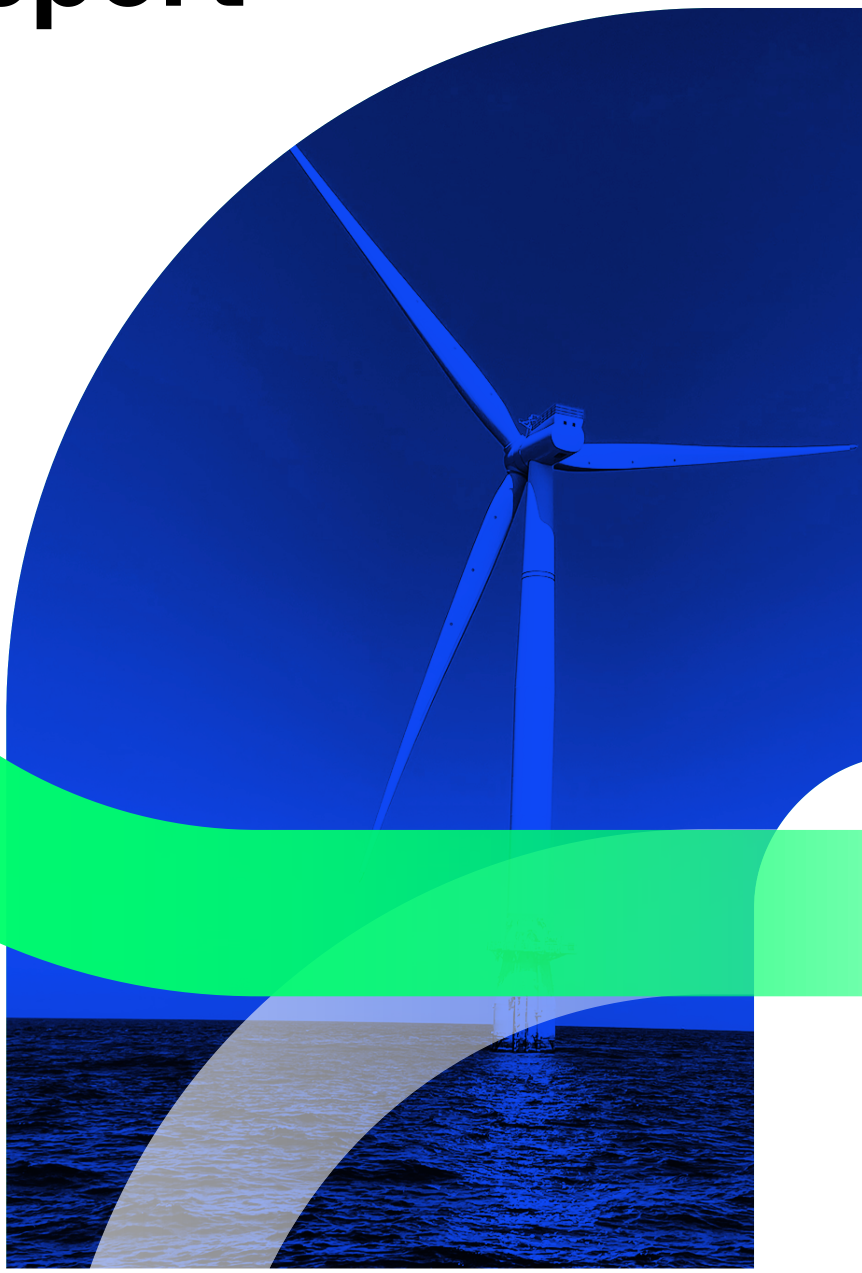
FLOATING WIND JOINT INDUSTRY PROGRAMME

Phase IV Summary Report

July 2022



About the report

The Floating Wind JIP is the Carbon Trust's collaborative R&D programme, dedicated to overcoming technological challenges and advancing commercialisation of floating offshore wind. The programme is a partnership between the Carbon Trust and 17 offshore wind developers. This summary report provides a high level overview of the four key research areas that have been carried out between 2020 and 2022, along with a current market overview and also includes descriptions of the six projects the Floating Wind JIP are currently working on in 2022.

Acknowledgments

This summary report has been produced by the Carbon Trust, with specific sections informed by studies delivered by the following external technical contractors:

- Wind turbine generators for floating wind: **Ramboll**
- Floating wind access and availability: **Seaspeed Marine Consulting, SeaRoc Group, Lavant Innovation**
- Floating wind yield: **Frazer-Nash Consultancy** and **NREL**
- Numerical modelling guidelines for floating wind: **Innosea** and **sowento**

Studies are based on an impartial analysis of primary and secondary sources, including expert interviews.

The Carbon Trust would like to thank everyone that has contributed their time and expertise during the preparation and completion of these studies.

Cover image courtesy of Alistair Morris, taken at Hywind Scotland.

Who we are

The Carbon Trust is a global climate consultancy driven by the mission to accelerate the move to a decarbonised future. We have been pioneering decarbonisation for more than 20 years for businesses, governments, and organisations. Drawing on a network of over 300 experts internationally, the Carbon Trust guides organisations through their journey to Net Zero. From strategic planning and target setting to delivery, activation, and communication - we provide smarter ways to turn intent into impact.

The Carbon Trust's mission is to accelerate the move to a decarbonised future.

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Abbreviations

AEP	Annual Energy Production
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CTV	Crew Transfer Vessel
DC	Daughter Craft
DLC	Design Load Case(s)
DLL	Dynamic Link Library
DP	Dynamic Positioning (system)
ESS	Extreme Sea State
EWM	Extreme Wind Model
EYA	Energy Yield Assessment
FD	Floater Design
FE	Finite Element
FEED	Front End Engineering Design
FLS	Fatigue Limit State
FLW	Floating Offshore Wind
FOW	Floating Offshore Wind (alternative)
FOWT	Floating Offshore Wind Turbine
GPS	Global Positioning System
Hs	Significant Wave Height

IEA	International Energy Agency
LCOE	Levelized Cost of Energy
NSS	Normal Sea State
NWM	Normal Wind Model
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
RAO	Response Amplitude Operator(s)
RNA	Rotor Nacelle Assembly
SOV	Service Operation Vessel
SSS	Severe Sea State
T&I	Transport and Installation
TLP	Tension Leg Platform
Tp	Wave period
ULS	Ultimate Limit State
VIV	Vortex-Induced Vibration
W2W	Walk-to-work (system)
WTD	Wind Turbine Designer
WTG	Wind Turbine Generator

Introduction

Introduction to the Floating Wind JIP

The Floating Wind Joint Industry Project (Floating Wind JIP) is a collaborative research and development (R&D) initiative between the Carbon Trust and 17 leading international offshore wind developers: bp, EDF Renouvables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, Ocean Winds, Parkwind, RWE Renewables, ScottishPower Renewables, Shell, SSE Renewables, TEPCO, Tohoku Electric Power Company, Total Energies, Vattenfall, and Wpd.

Since its formation in 2016, the programme has delivered two stages, each consisting of studies to outline the sector's critical needs to reach cost parity with other energy technologies. An initial review of policy needs, cost trends, and technology status for floating wind in Stage 1 resulted in the prioritisation of several key technical challenges which have been investigated in the ongoing Stage 2. Summary reports for previous phases of Stage 2 can be found here: Phase I, Phase II and Phase III.

This report presents the key findings from Phase IV projects (see sections 2-5). The Phase IV projects, outlined in this report, were completed in 2020-22. An overview of the Phase V projects that are in delivery 2021-23 can be found in section 6.

Objectives and scope

The primary objective of the Floating Wind JIP is to overcome the technical challenges and investigate opportunities for the deployment of large-scale commercial floating offshore wind farms. The programme is technology-focused, with a particular emphasis on:

- **Large-scale deployment:** Floating offshore wind technology has been proven at prototype and pilot scale, through single or a small number of multi-MW units. However, commercial wind farms will bring new technological and logistical challenges due to the increased scale of turbines and units deployed.
- **De-risking technology challenges:** Limited commercial deployment of floating offshore wind to date means that several perceived risks exist. It is expected that many of these challenges can be overcome using existing solutions from other sectors, but there is a need for further investigation to establish the true level of risk presented and undertake research that can reduce risk throughout the project lifecycle.
- **Identifying innovative solutions:** Several technology challenges will require the development of novel and innovative solutions. Innovation will be central to delivering optimised and cost-effective solutions for the industry, which is expected to present considerable opportunities for suppliers, innovators, research bodies, and academia.

- **Cost reduction:** All activity within the programme is guided by the need to deliver cost reductions ensuring that floating wind becomes a competitive energy technology in all major global markets. Cost assessments are included within the scope of most projects in order to build a robust estimate of the cost projections and cost drivers for programme partners to use when developing future commercial projects.

The Stage 2 Phase IV projects (the focus of this report) started in 2020 and with the conclusion of this phase, the phase V projects are well underway. The graphic below lists past projects from Stage 1 and Stage 2. Full project summaries for phase IV, including innovation and technology needs can be found in sections 2-5. An overview of the current projects being undertaken can be found in section 6.

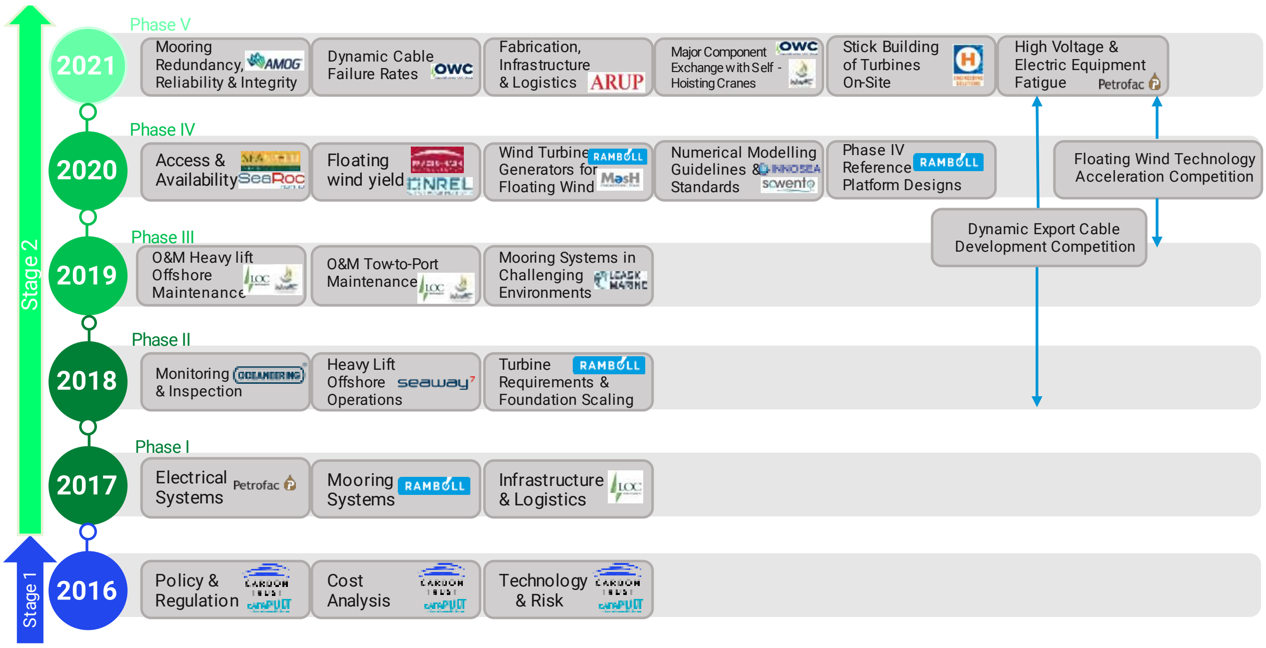

Figure 1: Floating Wind JIP projects (and delivery contractors) overview to date.

Executive Summary

Assessment of Wind Turbine Generators for Floating Wind Farms

Floating wind demonstration projects generally deploy wind turbine generators (WTGs) that are designed for fixed-bottom offshore wind applications, with a few minor adjustments. As floating wind is rapidly moving towards larger commercial projects, greater understanding is needed on the impact and performance of these WTGs with the relative motions of floating platforms, and the design adjustments required to maximise yield and ensure turbines are well suited through the whole wind farm life cycle.

This study built on previous learnings from the Floating Wind JIP Phase II project (Turbine Requirements & Foundation Scaling) and focused on exploring the differences in WTG load/motion envelope, when moving from a fixed-bottom monopile to a floating foundation, and the floating wind specific design adjustments that may be necessary to ensure the WTG and floating platform are well matched. Stiff-stiff towers were found to be feasible but tended to be less economic and more technically challenging. There is limited experience of floating-specific transport & installation (T&I), operations and maintenance (O&M) impacts on WTG components, but several topics of interest were identified after engaging with stakeholders, including wind turbine OEMs.

Floating wind access and availability

Predicting wind farm accessibility (which is dependent on method of access and metocean conditions), and hence availability (the amount of time the wind farm is capable of producing energy) for floating wind farms is key for developers to predict yield and revenue. The accessibility and availability of bottom-fixed offshore wind is relatively well known, however in floating offshore wind there are a number of factors affecting accessibility that require more understanding, namely environmental conditions, the method of access, floating substructure type and the geometry of the substructure below and above the water line.

This study assessed how vessel access methods and expected turbine availability will perform with regards to different platform types and access methods, and the effects of floating substructure motions on technicians for hypothetical minor repair campaigns when considering commercial scale floating wind farms. Within the limitations of this study, all floating wind access & availability strategies are likely to be similar to those for fixed-bottoms far-shore sites and optimisation of vessel size for specific environmental conditions is required, which will likely result in commercial benefits. The assessed conditions also indicated that floating turbine nacelle motion is not expected to be a significant problem for technicians ability to work, with respect to sea sickness and that the determining factor will be overcoming motions from the vessel itself.

Floating wind yield

Floating wind turbines are a relatively new technology, and the impact on yield is not well understood or quantified. The motions and dynamics of floating offshore wind turbines differ significantly from their fixed foundation counterparts, with floating foundations translating and rotating through additional degrees of freedom. These dynamics, coupled with the dynamics of the wind turbine generator itself, result in differences in the turbine power production.

Through this project, key floating wind effects were taken into consideration to ultimately try to understand, quantify and bound the impact of floater motions on wake effects and energy yield. This was carried out by assessing three key effects associated with floating turbines: the impact of tilt and mooring stiffness, the impact of persistent yaw oscillations and the impact of wave-driven tilt and surge motions, modelled on a 15MW turbine. Through key stakeholder engagement, a number of recommended practices for developers, foundation suppliers, turbine OEMs and Tool venders were developed.

