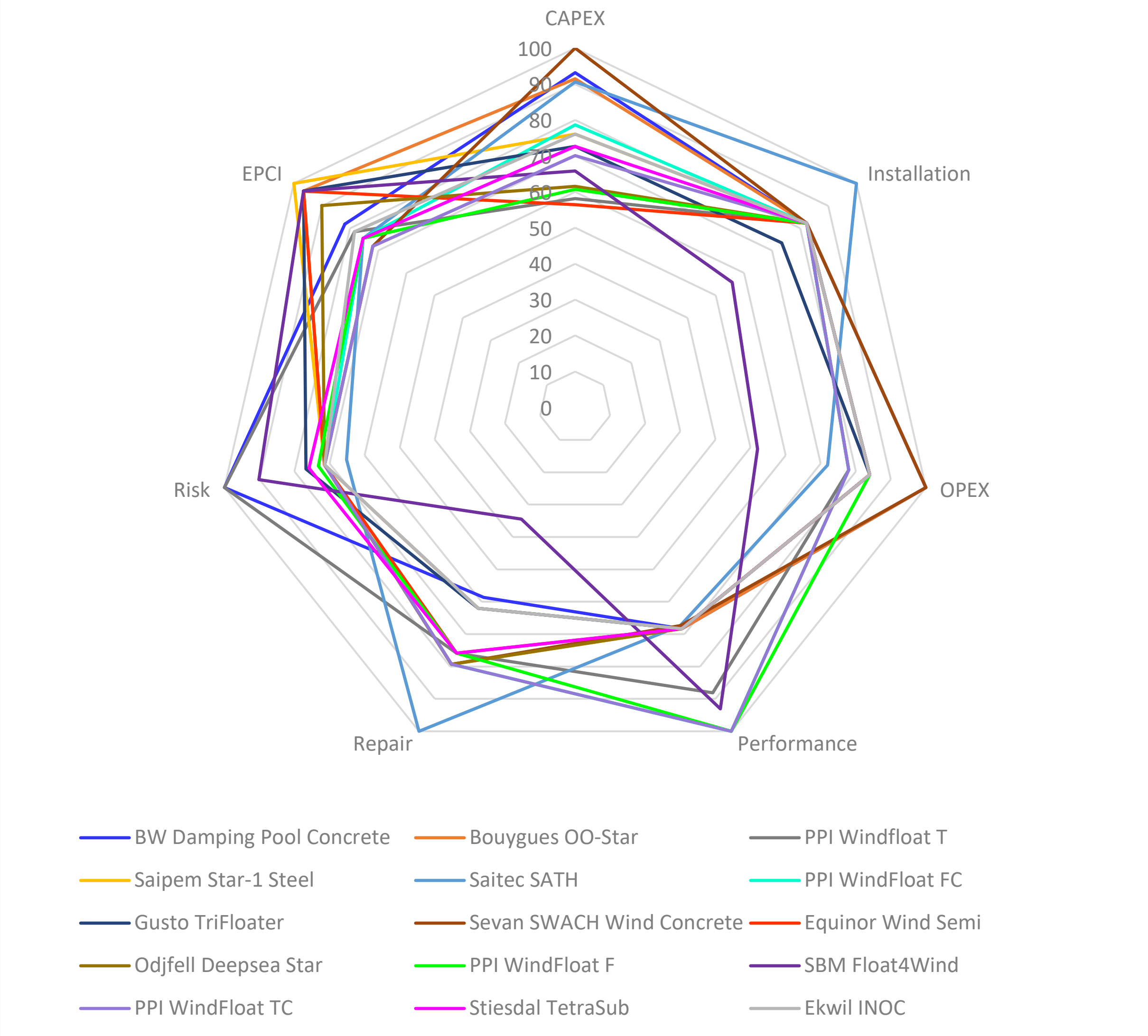

Figure 5-4: Relative score of the 15 highest-ranked concepts for North Sea projects ranking categories

5.2.3 UK-Based Concepts

The UK Government's 2050 Vision [17], Mission 5, aims to 'find and validate a winning home-grown foundation design by 2027.' However, no UK-based concepts have been highly ranked for North Sea conditions in the present study, generally due to the technical immaturity of the concepts, the weak balance sheet of the concept developers, and the limited EPCI experience of these companies.

The two highest-ranked UK-based concepts for North Sea conditions in FOW_RANK are:

- OSI UK FTLP (a bottom-fixed TLP) based in Whitburn, East Lothian, Scotland
- Trivane hybrid steel/concrete barge, based in Newquay, England

A detailed ranking of UK-based concepts is outside the scope of this study, but a further study of their score across the different ranking categories could provide a sound basis for a more focused development of the leading home-grown foundation designs.

5.3 Analysis of Sensitivity Cases

To examine the impact of the PWF values applied on the ranking of concepts, a sensitivity analysis was performed for 10 of the highest-ranked concepts for North Sea projects. The analysis was restricted to 10 concepts for clarity of presentation. This analysis is reported in Appendix D.

This analysis demonstrated that the concepts vary in sensitivity to the PWF applied, confirming the importance of reflecting client and project priorities in the selection of PWF.

6. Discussion

The following sections discuss the impact of hull selection on 3 critical areas.

- Commercial performance – CAPEX and OPEX
- Project Execution
- Operations and Maintenance

These areas are discussed in terms of the 5 groupings of the shortlisted concepts.

- Concrete barges
- Hybrid barges
- Concrete Semi-subs
- Steel Semi-subs
- Steel TLP

This discussion section is based on the following assumptions.

a) There will be sufficient fabrication yard and port space available to execute the project in the required timescale. We have not performed a yard survey at this stage and have relied on the findings from others [14, 22, 27]. It is assumed that the current investment plans will be sufficient to generate the required capacity in the schedule needed.
b) Concrete plants for FOW hulls will have aggregates available nearby, so we have not included the costs associated with importing aggregates to the site.
c) The target UK Content must be met in each scenario.
d) CAPEX is compared based on the EPCI contractor costs. Owners' costs are excluded.

6.1 CAPEX and OPEX

The objective of the ranking exercise in this study is to identify the foundation concepts which have the best chance of achieving an attractive LCOE with an acceptable level of project risk. The following sections discuss the impact of hull selection on CAPEX and OPEX and, hence, LCOE.

6.1.1 <u>CAPEX</u>

The main areas where the shortlisted concepts differ in terms of CAPEX are discussed below.
All four of the main hull types are available in either concrete or steel. As explained in section 5, only Barges Semi-subs, and 1 TLP have been shortlisted for our fictitious UK North Sea project.

Of the 15 shortlisted concepts, the distribution of the materials of construction is as follows.

	Steel	Concrete	Hybrid
Barge		BW Damping Pool Sevan SWACH	Saitec SATH
Semi-sub	PPI WindFloat-F PPI WindFloat-FC PPI WindFloat-T PPI WindFloat-TC Saipem Star-1 Gusto TriFloater Equinor Wind Semi Odfjell Wind Star Steisdal Tetra Sub Ekwil INOC	Bouygues OO-Star	
TLP	SBM Float4Wind		

Table 6-1: Hull material of the shortlisted concepts for North Sea projects

We can see that 3 out of 15 concepts use concrete hulls, 1 is a hybrid of concrete and steel, and the remaining 11 are steel hulls.

BW Ideol published a paper in 2016 comparing steel and concrete materials for their Damping Pool Barge [7]. This was based on the experience of building a steel and a concrete version of the Damping Pool barge for 2 separate projects. They concluded that the 2 hulls were equivalent in terms of performance, but that the concrete hull is significantly cheaper and has a much lower embedded carbon content.

At the OTC 2025 Conference TotalEnergies presented a paper "Concrete Floaters: A Promising Solution for Floating Wind Energy" [19], which concludes that "despite the challenges associated with their weight and load-out operations, concrete floaters present a competitive and cost-effective alternative to steel floaters in floating wind projects, particularly where efficient construction methodologies and local fabrication are employed".

In 2022, DNV performed a detailed comparison between steel and concrete hulls for floating wind projects [6] and considered both SPAR and Semi-sub hulls supporting 15 MW turbines. The study compared steel hulls built in Asia and shipped to Europe against concrete hulls built in Norway. The study concluded that the concrete hulls had a lower CAPEX (by around 40%) and a significantly lower carbon footprint.

The DNV study assumed that the steel hulls were entirely fabricated in the Far East and shipped complete to Europe. We believe this was pessimistic and that the CAPEX gap can be reduced in two ways.

a) Steel hulls built in Asia can be shipped as modules to the UK for final assembly and integration. This allows transportation costs to be optimised.
b) Some steel hull designs are transitioning from rolled plate and tubular construction to flat panel construction, enabling more automation and, consequently, lower fabrication costs (e.g., PPI's WindFloat-FC).

However, even with such optimisation, our analysis shows that concrete hulls would still be lower CAPEX than steel hulls for this typical UK project. Moreover, a concrete hull built in the UK has a high UK Content contribution, whereas by using steel hull modules from Asia, the UK content must be achieved in other ways, which will also impact CAPEX (see section 6.2.2 below).

Steel Semi-subs can be optimised for lower hull weights but there is a CAPEX trade-off between reducing hull weight and adding complexity through additional bracing. The multitude of steel Semi-sub designs encompasses various combinations of pontoons, columns, and bracings.

Comparing concepts reveals different approaches to steel weight and assembly time. Some hulls have been optimised for rapid assembly of hull modules, with few welded joints, whereas the other lighter braced structures require more complex alignment procedures and welding of multiple tubular joints.

The short windows of calm weather in the North Sea mean that ease of installation is a key differentiator between concepts. All of the shortlisted Semi-sub and Barge concepts should be suitable to use QCDC connectors for the mooring lines. However, the SATH barge is the only concept shortlisted using an SPM mooring, which enables rapid installation and disconnection, since the anchor lines and power cable can be pre-installed on a mooring buoy. On arrival in the field, the buoy is pulled into the mating receptacle and locked in position, which can be a rapid operation.