Numerical modelling guidelines and standards for floating wind

Design guidelines are a key part of floating wind turbine design, and obtaining reliable results is an important requirement for the design iteration process to drive down CAPEX as well as ensuring consistent comparisons are made. There are many tools available for this modelling either as stand-alone analysis or as a fully coupled system model. However, there is limited best practice guidance and at present, there is no consensus on load case selection relating to floating offshore wind.

The Numerical Modelling Guidelines project aimed to provide guidance for selecting and using numerical modelling tools for FOWT design, and detailed recommended load cases to run where possible, to significantly reduce simulation efforts. For optimal integrated modelling, wind turbine and floater designers should clarify how they will work together to couple software at the start of a project.

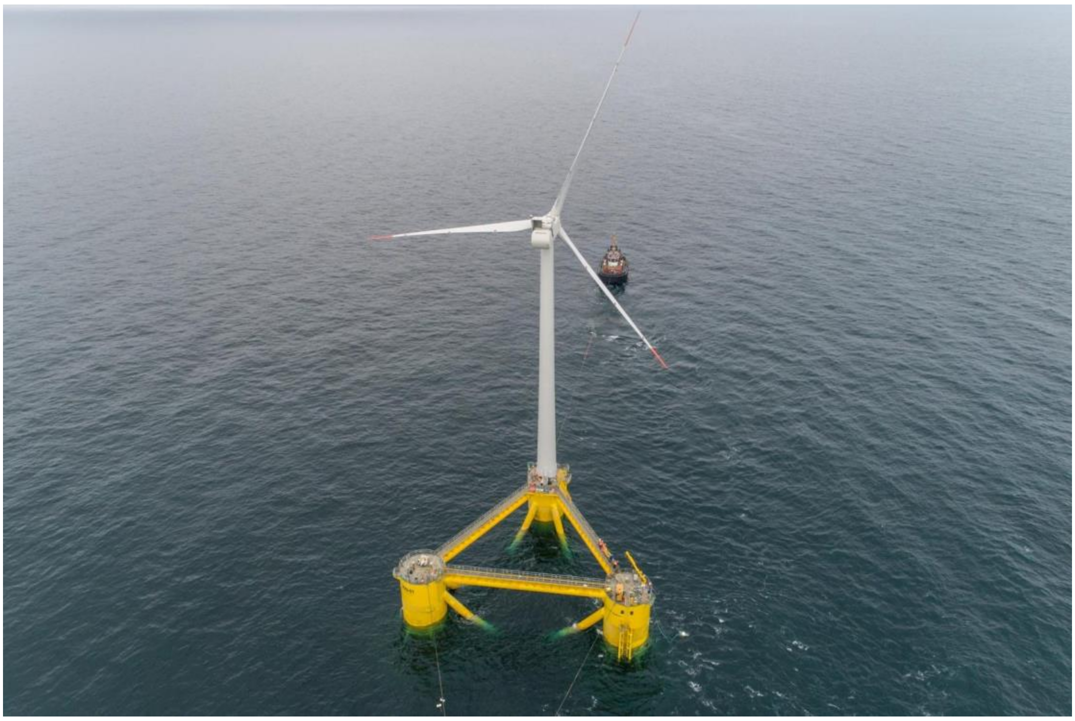

Figure 2: Floating platform using WindFloat technology at the Kincardine phase 2 wind farm. (Cobra Group).[1]

[1] Available at: https://www.grupocobra.com/en/proyecto/kincardine-offshore-floating-wind-farm/

1. Market overview

1.1. Market Growth

The Carbon Trust has undertaken a floating wind market analysis which provides and overview of projects in operation and under development (excluding details of pipeline projects). This analysis is not part of the Floating Wind JIP outcomes but aims to provide context to the current and future market as a reference.

1.1.1. Floating wind deployment to date

At the time of publication, a total of 124MW has been deployed across Asia and Europe, and this is expected to reach 225MW by the end of 2022.[2] The increase in installed floating wind since the Phase II Summary Report is largely due to the commissioning of the 48MW Kincardine Phase II wind farm in Scotland, UK. Figure 3 shows the increase in installed capacity expected up to 2023 for all projects in operation and under development, with these projects detailed in Table 1, overleaf.

With many markets setting floating specific targets of multiple GW by 2030 (e.g., the UK has set a 5GW floating wind target by 2030), the projected installed capacity to 2030 is expected to exponentially increase. The industry is currently moving out of demonstrator phase, and commercial scale floating wind farms are expected to start construction within the next few years, to be operational before 2030.

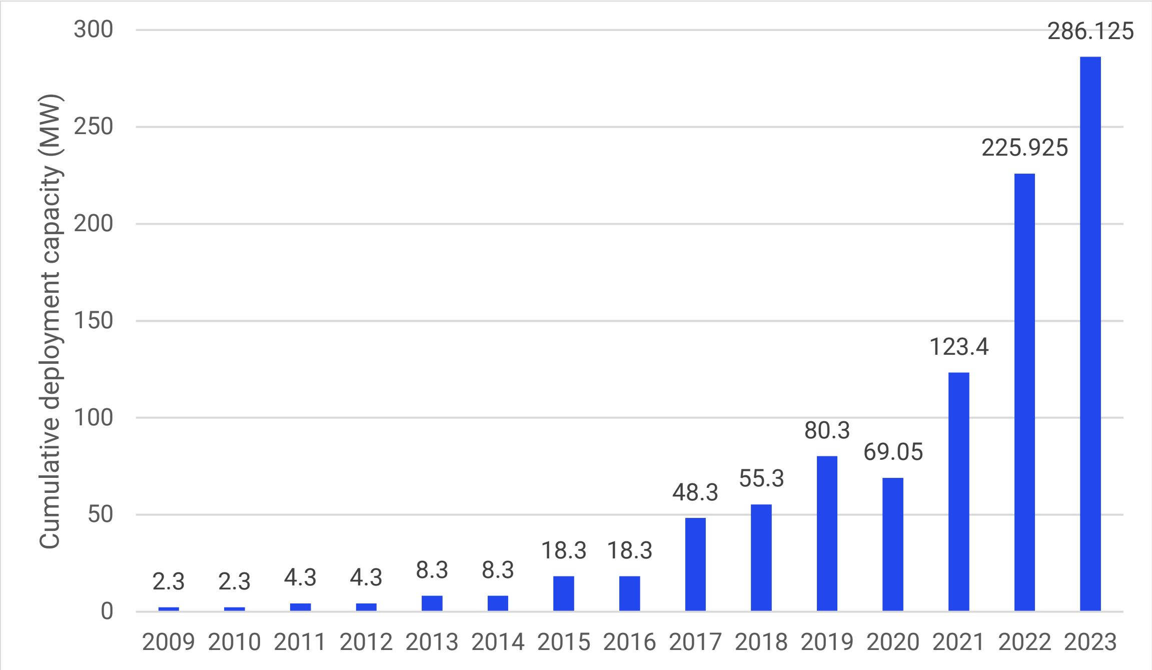

Figure 3: Global cumulative floating offshore wind capacity.[3]

[2] 124 MW total deployment at the time of publication excludes some smaller demonstration turbines that are below 0.2 MW.

[3] All data has been sourced using the 4COffshore database (accessed 26th April 2022).

Table 1: Decommissioned, fully commissioned and in-construction global floating wind projects.[4]

** Turbines have been or are planning to be re-deployed at other locations.*

Project	Country	Status	First Power	Project Developer	Technology Developer	Concept	Total Capacity	Turbine Rating (MW)	Turbine OEM
Hywind I	Norway	Fully Commissioned	2009	Equinor (Previously Statoil)	Equinor (Previously Statoil)	Hywind	2.3 MW	2.3MW	Siemens
WindFloat Atlantic Phase 1 *	Portugal	Decommissioned (2016)	2011	EDPR, Repsol, Chiyoda, Mitsubishi	Principle Power	Windfloat	2 MW	2.0 MW	Vestas
Kabashima *	Japan	Decommissioned (2015)	2013	Toda Corporation	Toda Corporation	Hybrid Spar	2 MW	2.0 MW	Fuji Heavy Industries
Fukushima Forward - phase 1	Japan	Decommissioned (2021)	2013	Marubeni Corporation	Mitsui Engineering & Shipbuilding	Semi-sub	2 MW	2.0 MW	Fuji Heavy Industries
Fukushima Forward - phase 2	Japan	Decommissioned (7MW – 2020) (5MW – 2021)	2015	Marubeni Corporation	Mitsubishi Heavy Industries	V-Shape Semi-Sub	12 MW	7.0 MW	Mitsubishi Power Systems Europe
Sakiyama 2MW Floating Wind Turbine	Japan	Fully Commissioned	2016	Toda Corporation	Toda Corporation	Hybrid Spar	2 MW	2.0 MW	Subaru
Hywind Pilot Park	United Kingdom	Fully Commissioned	2017	Equinor (Previously Statoil)	Equinor (Previously Statoil)	Hywind	30 MW	6.0 MW	Siemens
Floatgen Project	France	Fully Commissioned	2018	IDEOL	IDEOL	Damping Pool	2 MW	2.0 MW	Vestas
Kincardine - phase 1	United Kingdom	Fully Commissioned	2018	Pilot Offshore, Cobra	Principle Power	Windfloat	2 MW	2.0 MW	MHI-Vestas
IDEOL Kitakyushu Demo	Japan	Fully Commissioned	2018	IDEOL & Hitachi Zosen	IDEOL	Damping Pool	3 MW	3.0 MW	Aerodyn Engineering

[4] All data has been sourced using the 4COffshore database (accessed 26th April 2022).

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WindFloat Atlantic 2	Portugal	Fully Commissioned	2019	Ocean Winds, Repsol, PPI	Principle Power (PPI)	WindFloat	25 MW	8.0 MW	MHI-Vestas
Ulsan 750 kW Floating Demonstrator	South Korea	Decommissioned (2021)	2020	Unison, KETEP, Mastek Heavy Industries, SEHO Engineering, University of Ulsan	Mastec Heavy Industries	Semi-Sub	0.75 MW	0.75 MW	UNISON
Kincardine - phase 2	United Kingdom	Fully Commissioned	2021	Pilot Offshore, Cobra	Principle Power	WindFloat	48 MW	9.5 MW	MHI-Vestas
TetraSpar Demonstrator - Metcentre	Norway	Fully Commissioned	2021	innogy SE, Shell, Steisdal OT	Steisdal Offshore Technologies	Tetraspar	3.6 MW	3.6MW	Siemens
CTGNE Yangjiang Shapa - phase III - floating demo	China	Fully Commissioned	2021	China Three Gorges	China Three Gorges	Semi-sub	5.5 MW	5.5 MW	MingYang
PivotBuoy	Spain	Under Construction	2022	X1Wind	X1Wind	PivotBuoy	0.23 MW	0.2 MW	Vestas
DemoSATH - BIMEP	Spain	Under Construction	2022	Saitec	Saitec	SATH	2 MW	2.0 MW	TBC
GICON Schwimmendes Offshore Fundament (SOF) Pilot	Asia*	Pre-Construction	2022	GICON GmbH	GICON GmbH	Schwimmendes Offshore Fundament	2.3 MW	2.3 MW	Siemens
Hywind Tampen	Norway	Under Construction	2022	Equinor	Equinor	Hywind	88 MW	8.0 MW	Siemens Gamesa
FLAGSHIP - Metcentre	Norway	Pre-Construction	2022	Iberdrola, Core Marine	Iberdrola	OO-Star	10 MW	11.0 MW	MingYang
EOLINK 5 MW Demonstrator	France	Pre-Construction	2023	EOLINK	EOLINK	Semi-Sub	5 MW	5.0 MW	TBC
Provence Grand Large	France	Pre-Construction	2023	EDF, EN	SBM Offshore	TLP	25.2 MW	8.0 MW	Siemens Gamesa
Golfe du Lion	France	Pre-Construction	2023	Ocean Winds, Caisse des Depots	Principle Power (PPI)	Windfloat	30 MW	10.0 MW	MHI-Vestas

* following contractual issues GICON will deploy the 2MW demonstrator in Asia, with a 10MW demonstrator in Europe in due course.

1.1.2. Upcoming pilot projects

There is a pipeline of upcoming projects that, as well as continuing to prove existing floating wind technologies, will work to pioneer new technologies and designs. These projects will also help to demonstrate supporting infrastructure and component technologies, such as mooring systems and dynamic export and inter-array cables. The results of these developments will be essential for securing a future for offshore wind across global markets.

As confidence in the technology is improving, bigger projects are becoming more commonplace. The majority of these developments will be located in Europe, but there are also projects located in the US and in Japan.

Table 2: Upcoming floating offshore wind projects.[5]

Project	Country	First Power	Total Capacity	Turbine ratine (MW)	Project Developer	Technology Developer	Concept	Turbine Supplier
Floating Power Plant - PLOCAN	Spain	2022	8 MW	8.0 MW	Floating Power Plant	Floating Power Plant	P37 Hybrid Floating Wind and Wave Energy Device	Floating Power Plant
New England Aqua Ventus	United States	2023	12 MW	6.0 MW	University of Maine	University of Maine	VolturnUS	TBC
EolMed	France	2023	30 MW	10.0 MW	Qair, TotalEnergies	IDEOL	Damping Pool	MHI Vestas Offshore Wind
Ulsan 5MW demo	South Korea	2023	5 MW	5.0 MW	KETEP, Ulsan Metropolitan City, Hyundai	University of Ulsan	Semi-sub	UNISON
FLOCAN 5	Spain	2024	25 MW	5.0 MW	Cobra , Gobierno de Canarias	Cobra	Hybrid Spar	Siemens Gamesa
TwinHub	United Kingdom	2024	32 MW	8.0 MW	Bechtel Infrastructure and Power Corporation	Hexicon	Twinwind	TBC
Groix & Belle-Île	France	2024	28.5 MW	9.5 MW	Caisse des dépôts, CGN Shell l	Naval Energies	Sea Reed	MHI Vestas
Goto City	Japan	2024	16.8 MW	2.0 MW	Toda Corporation	Toda Corporation	Hybrid Spar	Hitachi
Blyth - phase 2	United Kingdom	2025	58.4 MW	8.5 MW	EDF, Tenaga Nasional	EDF	Semi-sub	TBC
Pentland FOW Demonstrator	United Kingdom	2025	12 MW	12.0 MW	Highland Floating Winds, CIP	Hexicon	Semi-sub	TBC
Erebus	United Kingdom	2028	96 MW	15MW	TotalEnergies, Simply Blue Energy	Principle Power (PPI)	Semi-sub	TBC

[5] All data has been sourced using the 4COffshore database (accessed 26th April 2022).