Only one TLP is included in the list of the 15 highest-ranked concepts, with a relatively low score. This is mainly due to the complexity of installation and the resulting high installation cost for North Sea projects. During the tow to site, the stability of a TLP is provided by buoyancy, but during installation, the provision of stability must be transferred from buoyancy to tension in the mooring tendons, requiring a more complex hook-up procedure than for other hull types. Some TLPs, such as the SBM Float4Wind, may require temporary buoyancy and temporary winches, which must then be removed, lengthening the overall installation period. This could lead to the need for multiple installation spreads to achieve the target number of units to be installed in one summer season. Significant waiting on weather (WOW) delays would also be likely.

6.1.2 OPEX

The shortlisted concepts will also differ in terms of OPEX, as discussed below.

Concrete hulls should have lower OPEX than steel hulls in areas related to maintenance, asset integrity and coating repair. Concrete is also a key enabler to a longer project life, with corresponding LCOE benefits (an extra 5 years of operational life can reduce the overall LCOE by around 5%, for example).

For the 500 MW EDF Fécamp wind farm offshore France, a consortium of Boskalis, Bouygues and Saipem has installed 71 concrete gravity base structures. Bouygues claim that this type of concrete structure can achieve a 100-year lifespan with minimal maintenance [8].

There is a longstanding tradition of concrete as a construction material for the marine environment, with well-established design and construction techniques. One example is the N'Kossa production barge, built of pre-stressed concrete, which has been operating offshore for 30 years and is expected to continue for a further 10 years [9].

Although similar levels of inspection will be needed for concrete and steel hulls, the level of repairs related to corrosion and coating on steel structures is expected to be significantly higher than the repairs needed for concrete structures due to spalling, for example.

Steel structures with complex bracing will likely be designed with an increased factor of safety against fatigue failure for nodes below water level to allow them to be considered as 'un-inspectable'.

Digital Twins are expected to be widely used for Asset Integrity management of hulls, whether they are made of steel or concrete. This technology has advanced quickly in recent years in the offshore industry and can be a significant benefit to FOW projects with multiple identical hulls.

As discussed above, SATH is the only shortlisted concept to use a Single Point Mooring (SPM). This allows the hull to weathervane around a fixed point, using a roller bearing (or friction bearing) and an HV electrical swivel. Both are mechanical components that will require regular planned inspection and maintenance. Both also have a failure rate (MTBF) and a repair time (MTTR), which may contribute to reduced overall system availability; however, an appropriate spare parts strategy can mitigate this.

The WindFloat variants have active ballast systems for the Hull Trim System (HTS), which will incur additional OPEX, although PPI claims this is offset by CAPEX savings and Performance gains.

6.2 Project Execution Plan (PEP)

This section discusses the impact of foundation selection on 3 critical areas of the PEP.

6.2.1 Project Schedule

The Basis of Design requires a total of 50 units to be installed over 2 summer seasons, meaning that the selected yards must build and integrate 25 units per year.

For concrete hulls, multiple production lines will be required, plus considerable space to allow the concrete structure to cure before turbine integration.

For steel hulls, an average delivery rate of one unit every 2 weeks will be needed to meet the schedule. The storage space required in the yard will be dictated by the length of the assembly and integration operation, and hence the number of parallel assembly lines.

In both cases, a sheltered anchorage will be needed to wet store multiple completed (or partially completed) units before the installation season begins [22], which must be addressed in the Environmental Impact Assessment for the project.

6.2.2 UK Content

The Basis of Design requires that the hull selection must enable sufficient UK Content for the overall project to meet the UK target. We have used the North Sea Transition Deal target of 50% UK Content [1] over the life cycle.

The UK Content analysis for the full project has considered 3 cases for the major components to investigate the impact on the execution plan for the hull.

	Hull	WTG	Cables and Substation
Base Case	Full UK Supply	Full Overseas Supply	Part UK Supply
Sensitivity Case 1	Blocks in Far East, Assembly in UK	UK Supply for Blades and Towers, Overseas for Nacelles	Part UK Supply
Sensitivity Case 2	Fully Assembled in Far East	Full UK Supply	Part UK Supply

Table 6-2: UK Content Cases

For the Base Case, whether steel or concrete, the overall UK Content, including OPEX, is above the 50% target if the hull is built entirely in the UK.

For Sensitivity Case 1, assuming a UK Content of 45% is achieved for the WTG (blades and towers), the hull must achieve around 45% UK Content to meet the target. Using a steel hull, approximately half of the hull blocks could be built in the Far East, and the remainder would need to be built in the UK, along with the full assembly scope.

For Sensitivity Case 2, assuming the hull steel blocks are built in the Far East and shipped to the UK for assembly and integration, 90% of the WTG CAPEX would need to become UK content – i.e. nacelles would need to be built in the UK (which is not currently envisaged) [28].

Using these 3 scenarios, we have run a budget-level (+/-30%) CAPEX estimate using our in-house tool for the full project based on a typical Semi-sub hull design. We have cross-checked this against the DNV report [4] for concrete and steel hull costs. The results are shown in Figure 6-2 below.

The Hull CAPEX is split down into 3 elements

- UK Scope
- Far East Scope
- Transport Costs (from the Far East to the UK).

The other 3 cost categories shown are

- WTG – the turbine costs, whether supplied from the UK or overseas
- Other Technical - including project manhours, mooring and anchoring systems, integration, commissioning, offshore installation, cables and substations, and insurance.
- Commercial – including profit, overheads, cost of finance, and contingency.

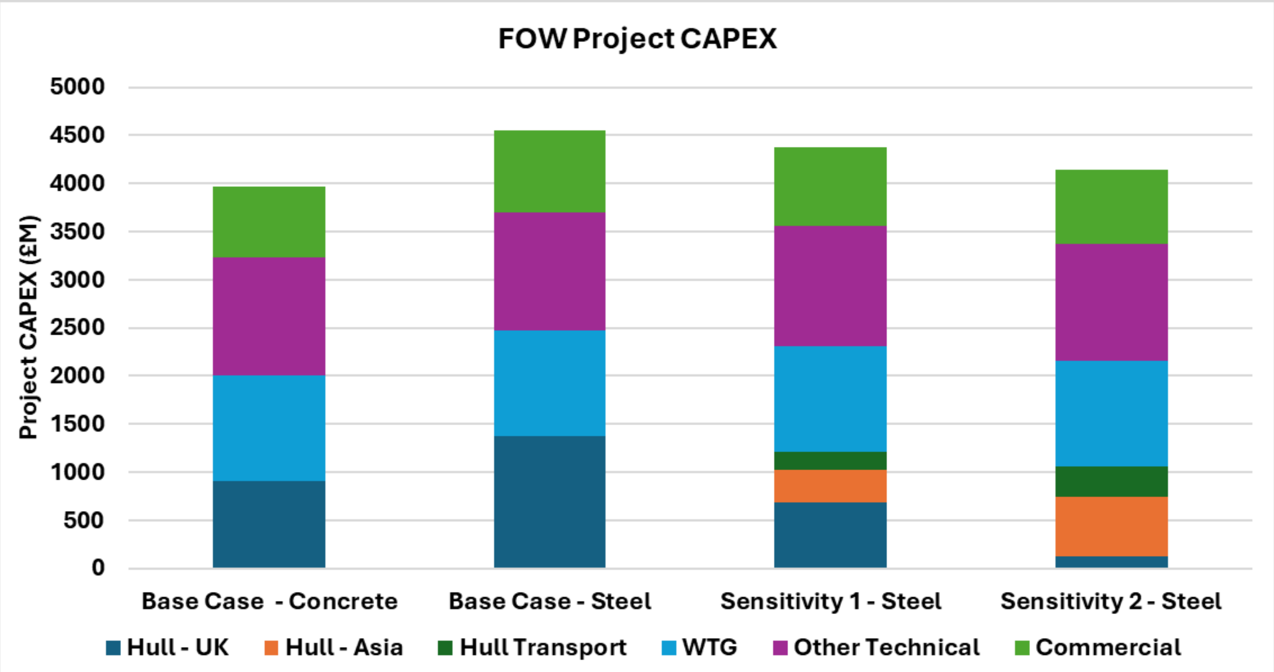

Figure 6-2: FOW Project CAPEX for Various UK Content Cases (750 MW Farm)

The analysis assumes that the concrete hulls would be built in the UK, to avoid excessive transportation costs, but that the steel hulls can be built in the UK, or the Far East (Sensitivity 2), or a combination of the two (Sensitivity 1). This assumes that UK port infrastructure has been developed and is available in time for the project timeline [22].

In the base cases, the WTG is assumed to be supplied from a European vendor. However, in the Sensitivity cases, we assume some UK content (blades and tower in Sensitivity 1, and full WTG scope in Sensitivity 2) to compensate for the reduced UK content in the hull fabrication.

The results show that the lowest overall project CAPEX is the Base Case in concrete, which is around 15% lower than the Base Case in Steel. This difference is driven by the cost of building steel hulls in the UK, which is approximately 30% higher than that of equivalent concrete hulls.

This difference between steel and concrete hulls can be reduced by fabricating hull blocks in the Far East and transporting these to the UK for assembly and integration. However, even with full or partial modularisation of the steel hulls in the Far East, the steel option is still around 5% to 10% respectively higher than the Concrete Base Case.

Further CAPEX reduction would be possible by considering WTGs from Chinese suppliers, where considerable discounts may be available. This option could be considered for the Base Case concrete and Base Case steel hulls, since no UK Content is required for the WTG. However, it would be more difficult for the Sensitivity cases where some WTG UK Content is needed to meet the target.

6.2.3 Port Selection

The Basis of Design defines the available water depth as 12m Chart Datum (CD). This is compatible with the main yards being suggested for the first FOW projects in Scotland, including Ardesier, Nigg Bay, Port of Cromarty Firth, and Scapa. A full yard review is outside the scope of this study.

Work has already begun on the redevelopment of Ardesier port for wind projects, including facilities to construct concrete hulls and a facility to recycle dredged sand as aggregate for concrete production [10].

As discussed in Section 5, no deepwater ports are available for SPAR fabrication and integration in the UK, since the draft could be in the region of 80m, so that option has not been shortlisted.

6.3 Operations & Maintenance

6.3.1 Performance

There are 2 main areas where the shortlisted concepts differ in terms of performance.

a) Static Incline.

The PPI WindFloat is the only shortlisted concept to have a Hull Trim System (HTS) designed to maintain the tower close to vertical. This HTS is patented by PPI [29] and consists of a redundant ballast system that redistributes water from column to column to compensate for changes in average wind velocity and direction, thereby maintaining the tower's mean tilt angle close to zero. This should reduce power loss from the turbine by maximising the rotor swept area, although gains can be small and come with additional OPEX.

The other shortlisted concepts rely solely on passive ballast and lack systems to actively adjust static trim to improve performance. Note that the Carbon Trust indicates that static incline has more of an impact on performance than dynamic motions [27] and has extensively studied the impact of static pitch angles on AEP [30].

b) Dynamic Motions.

Dynamic motions are generated by a combination of thrust from the turbine and wave action on the hull.

All concepts can be tuned to meet project nacelle motion limits, though generally at the expense of hull weight and CAPEX. This may involve increased ballast weight or changes in hull geometry (although this should avoid increasing wave loads).

The shortlisted concepts incorporate varied design features aimed at reducing dynamic motions within a compact design envelope:

- Steel Semi-subs, such as the PPI WindFloat T and Gusto TriFloater, typically feature heave plates or heave tanks on each column of the Semi-sub to increase entrapped water mass.
- Saitec SATH hybrid barge also incorporates heave plates.
- BW Ideol Damping Pool includes a patented system of stabilisation relying on entrapped water in the central pool.

Note that TLPs have inherently low motions, and the inclined mooring system of the SBM Float4Wind results in minimal nacelle motions. However, due to less favourable installation characteristics, the study has found that some TLP concepts are not well suited for North Sea conditions.

6.3.2 Reliability

With limited operational experience of FOW hulls and mooring systems, there is little direct feedback on reliability issues. However, the oil and gas industry's experience with similar structures provides much relevant feedback, indicating that high levels of reliability can be achieved. Nevertheless, there are also differences with FOW units, which may affect reliability levels. These are discussed below.

Oil and gas facilities are generally bespoke designs, with a project-specific execution plan, whereas FOW wind farms will have series-built hulls. This provides an opportunity to adopt a manufacturing approach to FOW hulls, with higher QA/QC standards than typical for oil and gas structures. However, where large numbers of FOW hulls are planned, module fabrication may be spread over multiple yards, negating some of the benefits.

Serial design and fabrication also have the potential to generate serial failures, requiring a high level of verification during design, procurement and fabrication to minimise risk. For this reason, OWRL believes that it is important for the hull concept to reach TRL 7 before moving into a commercial-scale project. However, since any significant changes to the structural configuration or connection details for the commercial-scale units may invalidate the concept TRL 7 status, the implications of such changes should be part of the project risk assessment.

The hull and mooring systems for oil and gas installations are generally designed for the 100-year return period design case, whereas FOW units are typically designed for the 50-year return period. This results in lower levels of reliability for FOW hull moorings. Combined with a large number of hulls, failures are likely to be more frequent than for oil and gas installations.

Production systems for oil and gas have redundancy in the mooring system as a requirement of Class, i.e. each mooring bundle comprises N+1 mooring legs. For FOW, this is typically not the case [24] and any requirement for redundancy will be a client decision. The failure of a mooring leg on a system without redundancy will result in loss of station keeping and potential damage to the power cable. (This is different for TLPs, where loss of a mooring leg could lead to the hull capsizing unless a redundant leg is provided.)

Synthetic rope is being considered for use in significantly shallower water depths than those deployed for oil and gas installations. For TLPs, chain and potentially synthetic rope are being considered for use as tendons rather than the steel tubulars typically used in the oil and gas industry. Operational experience is needed to validate the behaviour of these novel mooring systems.

However, it is worth noting that the oldest FOW in operation, the Hywind Demo / Zephyros One SPAR, has been in service for 16 years. The operator, Zephyros Ocean, has performed some life extension activities, but there are no reported reliability issues specific to the hull or mooring system [11].

The hull and mooring reliability topics discussed above could be addressed by industry bodies or by individual developers to achieve acceptable levels of reliability. However, current indications suggest that overall, FOW reliability is likely to be driven by the WTG, rather than the hull and mooring.

Due to a lack of publicly available information, there is uncertainty as to whether floater motions could be contributing to issues with WTG components.

6.3.3 Maintenance

IRM philosophies and procedures will be specific to the project and the project developer. However, there are 2 key areas where the shortlisted concepts differ in terms of their impact on maintenance.

a) Construction Material

Concrete hulls such as the BW Ideol Damping Pool and Bouygues OO Star should require similar levels of inspection but less maintenance than steel or hybrid hulls.

Experience with steel floaters for oil & gas installations indicates that IRM requirements for steel hulls increase as the installations age, particularly concerning fatigue, corrosion issues, repairs to hull coating or replacement of cathodic protection anodes. Although there is less experience with floating concrete hulls for oil & gas installations, these installations have generally had few integrity issues [9] and concrete FOW hulls are expected to require less maintenance over the full project life, leading to reduced OPEX.

b) WTG maintenance.

The ability to perform WTG maintenance on station is highly dependent on the metocean conditions at the FOW farm location. When conditions allow, change-out of nacelle components may be possible by lowering and raising components from a laydown area on the floater hull [27]. This approach may utilise the service crane in the nacelle to lift a larger crane in segments, which are then assembled on the nacelle. This was the method used by LiftOff to replace the generator on the PPI Kincardine WindFloat [12].

The above approach requires a suitable laydown area at the base of the tower that can be accessed directly from the turbine. Most of the shortlisted concepts inherently provide this capability, although some need to be adapted to make this effective.

6.3.4 Access

Both planned and unplanned operations will require access to FOW units for activities including:

- Planned regulatory inspections
- Routine planned maintenance
- Unplanned interventions for troubleshooting and repair
- Medical Evacuation (Medevac) in case of an accident during any of the above.

Obtaining year-round access to the FOW units in the North Sea projects will be challenging [26]. This is highlighted by the difficulty experienced in accessing Zephyros One offshore Norway, which led to the operator retrofitting a helideck to improve access [11]. Refer also to Appendix B for more operational feedback from the current global fleet of FOW units.

Achieving access is affected by several factors:

- Metocean conditions.
- FOW unit motion response.
- FOW unit facilities.
- Crew transfer means.

Planned access will be scheduled in accordance with metocean weather windows, but this will also be influenced by the response of the FOW units to the prevailing weather conditions. A project-specific analysis would be required to determine motions at the location of interest.

Multiple boat landing facilities can be provided on all shortlisted concepts, allowing CTV or SOV to approach from several directions – Carbon Trust estimates a 2% to 3% gain in availability if 2 or 3 boat landings are available [26]. However, access by CTV or SOV with W2W facilities is limited in harsh conditions. The access limits are dependent upon the FOW unit motions, the size and design of the CTV or SOV, and the performance of the W2W system.

Most shortlisted concepts have deck space available that would facilitate the fitting of a helideck, to permit access in harsher conditions. Routine access by helicopter may also be necessary for wind farms located far from shore, where the distance would make crew transfer by CTV impractical.

6.3.5 Major Repair Plan

Minor repairs to the hull and WTG will be carried out on station, but major repairs may necessitate R2P, i.e. disconnection of the FOW unit and return to port for repair against a quayside or in a sheltered location. The quayside requirements for repair will be similar to the requirements for the initial WTG integration. However, using a temporary up-tower crane to change components in the nacelle would remove the need for a quayside tower crane and may allow the operation to be performed in a sheltered inshore location away from a quay.

To facilitate quayside or inshore repairs, beneficial FOW characteristics include:

- A mooring leg QCDC system.
- An electrical cable QCDC system.
- Minimum preparation required for towing, e.g. no need for attachment of temporary buoyancy or retrieval of a suspended counterweight.
- A hull form with low drag and high stability.
- A draft suitable for several local repair quaysides.

Several QCDC systems are under development, and although not yet implemented, they could likely be integrated into all the shortlisted concepts. However, the Saitec SATH should benefit from only needing a single QCDC mechanism due to its SPM mooring. Electrical cable QCDC systems, once qualified, should be common to all shortlisted systems.

Typical mooring QCDC systems cannot easily be integrated into TLPs, which need to transfer stability provided by the tension in the tendons to stability provided by buoyancy. The complexity of mooring connection and disconnection is a contributor to the low score for TLPs for North Sea applications.

All other shortlisted concepts have high stability during tow, with the Saitec SATH expected to have the lowest drag. None of the concepts require significant preparation for towing, although changes in ballast may be beneficial to either further increase stability or reduce draft and the associated drag.

6.4 Special Case – Mingyang Ocean X

One further interesting hull concept was ranked highly, and although it has not been included in the final top 10 list, it is worthy of discussion. This is the Mingyang Ocean-X twin rotor unit, developed under a licence from Nezzy[2] [15, 16].

The prototype, fitted with two 8.3 MW Mingyang turbines, has been operating in China since late 2024 and has already withstood the impact of Super Typhoon Yagi. The concept benefits from several interesting features.

- The hull is a simple concrete structure.
- The twin turbines have counter-rotating blades, which Mingyang claims will increase power generation by 4.29% [13]
- The unit is moored by an SPM, which makes installation rapid and allows for easy disconnection for major repairs.
- The concept is one of the very few examples of a fully integrated design between hull and WTG offered by an OEM.

However, there are also some concerns with this concept.

- The inclined towers mean that there is no laydown area below the nacelles. Any crane operations would have to be directly to/from SOVs, which would be very difficult in typical North Sea weather conditions.
- The design incorporates two downwind turbines that stay fixed relative to each other, i.e. the nacelles are not able to yaw. Instead, the structure weathervanes around an SPM. As the turbine orientation is fixed relative to the supporting hull, this could introduce a misalignment between the WTG orientation and the prevailing wind, resulting in power loss.
- The SPM adds mechanical components that will require maintenance,
- Access is poor, and the design would need further development for North Sea conditions.
- The hull and WTG must be procured from the same OEM, which may be incompatible with typical UK project supply chain strategies.