1.2. Key markets overview

1.2.1. European market

According to current projections Europe is expected to be the largest floating wind market by 2030.[6] Traction has been building within the market, and in the last year many more markets are holding or announcing tender rounds for specific floating offshore wind (FLW) sites. In the last year, motivated by successful demonstration projects and technology advances, some markets have set floating specific targets. This includes government set targets of 5GW in the UK and 1-3GW in Spain by 2030, and targets suggested by industry of 3GW in France by 2030 and 5GW in Italy by 2040.[7]

Figure 4 below shows the impressive scale up and projections of floating wind projects in the pipeline. It should be noted that this is not an exhaustive list, and many other projects are planned in many of these markets. As the industry is moving out of a demonstration phase and into a pre-commercial phase, many test turbines and demonstration sites have been excluded from this image. This includes demonstration turbines in countries included in the map (Norway, Spain, France, UK) and some countries that are planning their first test turbines or sites (Germany, Greece, Malta).

In October 2021 the Kincardine FLW farm off the coast of Aberdeen, Scotland became fully operational. This is the largest operational floating wind farm to date, with 6 turbines installed on WindFloat® semi-submersible platforms, totalling 50MW. The UK continues to implement ambitious pipelines and targets for floating wind and recently increased its target of floating wind from 1GW to 3GW by 2030. To add to the existing 300MW Celtic Sea floating wind round, The Crown Estate (TCE) announced plans for another floating wind leasing round in the Celtic Sea to deliver an additional 4GW. The results of the Crown Estate Scotland (CES) ScotWind leasing round in 2022 announced that 15GW worth of capacity was awarded to floating wind projects.

Following the 250MW tender in Brittany, France has recently opened tenders for 2 floating wind sites, each 250MW, in the Mediterranean Sea. An additional 2 sites each of 500MW are expected to follow. France already has four demonstrator sites that are in early construction phases (see Tables 1 and 2).

The official offshore wind target in Italy is currently 900MW, however developers and key industry players can see the potential for the region. The Italian Ministry of Ecological Transition received over 60 expressions of interest for developing floating offshore wind projects, with developers recently entering into agreements for exploration and development. The Italian Wind Energy Association, ANEV, have stated that the industry should strive for 5GW of floating wind by 2040.

Spain's offshore wind roadmap, approved in early 2022 included a new target of up to 3GW of FOW by 2030. The Spanish government are expecting to invest at least €200m on R&D to help meet these targets. There is abundant resource not only around the coast of the mainland but also in the Canary Islands, with plans for many demonstration sites and commercial sized farms, the largest of which would be 300MW.

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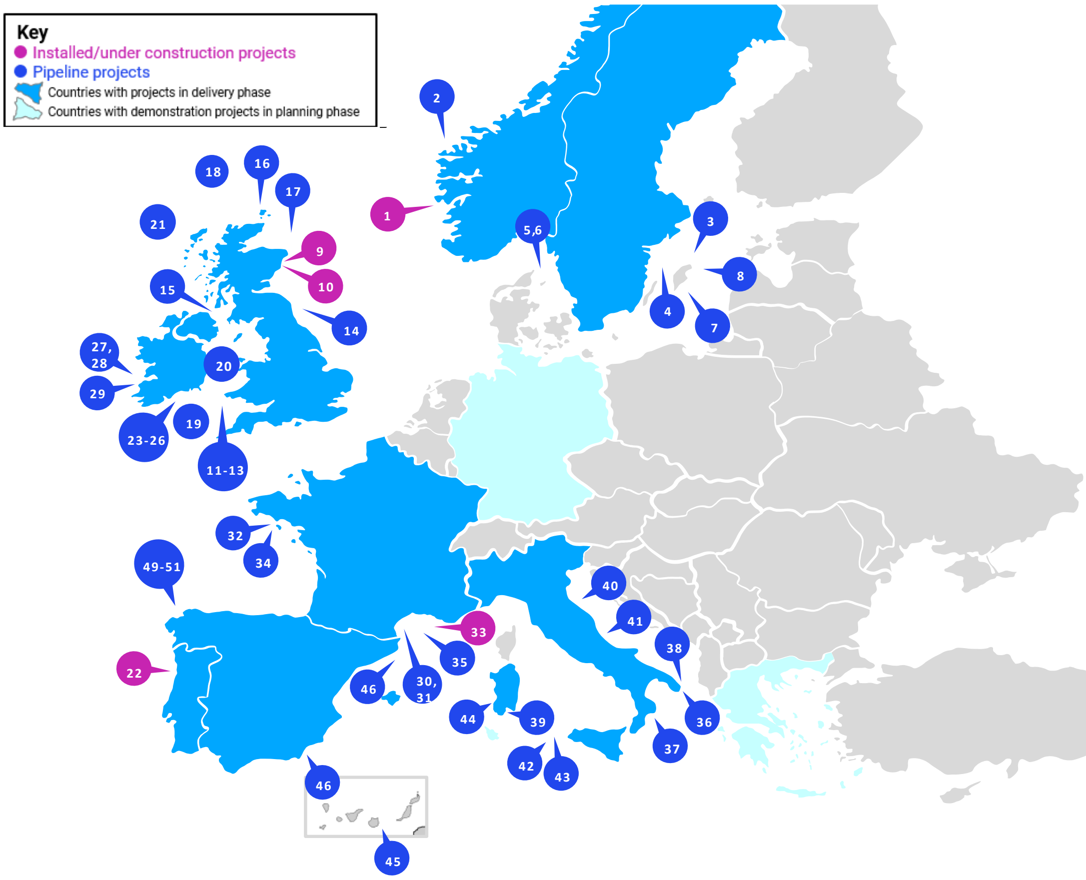
[6] Floating Offshore Wind – A Global Opportunity, 2022, GWEC

[7] UK to Raise 2030 Offshore Wind Target to 50 GW, 2022, offshorewind.biz link
Spain Targets up to 3GW of Floating Wind by 2030, 2021, offshorewind.biz link
Industry Majors Back 3GW by 2030 French Mediterranean Floating Wind Goal, 2018, offshorewind.biz link
Italy Pressed to Raise Offshore Wind Goal as Industry Flags 5GW Floating Potential, 2021, rechargenews.com link



Project	MW
Norway	
1. Hywind Tampen	88
2. Frøyabanken	500-1500
Sweden	
3. Dyning	2000
4. Kultje	2150
5. Mareld	2300
6. Poseidon Nord	1000
7. Skidbladner	2000
8. Herkules	2750
United Kingdom – floating target 5 GW by 2030 *	
9. Hywind pilot park	30
10. Kincardine	50
11. Erebus (commercial)	600
12. Petroc	300
13. Celtic Deep	398
14. Blyth	58.4
15. North Channel Wind	400
16. Dolphyn project	2000
17. Green Volt	480
18. Cerulean North Sea	3000
19. Crown Estate Test & Demonstration	400
20. Celtic Sea Floating	4000
21. Scotwind	15,000
Portugal	
22. WindFloat Atlantic	25

Project	MW
Ireland	
23. Emerald	1300
24. Inis Ealga	1000
25. Blackwater	1500
26. SSE Celtic Sea	800
27. Clarus	1000
28. Western Star	1350
29. Moneypoint	1000-1500
France – floating target 3 GW by 2030 **	
30. EOLMed	30
31. Gulf du Lion	30
32. Groix & BelleÎle	28.5
33. Provence Grand Large	25.2
34. Triskéol	250
35. Méditerranée I-IV	1500
Italy – floating target 5 GW by 2040 **	
36. Odra Energia	1500
37. Minervia Energia	675
38. KailiaEnergia	1200
39. Nora Energia	1395
40. Marche	840
41. Abruzzi	1760
42. MedWind	2800
43. Marsala	750
44. Sardegna Sud Occidentale	504

Project	MW
Spain – floating target of 1-3 GW by 2030 *	
45. Canarray I & II	180
46. Mar de Agata	300
47. Parque Tramuntana I	500
49. Parque Nordes I	525
50. San Brandan	490
51. San Cibrao	490

* target government set
** target set by industry

Figure 4: Map of European floating offshore wind deployment.
Data source: 4COffshore.

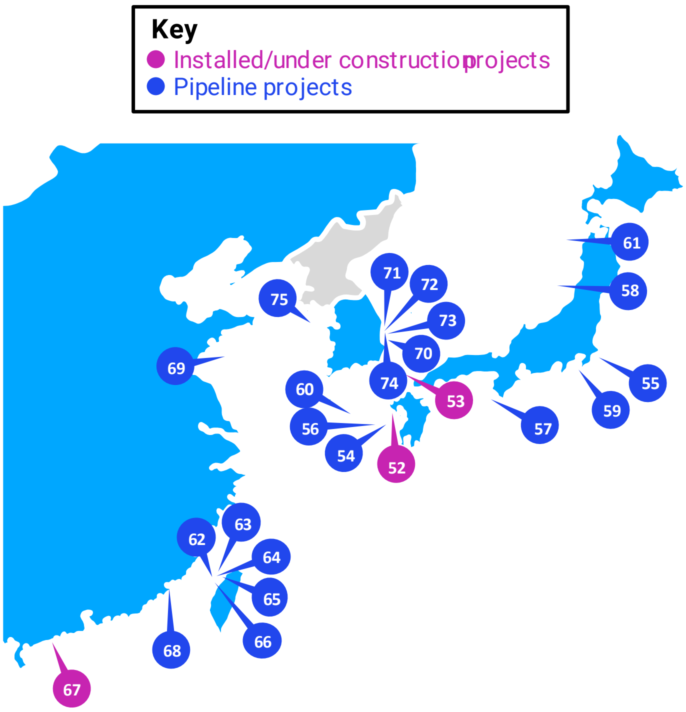
Please note, this is not an exhaustive list of pipeline projects.

1.2.2. Asian market

The Asian market is predicted to control the market share of floating wind in the coming decades and is expected to overtake Europe with the largest market share shortly after 2030.[8] The map below shows the number of projects in the pipeline in Japan, Taiwan, China and South Korea, which are already totalling nearly 25GW if all projects in the pipeline are realised, indicated in Figure 5 below. For those projects that may not become realised, it is still likely that other projects or wind farm zones will be developed.

Japan has been an early leader in Asia, with demonstrator projects already installed and in some cases decommissioned. The 17MW Goto City demonstrator is nearing construction phase and is expected to be commissioned in early 2024. The success of these demonstrator projects, has prompted developers to start planning commercial scale projects along much of the coastal line. Taiwan and South Korea are closely following behind Japan with developers announcing their plans for wind farm development, and many at stages of securing electricity business licenses.9 China recently commissioned their first floating demonstrator turbine, connected to a fixed bottom farm in the South China Sea.

There are also markets not shown in figure 5 that are expected to emerge over the next decade or so. Both the Philippines and Vietnam, for example, have geographical constraints for fixed bottom wind, meaning that floating wind is a very serious possibility for these markets.



Project	MW
Japan	
52. Sakiyama	2
53. IDEOL Kitakyshu demo	3
54. Goto City	17
55. Sakura	520
56. Kyushu	1000
57. Kishuu	450
58. Toki I & II	1100
59. Progression Energy Floating	800
60. Goto Sakiyama Oki Oki	500
61. Seihoku-ouki	600
Taiwan	
62. Eolfi Taiwan	500-2000
63. Chu Tin I & II	1300
64. Huan Ya	1400
65. Laifeng	950
66. Hai Shuo	1350
China	
67. CTGNE Yangjiang Shapa	5.5
68. Longyuan Nanri Island	4
69. Qingdao	2000
South Korea	
70. Ulsan Prototype	5
71. Donghae Sites	500-4500
72. Firefly	804
73. Munmu Baram	420-1500
74. Ulsan Floating	1000-2500
75. Incheon	1600

Figure 5: Map of Asian floating offshore wind deployment and pipeline. *Data source: 4COffshore.*

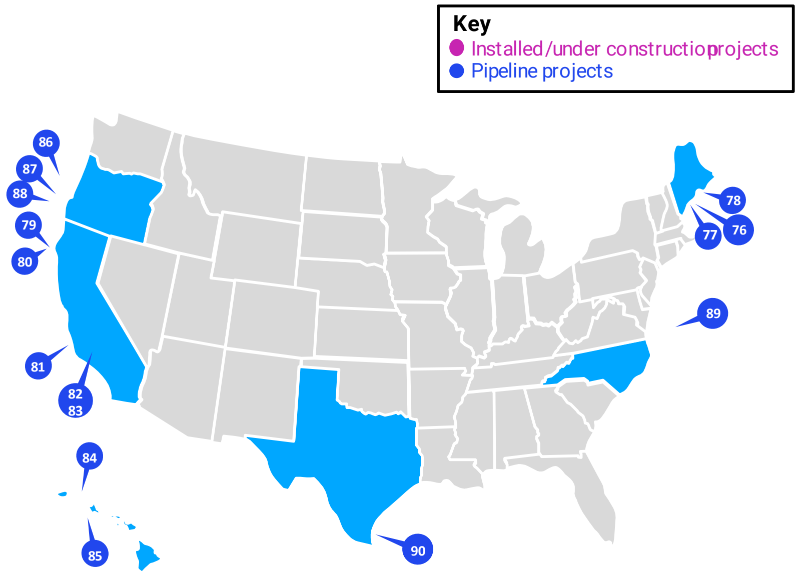
[8] Floating Offshore Wind – A Global Opportunity, 2022, GWEC

[9] Shell's South Korean Floating Wind Project Cleared for 1.3GW Capacity, 2022, offshorewind.biz link

1.2.3. American market

Although the United States is yet to deploy any demonstration projects, the forecast for floating offshore wind up to 2030 is still very high. Fuelled by a target set in 2021 of 30GW offshore wind by 2030, there is a big focus on floating offshore wind in certain areas, primarily the west coast (see Figure 6 below) which exhibits deeper seabed characteristics.

With the continued persistence and confidence of the leading states, and on the back of the national target, more states are committing to developing floating offshore wind areas. The States of California and Oregon have both set targets of 3GW floating offshore wind by 2030.[10] Some other states (North Carolina and Maine) have set OSW targets, though nothing specific to floating wind.



Project	MW
Maine	
76. Aqua Ventus	12
77. Maine Research Array	144
78. Future Floating *	450 - 1500
California	
79. Redwood	150
80. Humboldt WEA *	1600
81. Morro Bay *	700-1000
82. Lompoc/CADEMO	60
83. Castle Wind *	1000
Hawaii	
84. Oahu Northwest *	400
85. Oahu South *	400
Oregon	
86. Coos Bay *	10,000
87. Bandon *	2,800
88. Brookings *	3,400
North Carolina	
89. Central Atlantic E *	1000
Texas	
90. Gulf of Mexico *	2000

** = call areas*

Figure 6: Map of American floating offshore wind deployment. *Data source: 4COffshore.*

[10] Renews.biz, 2022

2. Key findings: Wind turbine generators for floating wind

2.1. The Study overview

Floating wind demonstration projects generally deploy wind turbine generators (WTGs) that are designed for fixed-bottom offshore wind applications, with only minor design adjustments to the Rotor Nacelle Assembly (RNA) and tower, along with changes to the WTG controller tuning. However, as floating substructures exhibit motions in 6 degrees of freedom, they operate in a significantly different loads envelope compared to their fixed-bottom counterparts. As floating wind is rapidly moving towards larger commercial projects, greater understanding is needed on the impact of floating wind deployment on WTGs and the design adjustments required to maximise yield and ensure turbines are well suited to Transport and Installation (T&I) and Operations and Maintenance (O&M) activities.