Overall, this is an interesting concept, but it requires further development to address O&M concerns for North Sea projects. Hence, despite reaching TRL 6 in China, OWRL does not consider it ready to be shortlisted for North Sea projects at this stage.

7. Conclusions

A historical review of the current worldwide fleet of FOW units with a capacity of at least 1 MW has identified 41 units rated at a total of 281 MW, of which 38 are still in operation. The review analysed the breakdown of this global fleet and gathered performance and O&M data, which was then used as background information for the study.

The proprietary FOW_RANK tool was used to perform a ranking study for a fictional FOW farm of 750 MW, located offshore Scotland. Foundation concepts were ranked to identify those likely to lead to the lowest LCOE with an acceptable level of risk. Project Weighting Factors were developed based on the most critical criteria relevant to this fictional project and its location, including installation, accessibility, performance and risk.

The FOW_RANK process yielded the following pool of 15 shortlisted concepts for this fictional North Sea project, based on the highest ranking scores.

- BW Ideol Damping Pool Concrete
- Bouygues OO-Star
- PPI WindFloat T
- Saipem Star-1
- Saitec SATH
- PPI WindFloat FC
- Gusto TriFloater
- Sevan SWACH Wind
- Equinor Wind Semi
- Odfjell Wind Star
- PPI WindFloat F
- SBM Float4Wind
- PPI WindFloat TC
- Stiesdal TetraSub
- Ekwil INOC

The above pool of concepts comprises 3 barges, 11 Semi-subs, and 1 TLP. The hulls for 3 units are built in concrete, 11 in steel, and one is a concrete/steel hybrid. Thirteen are spread moored, 1 incorporates tension legs, and one 1 uses an SPM. It is notable that the shortlist therefore encompasses a diverse range of available basic concept types.

A key selection criterion is technical maturity, but only 4 of the above shortlisted concepts (BW Ideol Damping Pool Barge, PPI WindFloat T semi, Saitec SATH barge, and SBM Float4Wind TLP) are currently at TRL 6 or higher. The 11 other concepts were rated highly for North Sea conditions due to their inherent design characteristics as well as the financial and project execution strength of the concept developers. However, these 11 concepts currently have a lower level of maturity as they lack a prototype demonstrator, which is a critical risk mitigation before entering full-scale commercial deployment. These 11 concepts, 10 semi-subs and 1 barge, would need to quickly progress to a higher TRL to enable final selection within the project schedule defined in the study basis.

A CAPEX and OPEX analysis of the different FOW hull types shows that variations between shortlisted concepts are in the region of up to 15%. The lowest CAPEX and OPEX, and hence LCOE, was found to be a concrete foundation – either a Barge or Semi-sub. Concrete hulls have a range of other advantages, including service life, robustness and easier delivery of UK Content, which makes them attractive candidates.

Steel semi-sub hulls are also a robust option, and there is a range of suitable concepts to choose from, albeit some are lower TRL and therefore currently have a higher risk profile. Steel semi-subs have a higher CAPEX if built in the UK, although this could be somewhat mitigated by partial or full fabrication of the hull modules in the Far East, which are then transported to the UK for assembly and integration. However, the loss of UK Content from the hull fabrication must then be compensated by increased UK Content for the WTG. Moreover, OPEX will be higher for the steel Semi-sub, especially in later life, due to preventative maintenance needed to maintain Asset Integrity as the steel unit hulls age.

The Saitec SATH, being a hybrid steel and concrete construction, was found to have some of the benefits of a concrete hull, but also the drawbacks of a steel hull. It is the only shortlisted concept with an SPM mooring, which allows rapid installation and disconnection, but also introduces critical mechanical components which must be inspected and maintained throughout the unit's life.

The main pros and cons of the different groups of concepts can be summarised as follows;

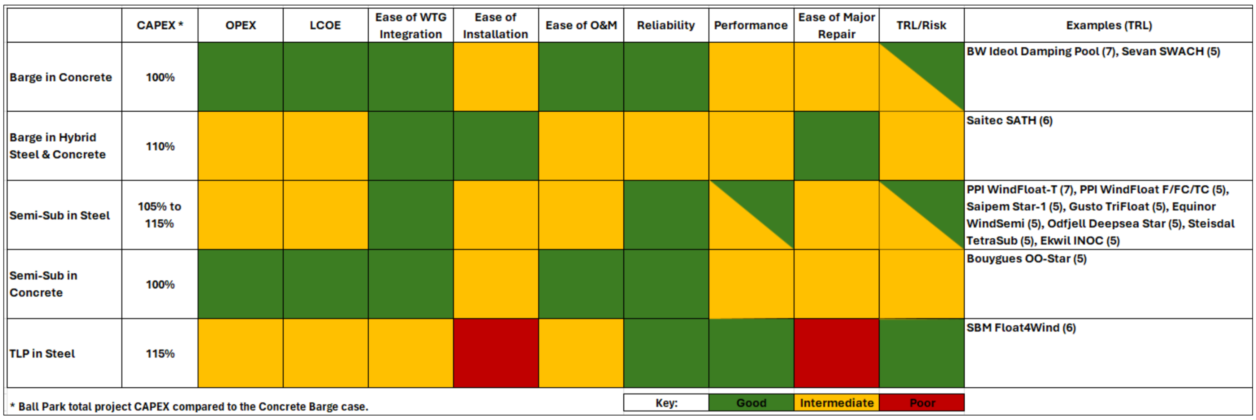

Figure 7-1: Generic Concept Pros and Cons

Deep-draft SPARs were excluded from the shortlisted pool because they depend on deepwater port facilities for turbine integration and repair at quayside, but suitable facilities are not available in the UK.

It should also be noted that, although only one TLP is included above due to the complexity and cost of installation in North Sea conditions, projects with milder metocean conditions may rank TLPs more highly, given their light weight and limited motions once installed, which can lead to a positive impact on AEP.

8. Recommendations

Based on this study, OWRL recommend the following actions.

a) Develop an Industry-Standard definition of TRL for FOW projects, clarifying the criteria needed to achieve TRLs 7, 8, and 9.
b) Verify the minimum FOW hull TRL level needed to obtain competitive project finance and insurance for major projects.
c) Investigate the long-term escalation of OPEX for ageing FOW units, including the OPEX difference between Concrete and Steel hulls.
d) Further study into the possible impact of floater motions on WTG reliability.
e) Accelerate the TRL progress for some promising FOW concepts that are not yet at the prototype/demonstrator stage. The 11 concepts below, all part of the shortlisted pool of concepts for the fictional North Sea project, are suitable for fabrication in UK fabrication facilities, subject to available capacity:

- Bouygues OO-Star
- Saipem Star-1
- PPI WindFloat FC
- Gusto TriFloater
- Sevan SWACH Wind
- Equinor Wind Semi
- Odfjell Wind Star
- PPI WindFloat F

- PPI WindFloat TC
- Stiesdal TetraSub
- Ekwil INOC

f) Study the leading UK-based concepts to examine their ranking and determine the scope and potential timeline to optimise their development paths for selection for North Sea projects.

9. Glossary

AEP	Annual Energy Produced
BOD	Basis of Design
CAPEX	Capital Expenditure
CD	Chart Datum
CP	Cathodic Protection
CRL	Commercial Readiness Level (see Appendix D for definition)
CTV	Crew Transfer Vessel
EPCI	Engineering, Procurement, Construction and Installation
FOW	Floating Offshore Wind
Hs	Significant Wave Height
IRM	Inspection, Repair and Maintenance
LCOE	Lowest Cost of Energy
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
OWRL	OpenWater Renewables Ltd
PEP	Project Execution Plan
PWF	Project Weighting Factors
PPI	Principle Power Inc
QCDC	Quick Connect and Disconnect
R2P	Return to Port repair strategy
SOV	Service Operations Vessels
SPAR	Single Point Anchor Reservoir
SPM	Single Point Mooring
TLB	Technology Leadership Board
TLP	Tension Leg Platform
TRL	Technology Readiness Level (see Appendix D for definition)
W2W	Walk to Work
WTG	Wind Turbine Generator
WOW	Waiting on Weather

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Appendix A - Basis of Design

NST2501 - FOW Ranking Report

Datasheet

Datasheet	DS01	REV:	A3	By:	MWW	SHEET	1
TITLE:	Basis of Design						

	Subject	Units	Data
1	FOW Farm Location		North Sea
2	Capacity	MW	750
3	Turbine Size	MW	15
4	Number of Units		50
5			
6	Water Depth	meters	100 to 150
7	Soil Conditions		Suitable for drag anchors or suction anchors
8			
9	Distance from shore	km	80 to 120
10	Distance from Assembly port	km	125
11	Distance from O&M port	km	125
12	Water depth required at port	meters	<12
13			
14	Date - Start of Operation		2030-2035
15	Schedule		Install over 2 summer seasons
16	Field life	Years	25 for Base Case, 30 for Sensitivity Case
17	Foundation Material		Open - Concrete, Steel or Hybrid
18	Coatings		Suitable to ensure full design life without need to recoat
19			
20	Mooring Redundancy		None, unless required for stability
21	Accessibility		CTV, W2W from SOV, Helicopter drop onto nacelle as a minimum
22	Laydown		Space for at least 1 container loaded from an SOV
23			
24	Contract Basis		EPCI
25	Local Content Requirements	%	Minimum 50% UK expenditure over life cycle (CAPEX + 6 years OPEX)
26	Module Fabrication Site		Open, subject to the above Local Content requirements
27	Assembly & Commissioning Site		UK port
28			
29	Turbine Supply - Base Case		Overseas content
30	Turbine Supply - Sensitivity Case 1		Blades and Towers in UK, Nacelle overseas
31	Turbine Supply - Sensitivity Case 2		Full UK content
32	Cable Supply		Full UK content
33			
34			
35			
36			
37			
38			
39			
40			

Appendix B - A Historical Review of Installed FOW Projects

A Historical Review of Installed FOW Projects

March 2025

1. Introduction

This paper reviews the current worldwide fleet of Floating Offshore Wind (FOW) units and their historical performance. It considers all FOW units that have been installed in open sea with a capacity of at least 1 MW, whether these are still operational or have since been decommissioned.