This study, delivered by Ramboll and MESH, sought to understand the difference in WTG load/motion envelope when moving from a fixed-bottom monopile to a floating foundation. The project was structured as a series of studies focused on different design elements including floating wind specific adjustments for different components of the WTG and on wider system level design considerations for floating WTGs. All studies were modelled as a 15MW turbine on a semi-submersible platform.

Prior to conducting the studies, characteristic loads and motions were calculated for different semi-sub substructure and tower combinations. The specific research area objectives, determined through a literature review and stakeholder engagement, included:

- **Tower and transition piece design**: To analyse different floating wind tower designs, specifically soft/stiff and stiff/stiff designs for the applicability for floating systems.
- **Loads and failure rates of RNA components:** To explore the impact of floating wind specific load effects on the failure rates of major RNA components (e.g., drive train, blades, and bearings).
- **Component level Operations and Maintenance (O&M), and Transport and Installation (T&I) considerations:** To explore the potential of modifying existing WTG O&M/T&I processes and component level design modifications, currently designed for fixed-bottom turbines.
- **Impact of WTG motion envelope requirements on floater design:** To quantify key trade-offs regarding how motion envelope requirements for the WTG (i.e., maximum static and total pitch angle for power production and parked cases) impact the mass and size of the floating platform cost, and to what extend floater size/mass reductions are possible when allowing pitch excursions beyond typical WTG allowable limits. These sizing studies were conducted with Ramboll's in-house substructure design tools for a generic semi-submersible.
- **Instabilities for Large 15+ MW Floating WTGs:** With stability aspects generally becoming more important for large WTGs, this study assessed how structural dynamics (e.g., global coupled eigenmodes including rotor modes) and aeroelastic stability margins are impacted by the floating substructure and its associated load/motion envelope.

2.2. Key findings

This study studied a 15MW turbine on a semi-submersible platform, shown in Figure 7. Regarding different tower designs, the analysis found that designing a strict soft-stiff tower for a 15MW WTG (where the first global tower bending mode is below the 3P rotor harmonic range) is challenging for floating systems as it requires towers which are uneconomically heavy, and which typically require relatively large outer diameters. Allowing for an intersection between the 3P rotor harmonic and first global bending mode yields soft-stiff tower designs with reasonable mass and geometry, even though they require a modified control algorithm that avoids prolonged operation at the resonance frequency between tower and 3P to avoid excessive fatigue loading. However, this controller modification was found to be feasible, avoids excessive load increases and does not result in significant penalties on power production or other aspects.

The tower design is one of the main components that needs to be modified for floating wind specific applications. Due to the free boundary condition at the tower base, an increase of the first global natural frequency is observed. This frequency increase complicates the application of soft-stiff tower designs towards floating systems as it often pushes the first global system eigenfrequency in the 3P operational rotor harmonic region. Current mitigation strategies here are either advanced control strategies like exclusion zones/frequency hopping to avoid 3P rotor harmonics that couple with the first global natural frequency or to switch from a soft-stiff to a stiff-stiff tower configuration.

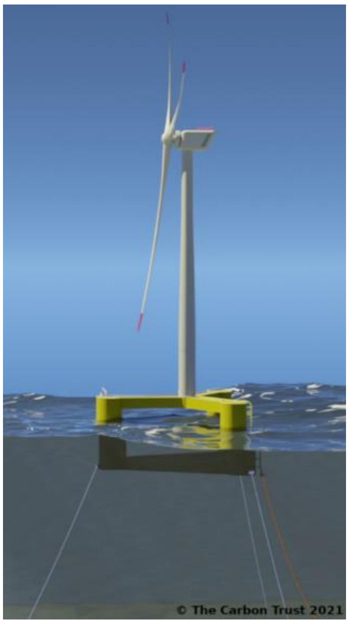


Figure 7: Artist impression of IEA Task 37 15 MW Turbine on FLW JIP reference design semi-submersible platform. (Carbon Trust)[11]

The main challenge identified for stiff-stiff towers (first global bending mode above 3P rotor harmonic range) is the fact that the required stiffness cannot be achieved by wall thickness increases alone, but also requires relatively large tower diameters (the larger the diameter the more economic/lighter the designs become). For WTG designs that have slim margins in terms of blade tip clearance, the increased

[11] Reference Floating Wind Designs and Scenarios, delivered by Ramboll for the Floating Wind JIP, 2021.

tower diameters could introduce significant complications (e.g., de-rating in certain conditions to maintain blade min. clearance), as well as manufacturing challenges (lack of large diameter tower fabricators).

Regarding loads and motions, it was found that the soft-stiff tower is dynamically more active and produces larger inertia loads (specifically in conditions with large waves), while the heavier stiff-stiff tower and the associated impact on the overall system centre of gravity yields slightly increased platform pitch motion which causes larger gravity induced loads during operational conditions with large platform pitch angles (i.e., at rated wind speed). It is noted that this is different from what is commonly observed for soft-stiff and stiff-stiff towers in onshore or bottom-fixed systems, where RNA loads are typically increased for stiff-stiff towers due to higher accelerations.

1 **The RNA component most affected by the floating-specific loads is the drivetrain. Idling and parked cases with large floater motions from waves particularly contribute to the increase in load.**

For RNA components, a variety of drive train related load channels were compared to understand the impact of switching from a monopile to a semi-submersible substructure. RNA fore-aft acceleration and yaw bearing fore-aft loads were found to be much higher for the semi-submersible floating foundation than a monopile. For drivetrain related load channels, it was mainly fatigue loads (damage equivalent loads - DELs) where large increases were seen, while ultimate loads only increased in the low double digits range. A significant amount of the increased fatigue loads can be attributed to parked/idling conditions where the load/motion profile of the floating system is significantly different due to the motion of the floating platform. These conditions also cannot be influenced by the WTG control system. No major differences in terms of ultimate and fatigue loads were observed for rotor blades.

It is important to note that the loads/motions observed are impacted by the choice of the selected floater and wind turbine and are not necessarily transferrable to other floater/turbine combinations. It should also be noted that the impact of the increase in loads seen in this analysis on turbine design, suitability or lifetime will depend on whether these load components are design driving for the system.

2 **There is limited experience of floating-specific transport & installation (T&I), operations and maintenance (O&M) impacts on WTG components, but several topics of interest have been identified.**

Stakeholder feedback on how WTG components (and procedures) can be improved/adapted for floating wind applications was gathered. Given the fact that floating wind specific O&M and T&I impacts on WTG components is still an area with little experience, the level of detail available is limited. Some common points raised included:

- **Lifting operations for installation or component exchange**: Feedback indicated that existing tools and motion/displacement requirements must be re-visited due to the increased motion profile of floating platforms, unless all key installation steps can be performed quayside with the floater fixed by some means (e.g., lowered to seabed), where existing installation tools/procedures should work as-is. A general lifting related comment was that nacelle cranes should be used as much as possible (and therefore potentially reinforced) for T&I/O&M activities to avoid the utilization of floating crane vessels as much as possible.
- **Tow- out processes from harbour to site**: This is still a new procedure for some WTG OEMs and standardized requirements and procedures are still being developed. The requirement of a power

supply for the WTG during long tow-out processes to ensure the ability to yaw and dehumidify the WTG was mentioned by some stakeholders.

- **Transition piece/tower connection reinforcement**: This was highlighted as an area of concern due to the significantly increased tower base bending moments for floating systems.
- **Access requirements for O&M**: The need for adding attachment/anchor points for temporarily removed equipment and maintenance personnel was widely recognised. In particular, the need for appropriate rope access and platforms for blade related work was highlighted.

3 **Allowing for larger static pitch angles can improve the levelised cost of electricity (LCOE) by reducing the platform cost, but needs to be balanced with the resulting power production loss and increased loads in production.**

For the early concept level design stage of a floating system, floater pitch angle related requirements (i.e., maximum static floater pitch angle and maximum total pitch angle) often impact the initial trajectory of the floater design process (initial sizing of global floater dimensions/masses).

With the aim of highlighting the effect of these pitch angle related requirements on the floater design, different scaling approaches for the 15 MW reference semi-submersible were applied to the floater geometry and their impact on floater mass, power production and motion response was assessed.

Three different scaling factors were applied to global design parameters like column diameter and column spacing, as shown in Figure 8. The floater static pitch angle, the floater mass and power production of the system were also compared. These data points were used to calculate the high-level impact of downscaled floaters with larger static pitch angles on the Levelized Cost of Energy (LCOE).

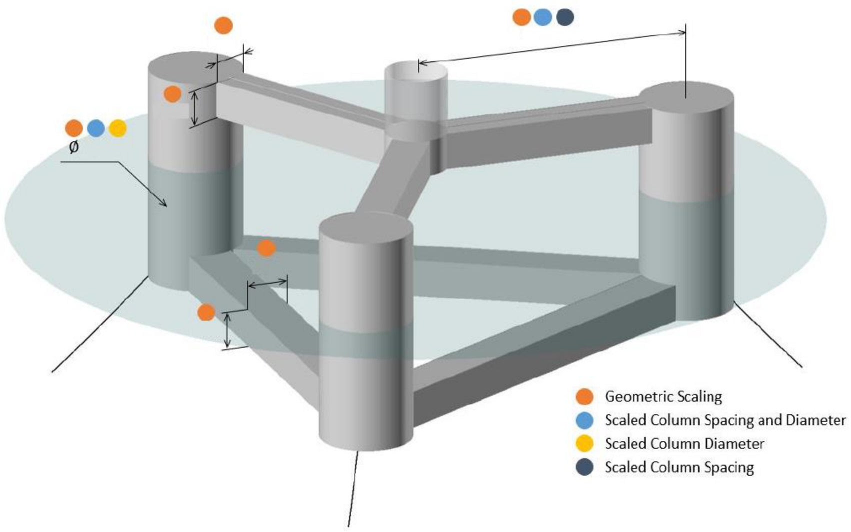


Figure 8: The applied scaling approaches assigned to components on a semi-submersible floater (Ramboll)

Different trade-off scenarios in terms of LCOE were investigated, depending on the contribution of the floater cost towards the total Capital Expenditure (CAPEX) and the correlation of the Annual Energy Production (AEP) with power production at peak thrust. Based on these preliminary findings, allowing for larger static pitch angles appears to be justified in certain scenarios. Moving towards smaller static pitch angles was also found to require significant increases in mass and consequently in LCOE.

In summary, while more compact floaters (designed for larger static pitch) tend to create larger loads/motions during power production with large rotor thrust forces, they can show an improved load profile for situations that are dominated by wave induced loads/accelerations compared to stiffer floaters designed for small static pitch.

4 **RNA mass mainly influences motions and loads in extreme conditions. While a lighter RNA reduces inertia loads it may also lead to larger motions due to a reduction of natural period.**

This study used the 15 MW WTG from IEA Task 37 as it's reference base case. Stakeholder feedback suggested that the RNA mass of the reference turbine was greater than the expected values from typical state of the art turbines of comparable rating. With the aim of illustrating and quantifying the impact of the RNA mass on the overall floating system, the nacelle mass was reduced with different scaling factors.

The effect of varying the RNA mass alone on metrics like pitch angles (static and maximum total), as well as on selected load cases and load channels was investigated. Regarding the maximum total pitch angle during extreme conditions, the effect of the RNA mass was prominent, with lighter RNAs producing higher maximum absolute pitch angles. The increase in maximum total pitch angle is mainly related to the fact that the RNA mass has a significant impact on the system's pitch natural frequency.

In summary, the impact of the RNA mass mainly manifests through the static moment from the RNA overhang (specifically when the turbine is idling), as well as through its impact on the frequencies of the rigid body pitch mode and the first global bending mode. However, it should be noted that this analysis kept all other design elements the same, just changing the RNA mass. In reality, wider design changes (such as increasing or decreasing the ballast in the floating platform) could be made to counteract the impact of a change in RNA mass on natural periods.

5 **System eigenfrequencies on a floater are different to those of a fixed-bottom monopile, but significant differences in aeroelastic stability were not observed in this study.**

Operating a wind turbine on a floating instead of a fixed-bottom foundation will significantly change some of the system eigenfrequencies (also referred to as natural frequencies) and the corresponding damping. With a Simpack model of the IEA Task 37 15 MW offshore reference turbine (Figure 9), the MAESTROS tool was used to calculate coupled structural Eigenmodes for a rotation speed range of up to 20 RPM, and aeroelastic Eigenmodes for a wind speed range of 3-25m/sec, corresponding to the turbine's operational wind speed envelope.[12]

[12] MAESTROS – MesH AeroElastic Stability analysis Tool for Rotating Systems, provided by MesH engineering. For more information please see https://mesh-engineering.de

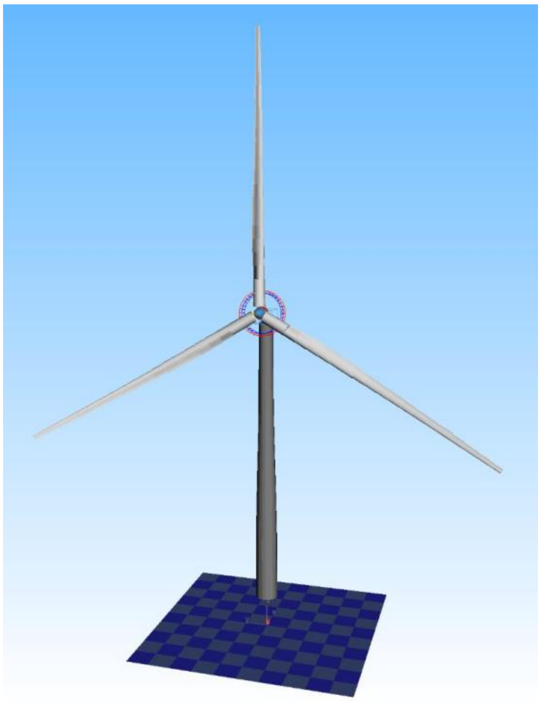


Figure 9: Simpack model of the IEA Task 37 15MW reference WTG (Ramboll and MeSH).

When comparing the IEA Task 37 15 MW reference turbine on a fixed-bottom monopile foundation and on a semi-submersible floater, the structural Eigenmodes with tower and foundation participation were strongly affected in both Eigenfrequency and damping, while blade modes did not seem to change much except when there was some coupling with a tower mode. However, it is possible that damping gradients over revolutions per minutes (RPM) are significantly changed, when interference between modes with similar Eigenfrequencies occurs for one foundation type but not the other, where Eigenfrequencies may be different.