There has been a slow but steady increase in the global installed capacity of FOW units since the first pilot was installed in 2009, as shown in Figure 1, with a clear acceleration in the last 5 years.

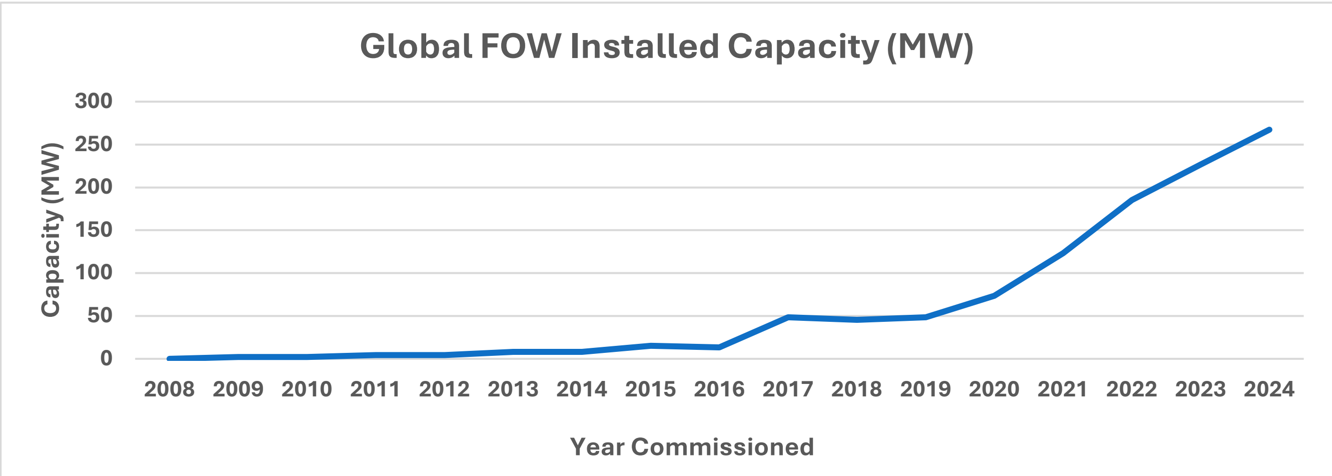

Figure 1

2. Distribution of FOW Technology

From our database, we identified 41 FOW units that meet the above criteria, with a total capacity of 281 MW. Of these, three have been decommissioned, leaving 38 units in operation today, with an installed capacity of 267 MW. (Note - WindFloat-1 was relocated from Portugal to Scotland but has only been counted once.)

The cumulative operating experience of the FOW industry today is around 176 unit-years (defined as 1 unit operating for 1 year), including those units now decommissioned.

We have analysed the global FOW fleet in terms of.

- Location
- Hull type and materials of construction
- Technology providers
- Wind turbine suppliers

The results from this analysis are shown in the following graphs

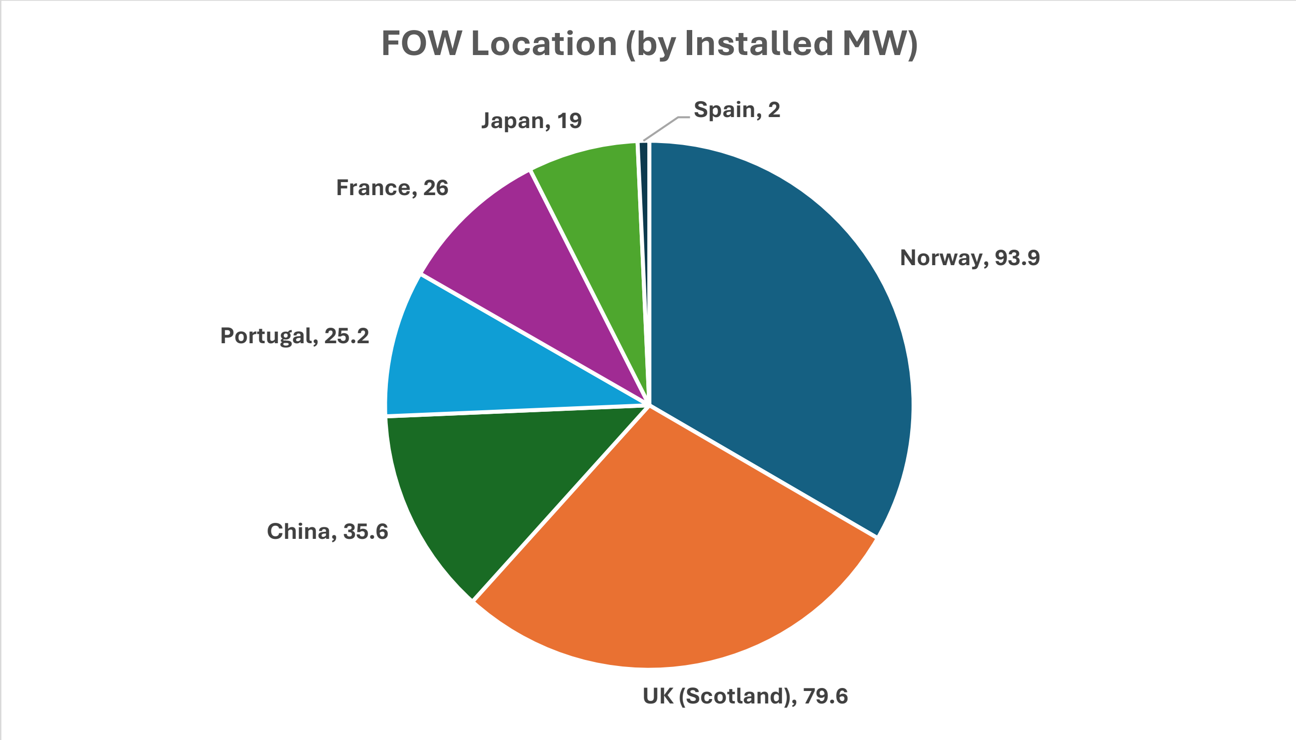

Figure 2

Firstly, considering the units' location and installed power (including the 3 units now decommissioned), we can see from Figure 2 that Norway and the UK (Scotland) dominate the market, with 173.5 MW installed (62% of the total installed capacity).

European FOW projects, including those in Portugal, Spain and France, make up a further 53.2 MW (19%), and the remaining 54.6 MW (19% of the installed capacity) is in China and Japan.

Secondly, looking at the type of hull used around the global FOW fleet, by number of installed units, we find in Figure 3 that SPARs are slightly ahead of Semi-Subs, at 20 units versus 15. In comparison, barges and TLPs have been much less widely deployed to date.

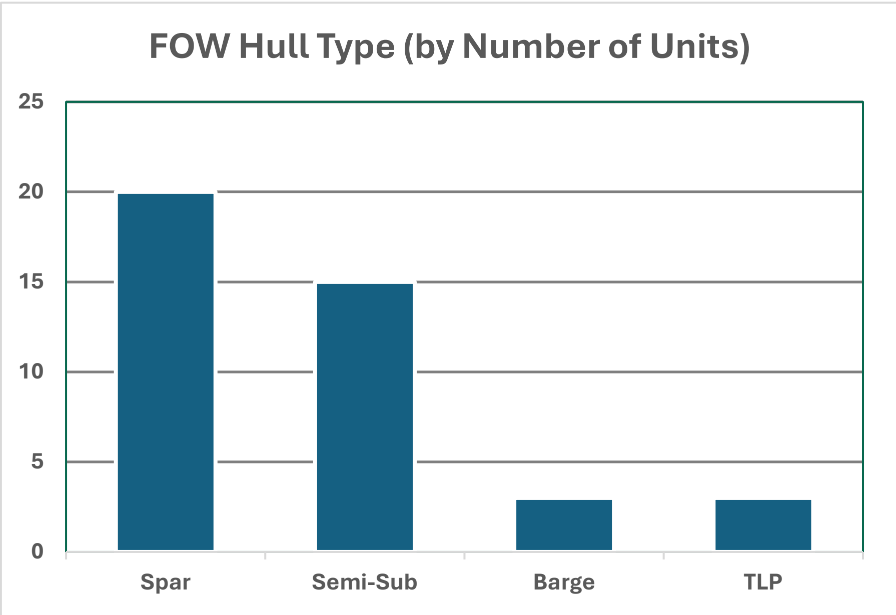

Figure 3

Although Semi-Subs have been selected for more demonstrator projects than SPARs (10 projects versus 6 projects), the large number of units installed on two Hywind projects pushes the total number of SPARs installed into the top position.

When the total installed capacity of the different hull forms is included, the gap between SPARs and Semi-Subs is closer at 47% and 42% respectively, followed by 9% for TLPs and 2% for barges.

Next, we have also analysed the materials of construction for the 41 units, which are shown in Figure 4 below. We can see that most of the units installed today have steel hulls, with 27 units against 13 concrete units and 1 hybrid concrete + steel (Saitec's SATH).

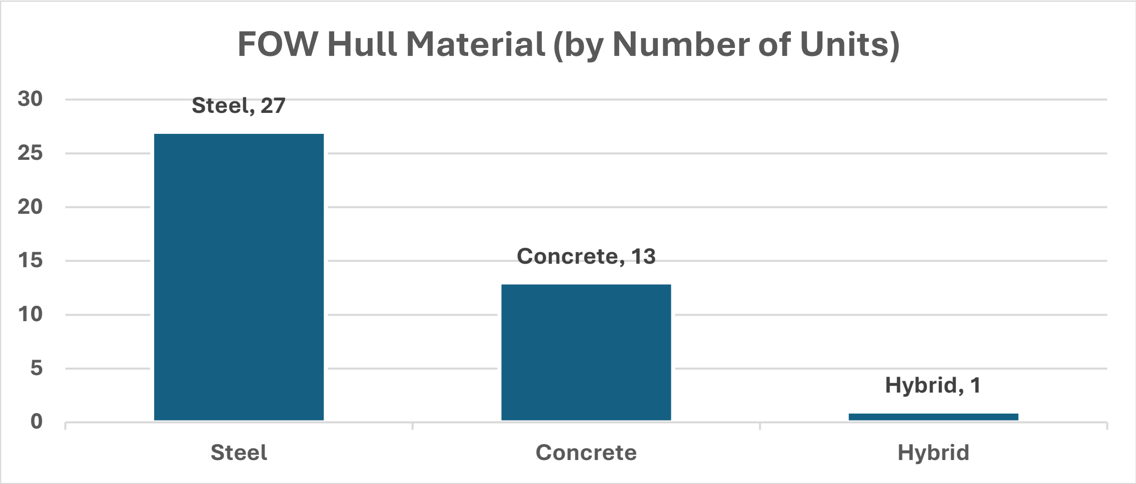

Figure 4

However, many of the concrete-hulled units have been installed relatively recently (such as the Hywind Tampen project and Mingyang's OceanX). If we compare the unit-years of operational experience, we find that 80% of the accumulated experience is with steel hulls, against 19% for concrete and 1% for hybrid. It is interesting to note that Equinor, in its drive to reduce LCOE, switched from steel SPARs on Hywind Scotland to concrete SPARs on Hywind Tampen.

Moving to Technology Providers, the picture becomes more complex as there are already 14 different designs of floating foundations installed, and 2 of these have also been supplied in both steel and concrete materials. Figure 5 shows that, when considering the number of operating FOW units, the designs from Equinor and Principle Power Inc (PPI) dominate with 63% of the total global fleet between them, followed by SBM Offshore and BW Ideol, ranked third and fourth respectively.

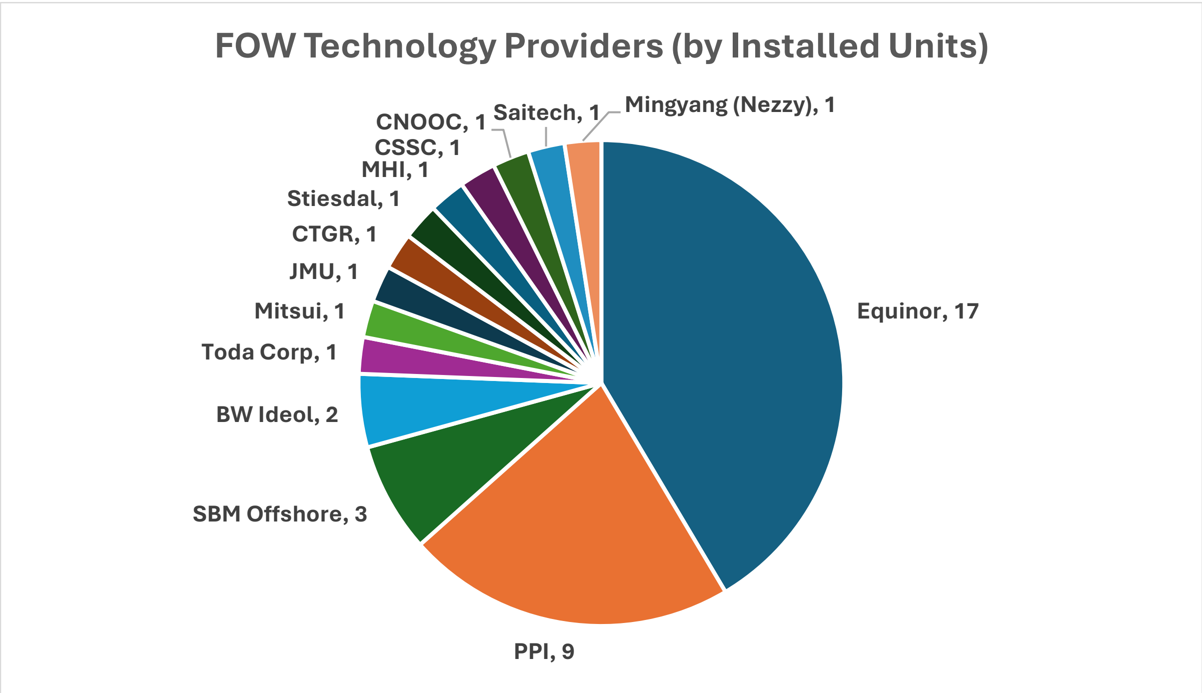

Figure 5

If we include the capacity of the units in the analysis, we get a slightly different view by summing the installed MW from each technology provider. Equinor and PPI still dominate with 69% of the global fleet capacity, and SBM Offshore remains in 3rd place, but Mingyang moves into 4th place due to their large demonstrator installed in China (based on a licence for the Nezzy[2] hull concept (Ref 1)). BW Ideol drops to 9th position in this analysis, due to the relatively small capacity of their two demonstrator projects in operation.

Finally, if we compare the Technology Providers by the accumulated operating experience of their foundation designs in unit-years (defined as 1 unit operating for 1 year), we get a different picture – see Figure 6 below.

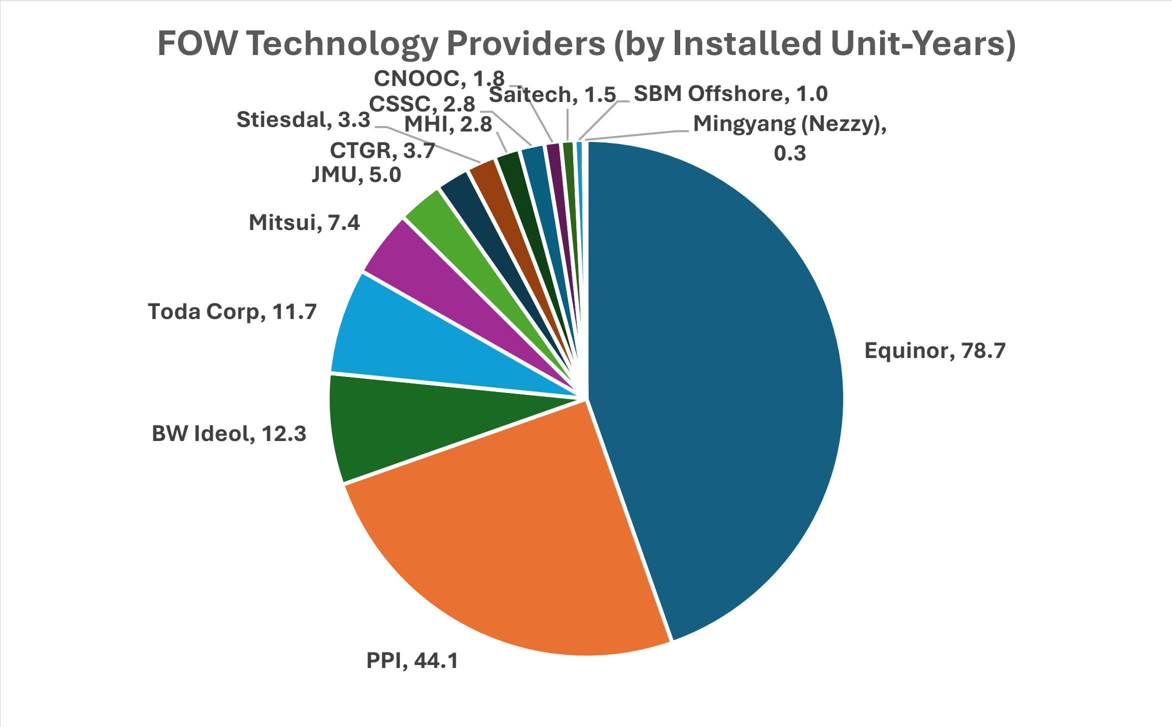

Figure 6

Whereas the Equinor and PPI designs still have the most operating experience, at 122.8 years (70% of the total), BW Ideol now comes third with 12.3 years (7%). Two Japanese companies, Toda Corporation and Mitsui, have also built considerable experience from their demonstrator projects in Japan, with a total of 19.1 years (11%) between them.

The two new demonstrator projects using technology from SBM Offshore and Mingyang (Nezzy[2]) currently rank lowest since both have only been operating for a few months.

Figure 7 (overleaf) shows the leading FOW turbine suppliers, again by installed unit-years of operating experience on the floaters. We see that Siemens Gamesa dominates the market with 83.1 years (47% of the total operational years), followed by Vestas and Hitachi.

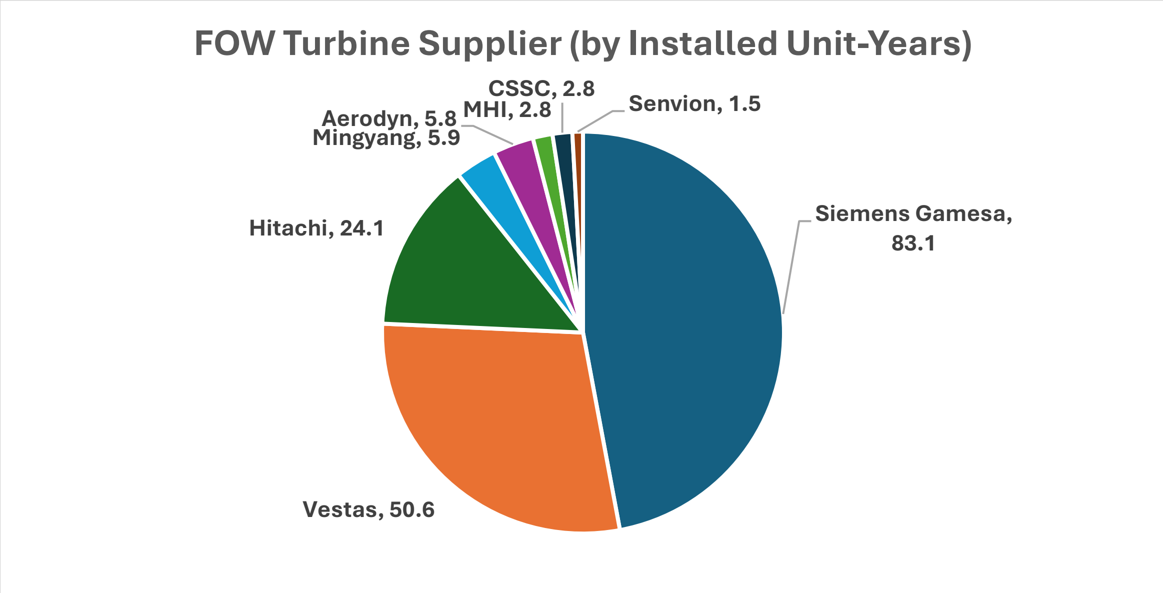

Figure 7

If, instead, we plot the total installed turbine power, SG and Vestas still dominate with 80% of the total installed capacity, but Mingyang (at 10%) moves ahead of Hitachi mainly due to their large new demonstrator project in China.