For the motion envelope effect on aeroelastic stability, the pitching motion of the floater is seen as the main area of interest. The asymmetrical airflow on the rotor from a constant backward pitch would lead to a 3p excitation of non-rotating system modes, so an intersection of the respective Eigenfrequencies with the 3p frequency range should be avoided – but because of other WTG typical 3p excitation mechanisms like tower passage of the blades, this is not a new, floater-specific requirement. Induced wind speed from dynamic pitching motion might contribute to blade flutter, so the flutter safety margin should be large enough to take this into account.

2.3. Innovation/technology needs

The analysis conducted in this project highlighted some of the WTG and wider system design impacts of moving from a fixed to semi-submersible floating design. However, it is important to note that there are limitations with this study, in that the results focus on a 15MW WTG modelled on a semi-submersible platform, and key findings are not necessarily applicable towards other floater concepts. Additionally, the designs developed in this study were based on ULS loads only, and the consideration of FLS loads would help to further refine the designs. Further research could focus on single tower designs with other platform types and floating wind concepts with integrated tower designs. However, some areas of interest, which would merit further research, were identified:

1 **Developing alternative materials or designs for WTG towers could deliver cost-effective soft-stiff designs.**

One of the challenges with a soft/stiff tower is achieving a tower design that is soft enough, which is why materials with lower young's moduli than steel could prove to be interesting alternatives. Using alternative primary materials for the tower such as Glass Fibre Reinforced Plastic (GFRP) was identified as a potential avenue to enable cost-effective, lightweight tower designs with a first global bending mode below the 3P region (i.e., a true soft-stiff design). GFRP is already widely used in rotor blades. Further research and development (R&D) into this and other tower materials could deliver cost savings for floating wind.

2 **For WTG T&I, the options for quayside assembly or onsite installation will both require either design alteration or updating the installation tools and procedures.**

Current T&I and O&M aspects related to the WTG are based on established fixed bottom offshore wind practices. However, there are floating wind specific challenges associated with T&I processes as well as O&M, accessibility, workability, major component exchange processes. These challenges were discussed during a stakeholder engagement exercise along with the potential need for design modifications for floating specific WTGs, to inform of requirements for the industry.

When considering lifting and installation operations related to the quayside (or offshore) assembly of tower and RNA on the floater (e.g., component exchange or other repair and maintenance), stakeholders suggested that existing tools and motion/displacement requirements should be revisited due to the increased motion profile. This is assuming all key installation steps cannot be performed quayside, with the floater fixed by some means, in which case existing installation tools and procedures should suffice.

Comments were made that generally, when lifting, nacelle cranes should be used as much as possible (but therefore may require reinforcement) for all lifting activities, to avoid the utilisation of floating crane vessels, which can be costly. A suggestion was made to also consider temporary damper systems to be installed on the nacelle roof during the blade installation process, to mitigate relative displacements during onsite lifting operations.

Although quayside operations with the floater fixed are expected to operate with existing tools and procedures, the towing process of WTG to site after assembly may result in more acceleration on the RNA. This needs to be considered in the design. Acceptable levels of accelerations and motions during tow shall be specified by WTG OEMs for floating specific applications. Towing an assembled turbine from harbour to site (or vice versa for O&M operations) is still a new procedure for some WTG OEMs and standardised requirements and procedures are still being developed. Stakeholders suggested that a power supply may be required during the long towing process, to ensure the ability to yaw, dehumidification of the WTG and potentially operate blade pitch systems.

3 **O&M operations on floating WTGs may require additional safety requirements and monitoring to secure technicians and moving materials.**

A need has been raised for additional anchor points to secure both people and material on the moving platform. Temporarily securing components during a component replacement procedure could be advantageous and can be executed by placing more fixation points. A safety device for the transport of material inside the wind turbine is also needed, this could be a simple guiding device which prevents the material from swinging while being transported with chain hoists.

Blade inspection and repair activities (e.g., Leading Edge Protection replacement) are another area of concern as they require special rope access and external cable platforms. Whether these access methods will be a suitable option for blade related O&M activities in a floating environment still has to be evaluated.

The bolted connection between the transition piece (TP) and tower base was raised as an area of concern, due to the significantly increased tower base bending moments for floating systems. Using additional condition monitoring systems (CMS) at the joints could potentially reduce the O&M efforts. When possible, decreasing the number of bolted and welded connections on the foundation and on the WTG is preferable, to reduce inspection requirements.

The attachment points for secondary equipment with the nacelle is another area of concern, for example the movement of cables (and trays). The use of a CMS could be a possible option to detect potential issues/damages due to cables rubbing against structure/each other. This could include motion sensor-based alarms, fluid level measurements and the placement of pressure valves on transformer and lubrication systems. In this context, it is important to mention that one WTG OEM clearly stated that no reinforcement to main components and/or modified O&M/T&I processes/schedules will be necessary when operating the WTG on a floating substructure.

4 **Control systems need to be adapted for floating foundations.**

A considerable amount of work is already underway to ensure control systems are adapted for floating WTGs to account for additional load increases. The adapted control systems need to ensure safety margins are large enough to account for induced wind speed from dynamic pitching motions, that might contribute to either classical blade flutter or stall flutter.

3. Key findings: Access and availability

3.1. Study overview

Floating wind turbine installations will likely be located in deeper waters and at greater distances from the shore compared to fixed bottom installations. The accessibility and availability (A&A) of bottom fixed offshore wind is relatively well known, however in floating offshore wind there is more uncertainty. As floating wind capacity is expected to increase rapidly in the next decade, it is important to understand how various environmental, human, and technical factors influence floating wind A&A.

Availability is the parameter that evaluates the potential of a windfarm to generate electrical power and as such is useful for estimating revenue projections, turbine design performance evaluation and may other purposes. Accessibility is the measure of how often environmental conditions are within acceptable limits, thereby enabling access onto the structure. It directly impacts the rate of availability and varies across different access methods, which have different limiting factors, in terms of wind speed and wave height.

This project, delivered by Seaspeed Marine Consulting Ltd with assistance from SeaRoc Ltd sought to assess the differences in A&A of floating versus fixed-bottom offshore wind, identify opportunities for improving A&A and reducing Operation and Maintenance (O&M) costs in the FOW sector. A literature review and stakeholder engagement exercise determined the key project objectives which were to:

- Estimate access performance of different platform types with different access methods;
- Define and optimise the access strategy for the expected environmental conditions;
- Assess the sensitivity of Wind Turbine Generator (WTG) availability based on accessibility;
- Determine the effect of floating substructure motions on technicians during O&M.

Four access systems considered were service operation vessels (SOV) equipped with a walk to work (W2W) system (that are required to link a moving ship to a moving platform), daughter crafts (DC), crew transfer vessels (CTV) and helicopters (Helo). The A&A performance of each of these floating structures and access systems was assessed in three different environmental conditions and at three different locations from the shore (25, 50 and 100 nautical miles).

The modelled floating structures were based upon four reference floating wind designs: spar, barge, semi-submersible and tension leg platform accommodating a 15MW reference wind turbine and sitting within a 50-turbine farm. The four access systems investigated were generic designs assembled from the average specifications of the most appropriate equipment available on the market at the time.

Three environmental conditions; benign, moderate and harsh were used in this study. All environments were set to operate at 150m water depth with 1year significant wave height (Hs_1) of 4.3m for benign, 7.0m for moderate and 9.5m for harsh conditions.[13] The soil types were selected as well graded medium dense sand, poorly graded loose sand and weak rock for benign, moderate and harsh conditions respectively.

[13] Reference Floating Wind Designs and Scenarios, delivered by Ramboll for the Floating Wind JIP, 2021.

3.2. Key findings

A variety of different access strategies are currently used within the offshore wind (OSW) industry, including crew transfer vessels, service operator vessels with the option of walk to work systems, daughter crafts, and helicopters , which are illustrated in Figure 10. The use of different access strategies is dependent on local weather environments, distance to shore, the likely failure rates, the corrective and preventive maintenance resources required and the performance of the access vessels during transit; all whilst balancing the cost of access and the cost of downtime. In many instances these access strategies are still maturing as technological advances are made to manage the ever-expanding variation of site characteristics and locations.

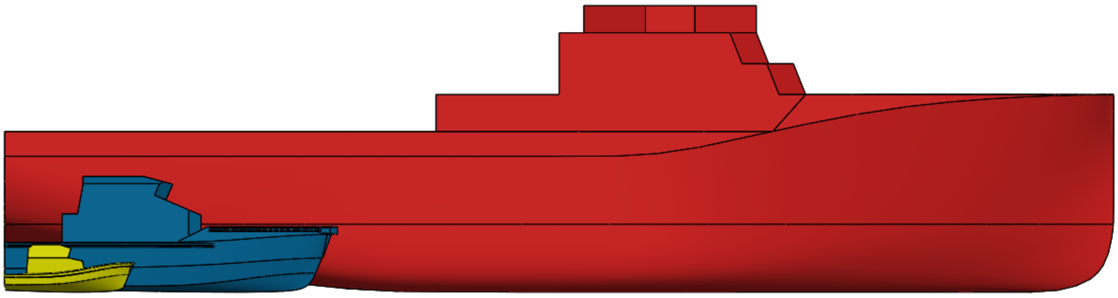


Figure 10: Scale comparison of the various access models DC, CTV, and SOV in ascending size order (Seaspeed Marine Consulting Ltd).

1 **In the conditions analysed it was found that the accessibility of TLP & SPAR floating platforms performed similarly to fixed bottom systems accessibility rate.**

Four reference platforms: Spar, Semi-sub, Barge and Tension Leg Platform (TLP), were modelled with three reference access vessels (SOV+W2W, CTV and DC) and the relevant platform mooring systems, an example of which is shown in Figure 11. A fixed bottom system was also modelled to assess the effects of floating against fixed systems. Key assumptions included the SOV always orientated head to the waves with the W2W system perpendicular to the vessel, which allowed the vessel to limit its exposure to beam waves and for CTV and DC conventional boat landings were assumed, with one landing aligned with the dominant wave direction.

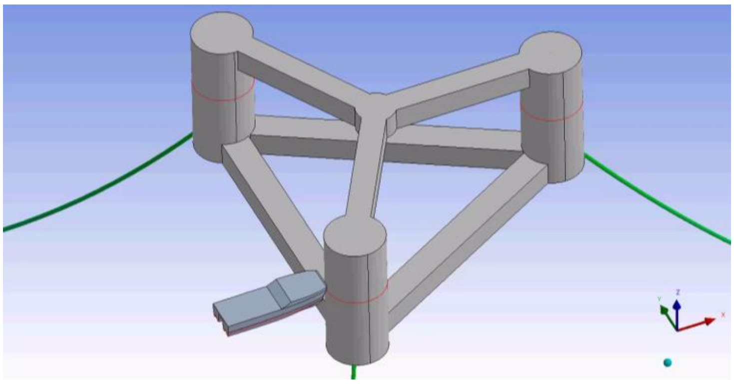


Figure 11: Example of a scale version of the CTV and a semi-submersible floating platform (Seaspeed Marine Consulting Ltd).

The Spar, Semi-sub and Barge platforms were modelled with catenary moorings well below the sea surface, and hence had no influence on the approach to the platform or access to landing areas of the access vessels. The TLP platform was modelled with moorings secured to a submerged frame, which had limited influence for access vessels in normal operations but could results in significant issues if a significant mooring failure were to occur.

There are some concept designs of floating platforms taking advantage of the benefits of moorings terminating above the water line. However, such arrangements could limit access significantly by restricting the operational position and orientation of access vessels when adjacent to the platform when using the reference case model.

Accessibility is defined as the percentage (%) of time that the sea state is below the limiting significant wave height (Hs) of the access vessel and the floating platform combination, whilst also accounting for wave period (Tp) and wave direction. The accessibility was calculated for each platform type and method using a monthly average of Hs and Tp. The results for the harsh environment can be seen in Figure 12.

Within the confines of this study, the SOV and helicopter consistently displayed the highest levels of accessibility across all 3 conditions and all 5 platform types (including fixed), and the daughter craft consistently produced the lowest accessibility results. The Spar and TLP produced very similar results to that of a fixed turbine. The Semi-sub and Barge platforms generally exhibited lower accessibility, which was thought to be a consequence of the large waterplane area of these platforms increasing the relative motions at their periphery, where access takes place.

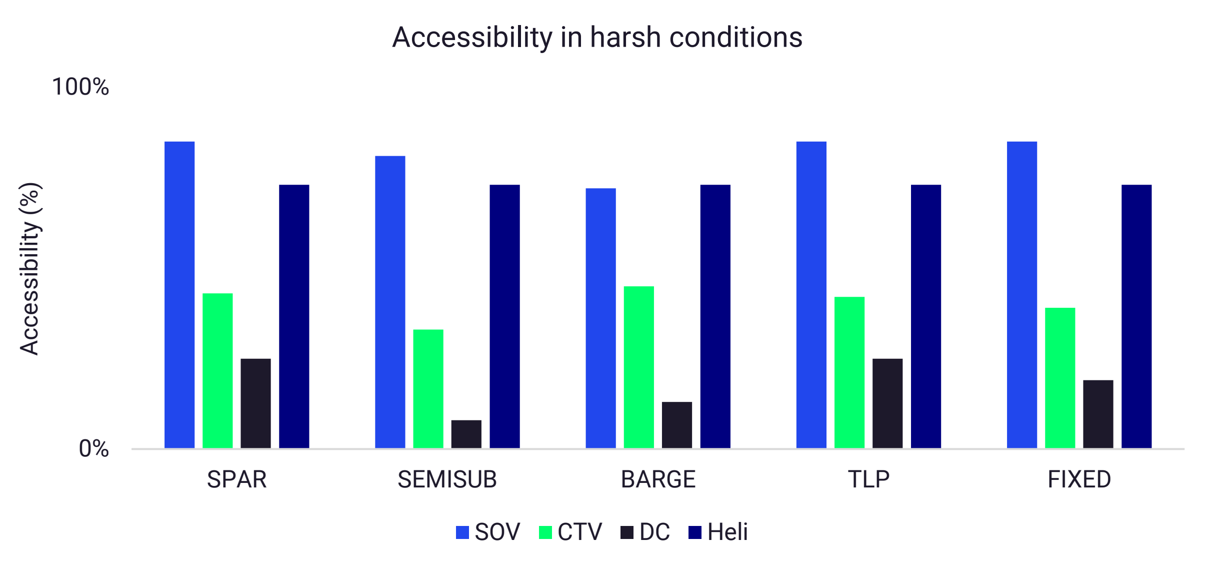


Figure 12: The accessibilities of the different platform types in harsh conditions.

Various side studies were also undertaken to investigate associated accessibility issues, and the following effects were found:

- The effect of increasing the number of boat landings to either two or three was found to increase accessibility by 2-3% in the Benign and Moderate environments.
- Scaling the platform geometrically up in size by 15% (resulting in a 50% increase in displacement) indicated a very small increased accessibility.
- The effect of marine growth on platform motion indicated a small increase in accessibility due to the result of increased displacement and damping.

2 **All floating wind A&A strategies are likely to be similar to those for fixed-bottom far-shore sites.**

This study concluded that the access strategies for floating offshore wind (FOW) will be similar to those already in existence for far-shore fixed-bottom solutions, that have equivalent metocean conditions to those used in this study. This study was limited to the assessment of O&M for minor repairs and did not cover access for major repairs or component replacements, which may require different vessel types and will generally be carried out in more favourable weather conditions. However, access strategies and subsequent vessel investment will be influenced to an extent by the need to support these major repairs or component replacements.

The performance of different access strategies was also assessed considering other influences such as cost comparison, wind farm availability, vessel emissions and vessel utilisations. Analysis was performed across the four floating platform types, four access vessels, three weather environments and three distances from shore, giving a total of 144 combinations of wind farm access arrangements.

A simple cost model was used to assess the relative opportunity cost of various strategies. The opportunity cost was calculated using vessel charter costs, vessel fuel costs, the cost of technicians and the cost of turbine downtime. Table 3 below shows the access strategies with the lowest costs for minor repairs only, assuming that only single access vessel arrangements are required.

Table 3: The lowest cost access strategies for minor strategies.

Environment	Lowest cost Access system		
	Distance offshore		
	25nm	50nm	100nm
Benign	CTV	(Helo)* SOV/W2W/DC	(Helo)* SOV/W2W/DC
Moderate	(Helo)* SOV/W2W/DC	(Helo)* SOV/W2W/DC	(Helo)* SOV/W2W/DC
Harsh	(Helo)* SOV/W2W	(Helo)* SOV/W2W	(Helo)* SOV/W2W
Note: The Helicopter offers the lowest system for minor repairs but does not offer the same level of general support as an SOV or CTV and is unlikely to be selected as a preferred access strategy on its own. For the helo-strategy, please note that costs for standby rescue vessels were not considered.*			

The cost model results clearly showed that SOVs and Helicopters dominated the majority of low-cost floating wind access strategies, which is largely similar to that of fixed turbines.

The only exception to this was a site near to shore (25nm) in benign conditions, where the CTV showed to be the most cost competitive. However, this lower cost comes with a greater downtime for repair, due to the restricted operational limits of the CTV (compared to other access methods). Although the CTV outperformed the SOV/W2W and helicopter in this condition, it is expected that the majority of floating wind farms will be constructed at further distances to shore, where the CTV transit times would be long, and in harsher metocean conditions.

In moderate environments, the SOV/W2W system was more cost effective than the CTV in all combinations except for barge platforms at a distance of 25nm. Utilising the DC with the SOV/W2W system proved more cost-efficient and offers the ability to significantly reduce SOV utilisation, thus allowing it to undertake other work such as major repairs. In harsh conditions the SOV/W2W clearly has a lower opportunity cost than the CTV, due to the time taken to transit for the CTV.

The Helicopter-only strategy was the most cost effective overall, since it minimises downtime associated with minor repairs at a charter rate far lower than the SOV. However, it is not considered to be a suitable single system strategy due to its inability to support major repairs and other O&M activities, where standby capability and/or heavy lift capabilities are required. It is more likely that it would be deployed as part of a mixed fleet, particularly on a large wind farm or for several smaller adjacent windfarm sites.

One of the main objectives of the OSW industry is decarbonisation. To ensure this happens holistically, the carbon emissions of the access systems were also studied and assessed as a performance parameter. The annual fuel emissions of each access strategy was calculated as a combination of direct vessel fuel emissions and the emissions associated from onshore non-renewable generation to account for wind farm downtime. The non-renewable generation was assumed to be made up of the baseline-power over the last 2 years from the UK electrical grid as a combination of coal, oil, gas, nuclear and biomass generators.

Generally, across all three environmental conditions, the SOV/W2W/DC combination proved as emission efficient as the Helicopter whilst the CTV consistently produced high emissions. Figure 13 illustrates the variation in emissions per platform type and at different distances to shore for the SOV/W2W/DC access method in moderate conditions.

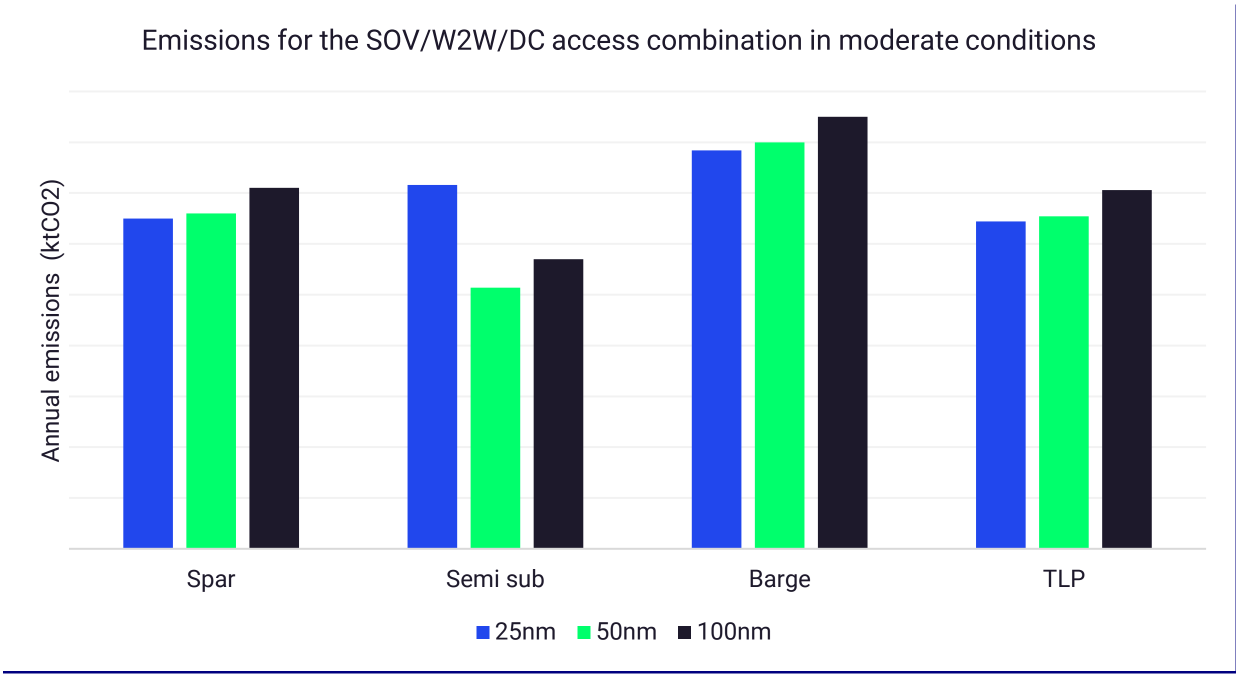


Figure 13: Annual emissions for the SOV/W2W/DC access combination in moderate conditions at different distances to shore, for different platform types.

Availability is defined as the percentage (%) of power produced, accounting for failures and maintenance, compared to the power that would have been produced in the relevant environmental conditions had no failures occurred or maintenance been undertaken. With the results gathered in this study, across the different parameters, the sensitivity of WTG availability to accessibility was found to be relatively low for high levels of accessibility. This was to be expected, as downtime is minimised for higher accessibility, with repairs and maintenance undertaken more quickly, thus resulting in higher availability.

3 **Floating turbine nacelle motion is not expected to be a significant problem with respect to sea sickness.**

It was identified that there is a wide range of human factors that might influence the access and availability processes, from physiological to psychosocial considerations to management and organisational arrangements. However, the only human factor component considered to be directly relevant to the scope of this study is the issue of low frequency (<1Hz) whole body vibration, covering sea-sickness and postural stability. Sea-sickness and postural stability are well known to be the most common limiting factors in the marine environment, influencing both comfort and task performance. Several criteria were assessed with the most relevant found to be the NORDFORSK limits, that are widely used within the marine industry, and an illness rating (IR) developed by Professor Jelte Bod of TNO in the Netherlands. While there are no strict developed acceptable levels of IR, it can be used as a comparator for the various platforms.

To investigate the issue of sea sickness and postural stability, each of the four floating platforms were individually modelled across a range of significant wave heights (Hs of 1 to 5 metres) and peak energy periods (Tp of 3 to 16 seconds) for the three reference environments. A number of motion parameters were investigated at various positions on the platforms, including: deck angles (a combination of pitch and roll angles), vertical and horizontal displacements, velocities and accelerations at the centre of gravity and at the nacelle. These motions were then investigated with respect to various human factor standards and their level of acceptability assessed.

The most relevant parameter in terms of technician comfort and/or ability to undertake tasks in the nacelle on a floating platform was found to be the horizontal acceleration, which reached or passed the NORDFORSK limit for all platform types, though the motion was not excessive. The Barge and Semi-sub tended to move more than the Spar or the TLP, which is likely to be due to the large waterplane areas for the Barge and Semi-sub platforms. When considering IR values, it was suggested that all the platforms have similar comfort levels.

When assessing the effects of accessing from the vessel to the floating platform, the level of motion sickness was expected to be lower than on the access vessel itself, for all access methods. The time required to recover from the motion experienced on the access vessel will be the main risk to technician task efficiency. There are still some unknown issues with the effect of motion sickness, such as the effect of transferring from one moving environment to another, and it is likely that only practical experience will lead to a proper understanding of this latter issue. In summary, it is expected that the percentage of technicians who will experience motion sickness whilst working on the floating platform over the course of a year is likely to be low.

4 **Optimisation of SOV/W2W vessel size for specific environmental conditions could result in commercial benefits.**

During the cost analysis, it was clear that the charter cost was the dominant factor for SOVs. Since charter rate is not only a function of the market conditions, but also a function of vessel size and W2W specifications, this suggests that there is scope for investigating less capable SOVs with the benefit of reduced charter costs, as a particularly large, high specification SOV was modelled in this study.

The study found that for high levels of accessibility, the relationship of availability to accessibility is relatively insensitive. Because of this it was concluded that SOV size could be optimised for particular windfarm environments (e.g., benign, moderate or harsh), allowing charter costs to be minimised for the less demanding applications and environments and the performance to be maximised for the more demanding environments. This would also make the SOV access strategy even more competitive in environments with other access strategies. For the Benign and possibly Moderate environments, the use of daughter-craft offers the ability to significantly reduce SOV utilisation, thus allowing it to undertake other work, such as major repairs or component replacements.

This study has only modelled three environmental conditions and further investigation is required to clarify the optimisation of SOVs in different environments.

5 **W2W systems are currently the limiting factor for SOV operation, further development will increase the accessibility of these vessels.**

Calculating accessibility requires knowledge of the limiting criteria of the vessel, which depends on different factors for each type of access vessel. The limiting performance of the different access methods was established from published data where possible and verified by stakeholder engagement. The limiting factors for the analysed access methods are listed below:

- The SOV is dependent on the sea-state, and the limiting factor was when the operational limits of the W2W system were exceeded, these primarily being the luffing and slewing rates.
- The CTV and DC were limited by the sea state and heading in which they could maintain a no-slip push-on transfer, for both vessels the headings are largely determined by the orientation and number of boat landings available on the floater. The limiting wave heights of the CTV and DC were lower than that of the SOV/W2W system.
- Helicopter access limitations are determined by the wind speed at which they can undertake a heli-hoist operation at the nacelle of the wind turbine.

For the SOV case, the W2W system was modelled in such a way that the availability of the W2W system was maximised. The relative horizontal motions between the floating platforms and SOV were relatively small, and could be largely compensated for by the W2W system.

As the W2W system is the limiting factor in SOV operation, there are significant benefits to be obtained from lighter, faster responding and more capable systems. At present, W2W and DP (Dynamic Positioning) systems are designed to work to a geo-stationary reference (i.e. the fixed bottom wind turbine tower). For floating wind, these systems will need to be adapted to work with a moving target reference point, and could result in significant cost savings. If the W2W system performance was improved, then it is expected that vessel motions, wind strength and possibly DP systems would become the next limiting factors.

In terms of current W2W developments, Figure 14 shows the L-Bow system (left) that can be deployed from a container, meaning that a Platform Supply vessel (PSV), which typically would have a lower day rate compared with an SOV could be used for technician transfers; and the Z Bridge transfer system (right), which transfers personnel via a travelling cage rather than a gangway and does not require a tower or high mounting position on the vessel and is small enough to be deployed from a large CTV which would have a lower day rate compared with an SOV.

Figure 14: Examples of a L-bow (left) and Z-bridge (right) W2W system.[14]

For the CTV and DC, the limiting wave conditions in which the bow fender slipped when pushing-on to the boat landing was also established through motion modelling. The slips were assumed to occur through excess buoyancy forces over and above that possible to counteract by friction of the bow fender when pushing-on with 85% MCR (Maximum Continuous Rating, engine output).

[14] Images courtesy of www.l-bow.co/ and www.zbridge.nl/.

3.3. Innovation/technology needs

With the floating offshore wind sector still maturing, the opportunities for technological and operational developments are significant. With respect to O&M access and availability, the focus is on reducing WTG downtime to a minimum, whilst minimising the associated operating costs. This study has demonstrated the necessity to view access approaches holistically, where the impact of access is seen in terms of overall costs, environmental emissions and general industry efficiency. It should be reiterated that the innovation needs concluded below are based on the conditions analysed, focusing on large turbines, large floating platforms and minor repairs.

1 **Design developments of the W2W system and associated platform to accept access from 360° would optimise performance whilst minimising demands on the DP system.**

An assumption in this study has been that the W2W system can deploy personnel to the turbine from any position, 360° around the floating platform. Many existing arrangements are limited to orientations to suit particular access gate positions and this clearly represents an inherent limitation, both for vessel motion and DP performance. Overcoming this limitation, with revised W2W gangway designs and/or access balconies will be important for the industry. Figure 14 (above) shows some of the current W2W developments, but further design configurations would help improve accessibility of W2W systems.

Similarly, additional access methods could increase the options for technician access whilst reducing costs and motions. Access hoists are a method of access that safely lift personnel from the moving deck of a vessel onto a turbine transition piece. Successful integration of such a system, to the extent that conventional CTV boat landings are not required, can make a substantial cost difference to both the turbine structure maintenance costs as well as the initial steelwork requirements. Though it should be noted there would be additional maintenance costs for the hoist system winch. One example of an active hoist system is the GUS (get-up-safe) system which is a heave compensated personnel lifting solution developed by Pict Offshore that has replaced the boat landing at Ørsted's Hornsea Two offshore wind farm project.