3. Historical Performance

We have gathered information from the public domain for each of the demonstrator and pre-commercial projects and analysed this in the following 7 categories.

3.1 Capacity Factors

A key attraction of FOW is to obtain higher Capacity Factors by moving further offshore, where wind speeds are generally stronger and more persistent. This is borne out by the published data from several of the demonstrator projects.

Based on published data for various UK (Scotland) and Norwegian projects [Ref 2, 3, 4, 5, 6], we find the following typical Capacity Factors.

- Peak Monthly Average (Winter) 62%-73%
- Peak 3 Monthly Average (Winter) 57% - 60%
- Peak Yearly Average 56%-57%
- 5-Yearly Average 50% - 54%

This compares to the average fixed bottom wind farm capacity for Scotland over the last 5 years of 34%, as reported by the Crown Estate in their Offshore Wind Report 2023 [Ref 7]. The figure for England and Wales is higher, at around 40%. (Note that the above data for FOW does not yet include the impact of the recent major breakdowns, discussed below).

The difference in Capacity Factors between floating and fixed wind farms is due to a combination of factors, including site wind conditions, average turbine size, reliability of more modern machinery, and turbine power density selected (the ratio of rated output to rotor swept area). Moreover, losses due to wake effects, which impact many large offshore fixed wind farms, are not yet a factor for smaller FOW demonstration projects.

The Capacity Factor is also expected to vary between FOW foundation types, because of different performance for static incline and dynamic motions, and the contribution of the hull to the overall availability of the unit (since this is an integral part of the Capacity Factor). However, there is currently insufficient information in the public domain to compare the respective Capacity Factors of different hull types, and this will be an area of future study.

3.2 Availability

The average availability for FOW units, which is publicly reported, ranges from 93% to 98% (Ref 6, 8, 9). However, this is not broken down between the turbine, hull, mooring systems and cables, and it also excludes the major breakdowns reported below, as they are relatively recent.

For UK fixed wind, the Crown Estate (Ref 7) report a 10-year average availability of 97.6%. The lower availability of FOW may be due to several factors, such as the prototype nature of these projects, more difficult crew access in deeper water and harsher locations, or the effect of motion on the turbines. So far, there is insufficient data to draw any firm conclusions, but this is a critical area, worthy of a more detailed study.

It should be noted that availability is an inherent part of the Capacity Factor, as it impacts the amount of annual energy produced. Hence, it is interesting to note that, despite their lower availability, FOW units still typically report higher overall Capacity Factors than fixed wind.

3.3 Major Breakdowns

Three major FOW breakdowns have been reported, all linked to the wind turbines.

The most serious are two failures which, impacted multiple units in both cases (Ref 14).

- Hywind Scotland, where all 5 SPARs returned to a deepwater port in Norway in the summer of 2023 for a major overhaul of the 6 MW Siemens Gamesa turbines, after less than 6 years in operation. The exact nature of the failure has not been made public, but Equinor reported that each nacelle was removed from the SPAR and returned to an onshore workshop for overhaul (Ref 10, 11, 12).
- Kincardine, where 3 of the 5 Semi-sub units required the main generators on their Vestas 9.5 MW turbines to be replaced, after one failed in the first year of operation. Two units have been towed back to Rotterdam for repair (in 2022 and 2023), and a third was repaired in situ offshore in 2024 (Ref 13, 14, 15). Repairs may still be needed on the two remaining units.

Changeout of the 30-tonne generator offshore on the Kincardine project was a complex operation and very weather-dependent (Ref 15), so performing the same procedure on the new generation of 15 MW turbines could be even more challenging. For this reason, unless there is rapid development of new technology or specialised vessels for in-situ WTG repairs, we expect to see "return to port" becoming the default strategy for major turbine repairs, using either a quayside crane or a temporary up-turbine crane in sheltered port conditions.

A third major breakdown was the repeated failure of the MHI 7 MW turbine on the Fukushima Forward Shimpuu project (Ref 16). This was a novel turbine with a hydraulic-drive system, which had such poor reliability that the project was eventually decommissioned after less than 3 years of service.

In general, hulls and moorings have been very reliable, with no reported major incidents. However, the vast majority are still relatively young, and any asset integrity issues are more likely to appear in later life.

Of the numerous small-scale (< 1 MW) prototypes deployed, three have sunk. Two of these (one in Norway and one in Spain) sank in bad weather when the scale model of the hull was swamped by large waves (Ref 17, 18). The third, in Japan, coupled a vertical axis turbine with a submerged tidal energy wheel on a single hull, but it failed once (in 2013) and then sank (in 2014) during re-installation, before being abandoned (Ref 19, 20).

3.4 Asset Integrity

Only 2 units have been operating for more than 10 years – the Hywind Demo (now Zephyros One) and Toda Corporation's Sakiyama Pilot in Japan. Both are steel SPARs.

The Sakiyama Pilot project has been in operation for almost 12 years. Eight similar SPARs are currently being built to be installed nearby (Ref 21), but this project has been delayed by 2 years after the discovery of structural defects on some of the new SPARs.

The oldest installation, the Hywind Demo / Zephyros One, has been operating for almost 16 years. Zephyros Ocean, now the owner and operator, presented information on operational experience over the last 5 years at a recent

Wind Europe event (Ref 22). They performed an uptime improvement and maintenance programme between 2019 and 2022, which resulted in an 18.1% increase in uptime over the complete year, for all seasons. Key to this was a preventive maintenance program and life extension project. An essential element was to address hull corrosion, and as a result, Zephyros Ocean is now understood to favour concrete hulls for future projects.

3.5 Accessibility

Further feedback from Zephyros Ocean (Ref 23) was that the sea states at the METcentre, 10km off Karmøy, Norway, are such that access by boat can be difficult, making maintenance problematic. A small helideck has therefore been added to the SPAR to enable the above preventive maintenance program to be safely implemented.

The ability to perform a medical evacuation by helicopter from an FOW hull was demonstrated by BW Ideol in May 2022 from their WindFloat Atlantic project, by making use of the deck space available on their Floatgen barge hull (Ref 27).

3.6 OPEX

There is little published data available for actual floating wind OPEX.

WindFloat Atlantic reports (Ref 9) that 18,000 hrs per year are spent on corrective and preventive maintenance. This looks consistent with a typical OPEX estimate of 2% to 3% of CAPEX per year (noting that this includes other elements such as spare parts and logistics, as well as manhours).

There is little information yet on how this OPEX may escalate with time as the condition of the units deteriorates, although some data has been published for smaller onshore turbines (Ref 21). This is another area worthy of further study, especially to investigate any difference between concrete and steel hulls.

3.7 Cyclonic Conditions

Three FOW units in China have been developed for cyclonic environmental conditions. The China Three Gorges Renewables (CTGR) Yangxi Shapa III project uses a Mingyang MySE5.5 typhoon-resistant wind turbine (Ref 24). Mingyang's OceanX twin turbine 16.6 MW demonstrator is also designed for cyclonic conditions and in 2024 withstood Super Typhoon Yagi in the South China Sea (Ref 25). A third demonstrator in China, CSSC's Fuyao project, also has a typhoon-resistant CSSC turbine rated at 6.2 MW (Ref 26).

These three demonstrator projects show that FOW units can be successfully designed, built and operated to withstand severe cyclonic conditions.

4. Conclusions

The total number of FOW units in operation is growing steadily, and the average size of these units is increasing as there is a move from demonstrators to pre-commercial farms. However, despite 14 different hull technologies already being deployed, only a few technology providers have the EPCI and operational experience to execute commercial-scale projects with a tolerable level of risk.

The situation is the same for the wind turbine suppliers, where 90% of the FOW operational experience is shared amongst only 3 manufacturers - 2 from Europe and 1 from China.

Capacity Factors for North Sea projects confirm the benefits of moving into deeper water with better quality winds, resulting in levels around 30% higher than typical UK fixed wind farms.

Availability data for FOW units is still scarce, but so far indicates levels below that of fixed wind. Similarly, little OPEX and Asset Integrity feedback is available. All three areas merit more detailed investigation, especially to compare the relative robustness of steel versus concrete hulls, and the possible link between floater motion and reliability.

Of the 8 FOW units that have required heavy turbine maintenance so far, 7 were returned to port for repair, and only 1 has been repaired in situ, and we expect to see "return to port" becoming the default strategy for major repairs.

5. Glossary

CAPEX	Capital Expenditure
FOW	Flowing Offshore Wind
LCOE	Lowest Cost of Energy
MTBF	Mean Time Between Failures
MW	Mega Watt
OPEX	Operating Expenditure
PPI	Principle Power Inc
SPAR	Single Point Anchor Reservoir
WTG	Wind Turbine Generator

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Appendix C - TRL and CRL Definitions

1. Technology Readiness Level (TRL) definitions

TRL	European Union (Horizon 2020)	Current NASA usage	DNV for FOW	Carbon Trust	OWRL Scale for FOW
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).	Actual system "flight proven" through successful mission operations	Floating wind turbine ready for fabrication and installation at large scale	Commercial project (>50 MW)	Commercial units with turbine of 100MW minimum capacity successfully completed 3 years' operating at sea.
8	System complete and qualified.	Actual system completed and "flight qualified" through test and demonstration	Components, e.g. floater design, ready to be integrated in a floating wind turbine. Wind turbine design qualified.	Pilot array (20-50 MW)	Commercial units with turbine of 100MW minimum capacity installed and operating at sea.
7	System prototype demonstration in operational environment	System prototype demonstration in a space environment	Prototype wind or farm in-place and operating.	>5 MW demo	Demonstrator with turbine of 1MW minimum capacity successfully completed 3 years' operating at sea.
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).	System/subsystem model or prototype demonstration in an operational environment	Prototype wind turbine designed for specific application.	1 – 5 MW demo	Demonstrator with turbine of 1MW minimum capacity installed and operating at sea.
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).	Component and/or breadboard validation in relevant environment	Design of component / wind turbine verified.	Scaled testing (<1 MW)	Detailed design of demonstrator completed for target offshore environment. Turbine capacity of 1 MW minimum.
4	Technology validated in lab.	Component and/or breadboard validation in laboratory environment	Laboratory tests confirmed concept design.	Tank testing	Model basin test campaign successfully completed.
3	Experimental proof of concept.	Analytical and experimental critical function and/or characteristic proof-of concept	Concept feasible.	Numerical modelling	Verification of the concept through analytical studies completed (CFD, coupled aero-hydro analysis, FEA etc).
2	Technology concept formulated.	Technology concept and/or application formulated	Not defined	Proof of concept	Concept drawings of the platform configuration produced and validated by basic calculation.
1	Basic principles observed.	Basic principles observed and reported	Not defined	Initial concept	Basic concepts identified – for stability, station keeping, and principal systems.