2 **Vessel developments, including reduction of emissions, should be a continued goal for the industry, to improve accessibility and reduce overall industry emissions.**

This study showed that when assessing and choosing different access methods, the minimisation of cost is not always compatible with the maximisation of availability nor the minimisation of emissions. Further development and availability of non-fossil-fuel based energy sources should be a prioritisation for the industry. This area is already developing rapidly and is expected to do so because of the necessity to reduce emissions within the marine industry. The offshore wind sector is already showing good progress, with a number of hybrid CTVs already operational as well as plans for hybrid SOVs to enter the market.

With respect to CTVs, it is expected that crafts offering greater accessibility will be required. This could possibly lead to larger vessels and/or SWATH (small waterplane area twin hull) or Semi-SWATH configurations. There has been a limit to the size of vessel that is permitted to push-on to a fixed turbine (approximately 100 tonnes displacement) for reasons of likely impact forces on the boat landing as well as the turbine. For floating turbines, it may be possible that floating platform structures, might be more resilient with respect to boat impact forces. With some changes to the standard boat landing structure, it may therefore be possible to accommodate larger CTVs than what is currently feasible for conventional fixed platforms.

Throughout this study, the daughter craft was found to have a beneficial effect on the utilisation of the SOV, particularly in the Benign and Moderate environments. It is expected, and suggested, that these concepts would be further developed to increase the transfer limits, which would in turn allow these crafts to further supplement the work of an SOV. Future daughter craft are likely to include increased freeboard, reduction of bow slipping forces, stabilisation of motion using active systems and use of single and twin hull arrangements which should further increase their potential.

3 **The development of remote or autonomous systems aimed at reducing human intervention offshore, will likely lead to significant cost reductions in O&M in the medium to long term.**

The impact of autonomous systems is expected to be very significant with respect to access, mainly by reducing the need for human intervention offshore, by reducing the need for manned ships or helicopters. Surveying and external monitoring are already benefitting from the use of autonomous systems and it is expected that turbine-resident robots will soon undertake some minor repairs and resets. It seems that this area is well covered by existing research projects. With respect to floating wind as opposed to fixed installations it is thought that the inspection of the mooring lines and the underwater hulls of these floating platforms will be the main area for developments, probably using USVs (unmanned surface vehicles) that will deploy UUVs (unmanned underwater vehicles) and ROVs (remotely operated vehicles).

The increase of automation is likely to reduce the demand for access which alongside increased reliability of turbines will result in considerable savings in opportunity costs. Thus, it is recommended that automation in survey, inspection as well as the undertaking of maintenance and minor repairs, is progressed as rapidly as possible.

4. Key findings: Floating wind yield

4.1. Study overview

Rapid adoption of floating foundations for offshore wind farms is highly dependent on the floating technology becoming cost competitive as quickly as possible. For developers, the cost of capital is critical to the business case, whilst for financiers, lowering the cost of capital depends entirely on the risk picture. For a wind farm, the return on investment comes from sale of the produced energy and hence one of the key risks is yield. Since floating wind turbines are a relatively new technology, the impact on yield is not well understood or quantified. This uncertainty directly corresponds to an increase in the yield risk which in turn raises the cost of capital, which raises the barrier to rapid deployment of the technology.

The motions and dynamics of floating offshore wind turbines differ significantly from their fixed foundation counterparts. In general, the floating foundation can translate and rotate to some extent in every degree of freedom, as it is typically not rigidly constrained by its moorings. These dynamics, coupled with the dynamics of the wind turbine generator itself, result in differences in the turbine power production and thus the turbine wake.

The aim of this project was to understand the impact of floater motions on wake effects and thus energy yield when compared to that of an individual fixed turbine, and then how this translates to the overall AEP at the farm level. A review of current literature highlighted key knowledge gaps within the industry and shaped the subsequent activities carried out in this project. Three key effects were analysed, these were:

- **Impact of tilt and mooring stiffnesses.** Finite stiffness in the mooring systems means the floating wind turbine can tilt in the fore-aft direction and can translate in the streamwise dimension, both of which impact the power production and wake characteristics.
- **Impact of persistent yaw oscillations.** Light structural damping of the floating foundation means that oscillations in the yaw degree of freedom can persist for a long time, which impacts the breadth and depth of the turbine wake.
- **Impact of wave-driven tilt and surge.** Tilt and surge motion of the floating foundation cause a change in the apparent wind speed at the turbine rotor. These motions can be driven by waves, and the corresponding effects on power and wake are examined.

The outcome of this project was that engineering models for three floating wind wake effects of interest were successfully developed and implemented into the FLORIS[15] toolchain. These engineering models are designed to be fast running to afford the appraisal and optimisation of the performance of future floating wind farms. These models have been developed from first principles and specific tunings to the

[15] FLORIS (FLOw Redirection and Induction in Steady state) is an open-source wind farm optimisation tool chain available through NREL. Further information is available at: https://www.nrel.gov/wind/floris.html

results of detailed simulations from OpenFast[16]-SOWFA[17] and are shown to be sufficient to capture the behaviours of interest. All numerical studies were performed using the IEA 15MW turbine.[18] Relevant parameters include a diameter (D) of 240m and a hub height of 150m.

The models were configured in FLORIS to be as independent of the foundation solution as possible, meaning that from a wind farm yield perspective the effects can be modelled with little knowledge of the mooring system, inclination at peak thrust and response amplitude operators (RAOs) which would either be provided by the foundation original equipment manufacturers (OEMs) or derived from independent load models of the coupled turbine-foundation system.

Following the development of the tool chain, all the effects listed above were brought together to make some assessments about the overall impact of floating wind turbines on wake effects and yield based on a pre-determined reference site. The results from this in combination with a project partner questionnaire were used to develop a series of draft recommended practices for floating wind yield assessment.

[16] FAST is an engineering tool for simulating the coupled dynamic response of wind turbines. Further information can be found at https://www.nrel.gov/wind/nwtc/fast.html. All NREL FAST simulations are now opensource (OpenFAST). Further information can be found at https://www.nrel.gov/wind/nwtc/openfast.html

[17] SOWFA (Simulator for Wind Farm Applications) is a set of computational fluid dynamic solvers, boundary conditions and turbine models available open-source through NREL. It is available coupled with FAST. Further information is available at: https://www.nrel.gov/wind/nwtc/sowfa.html

[18] Definition of the IEA 15-Megawatt Offshore Reference Turbine, NREL, 2020. Available at: https://www.nrel.gov/docs/fy20osti/75698.pdf

4.2. Key findings

Floating wind projects have quickly transitioned from single turbine demonstrators to small multi-turbine sites over the past ten years with tenders for full scale sites currently open. These commercial scale projects will require significant financing and so accurate pre-construction yield assessments are crucial to their ongoing success.

1 **Physical effects of floating offshore wind will have an effect on wind farm production, compared to fixed foundations, and need to be integrated into existing tools.**

The various physical effects that may impact production from a floating wind farm (compared to that of the same nacelle on a fixed foundation) were classified as:

- **Turbine level effects**, which relate to changes to the wind turbine controller (e.g., thrust limits, set-points, ramp rates)
- **Foundation level effects**, which relate to the impact of platform statics and dynamics on single turbine performance (e.g., tilt offsets at peak thrust in passive concepts)
- **Park level effects**, which relate to the impact of platform statics and dynamics on wake lengths, spreading, meandering and direction.

A review of literature and existing tool chains found that the turbine and foundation level effects are largely well represented by existing tool chains for loads calculation and power curve generation. However, there are a small number of aerodynamic interactions that are relevant to floating wind turbines that are not included in these existing tool chains including turbine motions causing the rotor to pass through its own wake and the aerodynamic loading in the case of large persistent yaw motions.

When modelling floating turbines, there are a number of effects related to reducing loads by changing an operating point, that are seen as design decisions rather than fundamental limitations on yield. One example is that limiting peak thrust is not a fundamental limitation, in fact increasing the thrust limit can be readily achieved but is not, simply because the additional power produced is unlikely to outweigh the additional CAPEX of increasing capacity.

At the farm level, the nuances of floating wind are not accounted for. This in part is due to an insufficient body of evidence, either in simulation or physical testing. Effects at farm level may be small but, until properly quantified, they may significantly impact the perception of uncertainty.

It is not only important to understand these key physical effects, but to also consider how they should be integrated into existing tool chains without being prescriptive on approach. Operators use different types of tools (e.g., CFD vs N. O. Jensen for wake losses) so the developments need to not bias one or the other.

2 **Floating effects on yield have been quantified and bounded.**

One of the fundamental aims of this project was to reduce uncertainty around floating wind yield with the purpose of creating a corresponding reduction in the cost of capital for developers looking to build floating wind farms.

Throughout this project the various aerodynamic and hydrodynamic phenomena which could give rise to the difference between floating wind and fixed bottom yield have been investigated. They have been quantified in relation to both fundamental test cases and when applied to a realistic reference site. As a result, bounding magnitudes for the floating effects on yield have been derived.

3 **Persistent yaw oscillations may increase wake recovery rate.**

From the engineering models configured in FLORIS it was found that the effect of persistent yaw oscillations may increase the apparent rate of recovery of the wake. The effectiveness of this increased recovery is a function of the incoming wind speed, turbine diameter and period of oscillation. Although not certain, there exists at least the potential to adjust the coupled system response to tune the point of maximum recovery to optimise overall AEP. However, this effect is highly dependent on the detail of the foundation/mooring arrangement and characterisation of the yaw oscillation behaviour through detailed simulation or other means. Hence, in the first instance it is recommended that conservatively no net benefit is attributed to this mechanism.

It is important to remember that the factors that have the largest effect on the accuracy of energy yield estimates today may be different to those of later commercial sites. More specifically, whilst the technology is still relatively new, factors such as foundation availability will weigh heavily on any differences between forecasted and actual yield. Likewise, differences in behaviour between simulations and installed prototypes may lead to significant increases in triggers of supervisory systems and/or requirements to curtail.

4 **Static effects have a larger overall yield impact than dynamic effects.**

The modelling tools were applied to some representative reference sites in reference climates to determine the impact of floating foundations on wake and yield, with the aim of providing indications of when the impact of floating foundations should be incorporated into yield analysis, and when it is suitable to be neglected. The reference site data was introduced in section 3.1, and is the same used across these phase 4 projects.[19]

Four different floating platforms were considered (spar, semi-submersible, barge and tension-leg platform), however as the barge foundation showed some of the greatest floating motion effects it was the main focus of this analysis, to ensure the modelling outputs were manageable. Three reference layouts were modelled:

1. A short row of turbines which, although does not represent a realistic farm layout, facilitates a deeper understanding as many wake effects can become layered on top of one another.
2. A 3x3 turbine array to provide some insight into sensitivities to various parameters. 2 different turbine spacings were modelled, 4D and 10D, representing either ends of the range of turbine spacing. This smaller simulation was chosen to provide insight into parameter sensitivities to various parameters.

[19] Reference Floating Wind Designs and Scenarios, delivered by Ramboll for the Floating Wind JIP, 2021.

3. A 10x10 turbine array which provides a more realistic number of turbines within a windfarm, again with 2 different spacings. However, due to large computational power, fewer sensitivity studies were performed.

At a high level, within the confines of this study it was found that static effects (tilt and streamwise deflection) had a larger overall yield impact than dynamic effects (persistent yaw oscillation and wave-driven platform motion). Figure 15 shows the difference in wake effects at different wind speeds for different turbine spacings in the benign climate. When making assessments of yield for floating wind farms, primary consideration should therefore be given to the yield impacts of static effects.

Streamwise deflection was found to have the most significant impact on power production, regardless of wind/wave climate. This then resulted in a net decrease in array power output, since this effect deepens the wake seen by the turbine behind it, causing a lower apparent wind speed and thus, lower power production. However, this effect was found to have a smaller impact at larger spacings since the wakes have more time/distance to recover and was found to have less impact again at larger turbine sites.

Turbine tilt was also found to have an impact on power production, though lower than the streamwise deflection. The impact of tilt was found to be more pronounced as the climate conditions were exaggerated, whereas the other modelled effects remained approximately the same. This is likely to be due to the increased mean wind speed and turbines spending more time at or above rated speed. As the turbine site increased, the power production impact was less sensitive to the tilt angle.

Persistent yaw oscillations and wave-driven tilt/surge motion claimed net power benefits under specific conditions. The impact of yaw effects was higher at wider turbine spacing, perhaps because narrower spacing results in a narrower wake downstream and therefore, unless the wind is directly aligned with the rows, the wake deficit is less pronounced. In contrast, wider spacing where the wake is wider at the downstream turbine causes a bigger yield reduction. In general, the smaller the turbine spacing, the greater the impact of number of turbines at the site. I.e., turbines spaced further apart are less influenced by turbines around them and are closer to seeing the free stream wind speed.

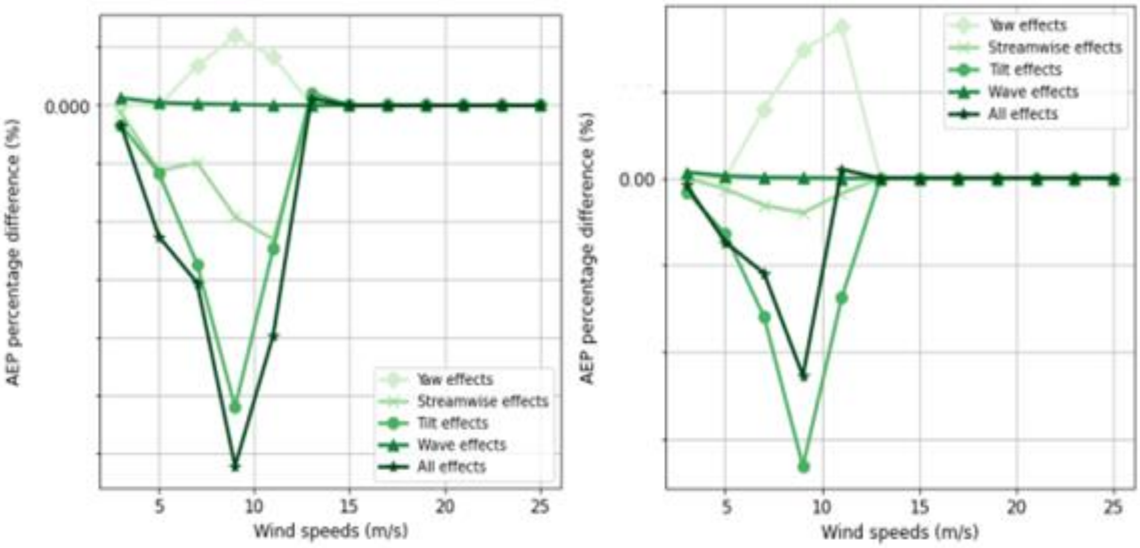


Figure 15: AEP impact of floating wake effects in benign climate for 4D spacing (left) and 10D spacing (right).