Table C1: Comparison of FOW TRL definitions

2. Commercial Readiness Level (CRL) definitions

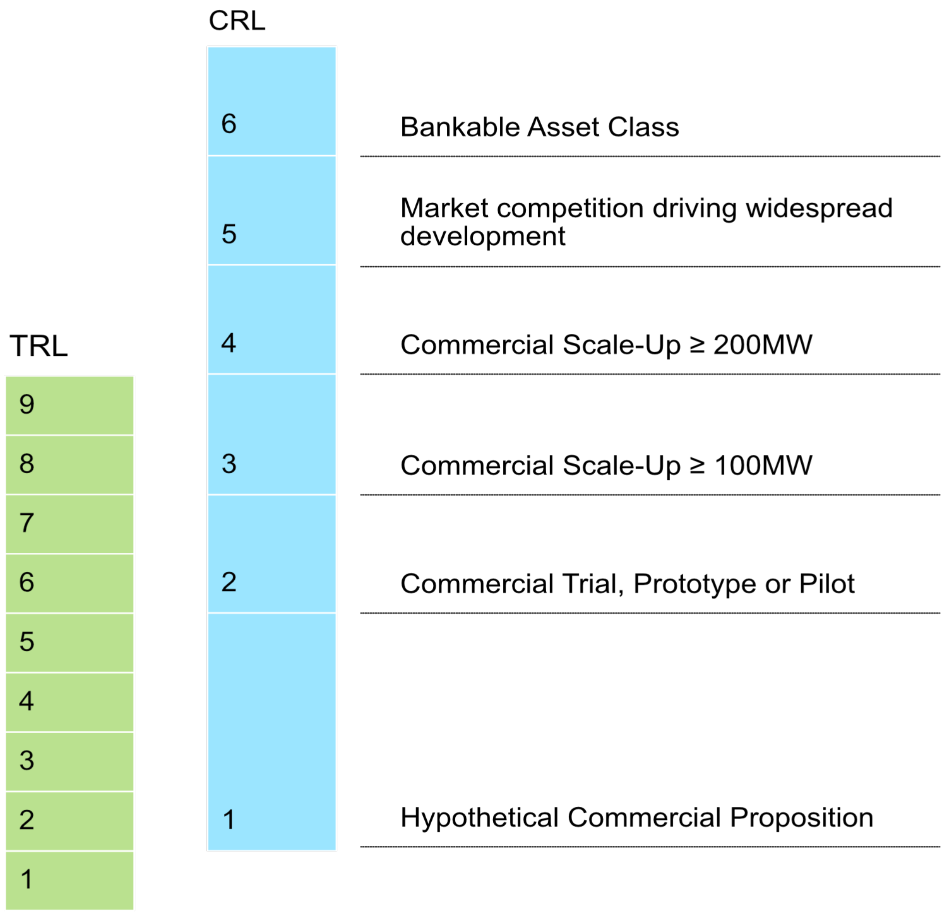

Figure C1: Definition of Commercial Readiness Levels (CRL)

Derived from CRL index developed by ARENA [Ref 5]

Appendix D – Sensitivity Study

To examine how the ranking order varies with the values of PWF used, a sensitivity analysis was performed for the top 10 ranked concepts for North Sea projects.

In a detailed assessment for a given project, the range of PWF for each criterion is agreed upon with the project developer, and each PWF is then varied individually to assess the impact. However, for this more generic North Sea study, PWFs were varied in the groups defined in Table 5.1.

The groups used approximately correspond to the following criteria categories:

- Group A: CAPEX/OPEX/Performance
- Group B: Risk/EPCI
- Group C: Installation

Although PWF ranged between 2 and 4 for the base case, values between 2 and 5 were used for the sensitivity study to provide a more robust assessment.

The analysis results are presented in Figure D1 below, which illustrates the ranking obtained from the combinations of applied weighting factors. Each point corresponding to a PWF combination is discrete, and the lines connecting the points are provided to aid in the identification of each concept only – they do not represent a continuous series.

As shown in Figure D1, the BW Ideol Damping Pool in concrete is insensitive to the North Sea PWF applied and consistently ranks at the top. This results from the concept's relatively high scores across all criteria categories. Odfjell Deepsea Semi is also insensitive to the North Sea PWF, ranking at the lowest level among the 10 concepts, but this is primarily due to its relatively low scores in most categories.

Most mid-ranking concepts demonstrate limited sensitivity to PWF, naturally ranking higher when an increased PWF is applied to categories where they have high scores, while a low PWF is applied to categories where they have low scores. However, interpretation is complicated by the relative nature of the rankings; for example, a concept may move up the rankings primarily because others have moved down.

Saitec SATH exhibits the greatest volatility, with its ranking position fluctuating between 2 and 9. This variation in ranking is primarily due to its high scores for the Group C criteria compared to its scores in the other groups, reflecting its advantageous installation characteristics (Single Point Mooring, low drag for tow, etc.), along with limited project execution experience and a weaker balance sheet.

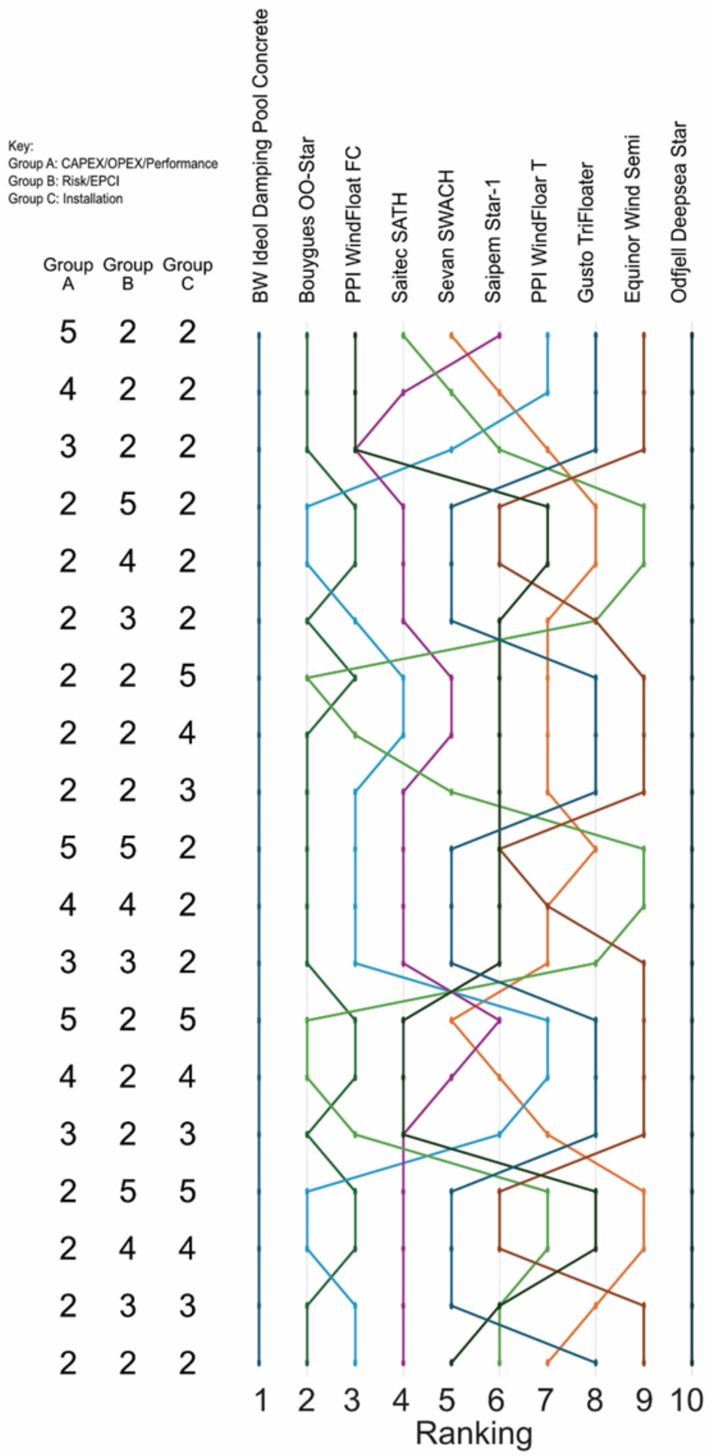

Figure D1: Impact of Group weighting factors on ranking of Top 10 concepts for North Sea projects

The top 10 ranked concepts for North Sea projects are listed in Table 5-5 below, together with their mean position in the sensitivity rankings.

Although not mathematically rigorous, the similarities between Base Case Ranking and Sensitivity Mean Ranking support the selection of these 10 concepts as candidates for North Sea projects.

Concept	Base Case Ranking	Sensitivity Mean Ranking
BW Ideol Damping Pool Concrete	1	1
Bouygues OO-Star	2	2
PPI WindFloat T	3	3
Saipem Star-1	4	4
Saitec SATH	5	6
PPI WindFloat FC	6	5
Gusto TriFloater	7	7
Sevan SWACH Wind	8	8
Equinor Wind Semi	9	9
Odfjell Wind Star	10	10

Table D1: Base Case Ranking versus Mean Sensitivity Rankings

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