When considered in the context of annual energy production for a farm with grid layout, the overall impacts are smaller. This is largely attributable to the fact that the farm-scale impact of many of these effects are down to wake, which is only relevant for wind directions aligned with rows/columns of the array. The extent to which this is true is highly dependent on layout, climate, and wind sector distribution.

5 **Yield optimisation strategies for floating wind could be viable and can be leveraged to make LCOE decisions about foundations and turbines.**

In commercial scale wind farm design, there are several points in the design process where trade-offs are required between yield and loads. These decisions are often based on the criterion of optimising the levelized cost of energy (LCOE). Since floating wind farms are yet to reach commercial scale, and with less certainty to yields and load characteristics, these decisions may play out differently in the design of a floating farm. An initial investigation was performed using the FLORIS toolchain to examine the compatibility of floating wind with yield optimising strategies with two of the most common areas where optimisation is required: induction control and active ballasting.

Induction control optimisation was conducted for both fixed bottom and floating turbines, in order to provide a baseline. The application of induction control was found to lead to an increase in power production from a short turbine row for both fixed and floating cases, though this appeared to be marginally less worthwhile for the floating case. The close coupling between thrust, platform inclination and wake deflection means that the exact benefit for a given wind direction and speed will be different to that of fixed bottom assets. Since induction control lowers the maximum thrust seen across all turbines, it would be instructive to understand the impact of this thrust reduction on foundation CAPEX. This will have impact for the LCOE-optimal design choices for commercial floating wind farms.

Active ballast systems allow the foundation control system to, by various means, alter the mass distribution around the structure in order to affect the platform pitch angle. The effect has been well studied for fixed bottom turbines, however within the context of a floating wind farm the balance may look different since tilting the turbine rotor deflects the wake vertically. Purely from an energy yield perspective, active ballasting appears to offer some AEP benefits compared to free ballasted configurations as the tilt of individual platforms can be managed to deflect wakes and optimise yield. Initial results indicate that for some scenarios the management of wake deflection could be such to increase yield above that fixed bottom assets; however, this is expected to be an upper bound on performance. Furthermore, it must be remembered that the selection of static tilt angle is closely linked to shutdown loads and the yield benefit needs to be taken in in relation to the DEVEX/CAPEX of the active foundation. Further work is required, to understand this interplay and the benefits of active ballasting at the business case level.

6 **Recommended practices for developers, foundation suppliers, turbine OEMs and Tool vendors have been outlined.**

In collaboration with the Floating Wind JIP partners and advisory group representatives, recommended practices were developed to guide developers, foundation suppliers, turbine OEMs and Tool Vendors in their planning for future floating wind projects. The practice has been worded in a way that is as agnostic as possible to existing tools and processes, such that as much freedom as possible is allowed for stakeholders to implement these recommendations as they best see fit.

Recommended practices for Developers:

#	Current practice	Reason for change	Recommended practice
1	Yield impact for floating wind farms is not currently considered.	The move from demonstrators and pre-commercial scale farms towards commercial scale farms will necessitate more focus on the business case, into which the yield impacts of floating foundations play a part.	The yield impact of floating foundations should be considered through the lifecycle of a floating wind farm project.
2	The fixed foundation yield assessment is used as input to the business case.	Floating turbines come with an AEP impact which is likely to be difficult to characterise at early project stages. Applying a broad conservative global correction will let developers assess how much of an impact this has on the business case and correspondingly how much effort should be put into refining the estimate.	At early stages, a reduction in AEP should be applied on top of fixed Energy Yield Assessment (EYA) to account for the worst-case aerodynamic and hydrodynamic loss associated with floating foundations to assess the impact on the business case.
3	Early assessments of AEP for a potential wind farm are made using either in-house or third-party tools.	The yield assessment for a fixed farm will be different to that of a floating farm. An understanding of the magnitude of this impact will help to steer the required studies, even if this is relatively conservative towards the beginning of the project.	A floating EYA estimate should be made as early as possible in the project, using a set of initial assumptions about the engineering model parameters which are to be refined later. Note that we do not state which tools should be used.
4	The yield impact of floating turbines is not considered. The yield assessment may not be revisited frequently during the project	Since yield is critical to the business case and the maturity of the engineering models can be expected to improve as the project progresses, the yield impact should be regularly revisited.	The floating EYA impact should be regularly revisited as the designs and models are updated to ensure business case validity. The frequency with which this reassessment happens may need to be increased as compared with fixed foundation farms.

5	Foundation model parameters are expected to be delivered by the foundation designer on a per-project basis.	At least in pre-commercial and early commercial floating wind projects, developers having their own library of engineering models of various floating foundation types could help conduct floating EYAs.	A record should be kept of the engineering model parameterisations so that an appropriate model can be re-used for later projects.
6	There is a level of collaboration expected between the developer, foundation supplier and turbine supplier in fixed foundation wind farm developments.	The scope of this collaboration needs to be augmented to facilitate the development of engineering models for floating yield assessment.	The developer should coordinate with the foundation and turbine suppliers to build and validate engineering models but recognise that the responsibility lies with the developer to ensure the mechanisms are in place to allow this to happen.
7	Some level of contractual information sharing between the developer, foundation supplier and turbine supplier exists already.	It will be necessary for the developer to understand and implement any contractual changes required to support the development of engineering models.	The developer should seek to ensure timely alignment via contractual instruments when selecting turbine and foundation suppliers.
8	The risks associated with inaccurate yield assessments are already understood, managed and mitigated by developers.	The risk picture is increased by the potential inaccuracy of floating yield model parameterisation and the fact that the models are engineering approximations. Therefore, the scope of the developer’s risk identification and management practices should be expanded to cover this.	The developer should own and actively seek to mitigate the risks associated with floating yield impact and model parameterisation.
9	Developers’ internal processes for capturing the impact of floating wind yield either do not exist or are relatively immature	Assessment of the yield impact of floating foundations adds one or more new steps into the EYA process for developers. Agreement on the processes that will be followed and rollout of these processes into the organisation are critical to minimise business impact.	Developers should seek to align quickly on internal process for addressing floating correction. For example, this could initially be via global correction factors derived from FLORIS, followed later by integration of engineering models into in-house tools.

10	Various sensitivity analyses are likely to comprise part of existing yield assessments. These are useful to understand the criticality of accuracy of certain parameters, which in turn drives the level of investigation required into obtaining these data.	The impact of accuracy of parameters of the engineering models will vary depending on many factors, including foundation model, turbine model, site layout and climate. Therefore, assessment of this impact on a per-project basis is important.	Developers should leverage the tools as much as possible to undertake sensitivity analyses to quantify the risks associated with accuracy of model parameters and the sensitivity of the business case to uncertainties in the foundation concept.

Recommended practices for Foundation Suppliers:

#	Current practice	Reason for change	Recommended practice
11	For fixed foundation projects, the amount of data supplied to developers by the foundation supplier is limited. For demonstrator and pre-commercial floating wind projects, there is existing integration between the foundation supplier and the turbine OEM.	Since it is expected that the developer will own the responsibility and the risk associated with yield, the developer will require information from the foundation supplier to make this assessment.	Foundation designers should expect that supplying some data towards the developer to support development of engineering models will be expected in future floating projects. Which data is required and at what point in the development process will it become clear, as commercial floating projects become increasingly common.
12	Floating foundation designers are free to make decisions about key parameters of the foundation (e.g., masses, inertias, mooring stiffnesses) as they see fit to minimise the foundation cost whilst withstanding design loads.	Some of these foundation parameters will impact the turbine yield. There may be an expectation from developers that foundation designers consider the yield impact of design decisions in addition to loads and cost considerations.	Foundation designers should engage early with developers to agree on if and how the impact of foundation design decisions on yield should be assessed. The engineering models developed in this project provide one mechanism for achieving this.

Recommended practices for Turbine OEMs:

#	Current practice	Reason for change	Recommended practice
13	Turbine OEMs share information with the foundation designer and the developer to allow them to make load and yield assessments.	The scope of this information sharing may need to be increased to allow the development of engineering models, since the behaviour of the floating turbine that the engineering models are designed to capture will be influenced by the turbine and its controller.	Turbine OEMs should expect that supplying some data towards the developer to support these modelling activities will be expected in future floating projects.

Recommended practices for Tool Vendors:

#	Current practice	Reason for change	Recommended practice
14	Third party yield assessment tool vendors integrate new features and updates into their software on a regular basis, driven by the demand from users.	The engineering models for floating wind yield constitute a new set of features that may be integrated into third party tools at the discretion of the vendors.	Third party tool vendors should understand the extent to which the expectation from developers is that their tools will eventually support modelling of floating effects and begin to plan these into their roadmaps.

4.3. Innovation/technology needs

1 **Usage of models will require increased collaboration between OEMs and developers.**

The move from demonstrators and pre-commercial scale floating wind farms towards commercial scale farms will necessitate more focus on the business case, into which the yield impacts of floating foundations play a part.

There is a level of collaboration expected between the developer, foundation supplier and turbine supplier in fixed foundation wind farm developments but the amount of data supplied to developers by the foundation supplier is limited. Due to the increasingly coupled nature of the floating turbine-foundation system, it is anticipated that the scope of this collaboration will need to be augmented to facilitate the development of engineering models for floating yield assessment.

Whilst the developer will own the responsibility and the risk associated with yield, the developer will require information from the foundation supplier to make this assessment. Foundation designers should expect to supply some data on a per-project basis to the developer to support development of engineering models. Which data is required and at what point in the development process will become clearer as commercial floating projects become more common.

2 **Model validation is key for industry acceptance.**

A key aspect of all wake modelling is validation to promote industry wide acceptance on recommended practice for model settings/tunings and consensus on applicable levels of uncertainty. Whilst some cross-verification of engineering models can be achieved by comparison to high-fidelity simulations, validation against offshore campaigns (i.e., SCADA and/or LiDAR[20]) will ultimately be required. This is complicated further for floating installations as the wake behaviour is closely tied to the dynamic response of the foundation which will also need to be measured or otherwise quantified.

Throughout pre-commercial and early commercial phase floating wind projects, it is envisaged that collaboration between developers and floating foundation will enable developers to build a library of engineering models of various floating foundation types to help conduct floating energy yield assessments. A record should be kept of the engineering model parameterisations so that an appropriate model can be re-used for later projects.

Within time, to support industry acceptance, it is hoped that developers will be willing to publish their experiences of model validation either directly or through sharing data with research consortia to do the same.

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[20] The Supervisory Control and Data Acquisition (SCADA) system is responsible for data acquisition, transmission and storage system covering all wind farm assets, with a full operating history of the wind farm.
Light Detection and Ranging (LiDAR) systems are remote sensing anemometry devices which use lasers to measure wind speed and direction.
For further information see: https://www.thecrownestate.co.uk/media/2860/guide-to-offshore-wind-farm-2019.pdf

3 Integration of floating wind features into third party tools will be driven by user demand.

The methods developed within this project have been implemented within the open-source FLORIS framework. FLORIS has been chosen as it is an open framework capable of supporting the building of new methods, has a number of fundamental models developed for wake steering which have been adapted for the purpose of floating wind simulation and affords the transparent sharing of algorithms between the Floating Wind JIP Partners. However, it is recognised that across the offshore wind community a wide range of third-party vendor tools are used, and acceptance of any new features depends heavily on already pre-existing corporate workflows.

Third party yield assessment tool vendors integrate new features and updates into their software on a regular basis, driven by the demand from users. The engineering models for floating wind yield constitute a new set of features that may be integrated into third party tools at the discretion of the vendors.

5. Key findings: Numerical modelling guidelines and standards for floating wind turbines

5.1. Study overview

A Floating Offshore Wind Turbine (FOWT) comprises many components, which are all typically delivered by separate contractors. This includes the wind turbine, platform and mooring system. Due to the dynamic nature of FOWTs, the design of each component will influence the dynamic behaviour of the overall system; this will in turn influence the design of the components. Consequently, an accurate estimate of design loads is required, using so-called “integrated modelling” or “coupled modelling”, which increases the level of accuracy of the structural load assessment, satisfying the Front End Engineering Design (FEED) requirements that forms a basis for the load mapping and detailed structural design.

An integrated loads assessment generally takes place at a relatively advanced design stage, once the preferred floater designer (FD) and wind turbine designer (WTD) have been selected. A preliminary sizing of the floater and mooring system will have taken place, using either a non-integrated approach or a simplified coupled approach, based on basic information such as general dimensions and masses.

For fixed-bottom OSW, the integrated modelling process is fairly standardised across the industry, with a clear understanding of requirements and processes for exchange of data between foundation and turbine designers. The typical design approach for integrated modelling is to progress through a series of design loops, requiring data from and cooperation between different component designers.

In comparison to fixed-bottom OSW, the design of FOWT faces some additional difficulties, both in the complexity of the design interfaces, but also in that there is no standard process for FOWT design, nor guidance on how responsibilities should be shared between the platform and wind turbine designers.

The objective of this project was to provide guidance for selecting and using numerical modelling tools for FOWT design, and on the recommended load cases to run. In particular, the project team focused on addressing key knowledge gaps in the pre-FEED, FEED, and advanced design process, which could help to streamline the process and reduce the number of Design Load Cases (DLCs) to be analysed, as well as the number of simulations required per DLC. These knowledge gaps included:

- Which ultimate loads are driven by wind loads, which ultimate loads are driven by wave loads?
- How can the pre-FEED design be streamlined knowing the driving external forces for each floater type (Tension Leg Platform (TLP), spar, semisubmersible and barge)?
- How can the global natural frequencies be obtained reliably at early design stages?
- How sensitive are fatigue loads to different controller tunings?

The project team carried out stakeholder interviews with software developers and wind turbine and floating platform designers to identify open-source and commercially available integrated (unified equations of motion) or coupled (co-simulation) modelling tools, which are in use for integrated loads assessments. They also assessed the way these models can be coupled together and how floater and wind turbine designers can collaborate to transfer data and couple models.

5.2. Key findings

As part of this study, Innosea and sowento developed best practice guidance for how to align data gathering and processes (Table 4), to the modelling procedures which will follow three design iterations: pre-FEED (1st iteration), FEED (2nd iteration), and advanced design (3rd iteration). Each iteration involves two streams – defining the Design Load Cases (DLCs) required in the loads assessment, using sensitivity analyses of the physical and environmental conditions, and defining the numerical modelling strategy through accurate selection of the load transfer strategy and modelling software tools for WTG and floater/mooring.

Table 4: FOWT numerical modelling general logic diagram and the seven-step process for establishing an integrated loads assessment methodology.

Step	Detail
1	Characterisation of the site
2	Characterization of pre-FEED physical effects (1st iteration)
3	Selection of Design Load Cases list
4	Selection of structural analysis model and load transfer strategy
5	Decision on tool coupling and responsibilities
6	Characterization of FEED physical effects (2nd iteration)
7	Characterization of advanced load effects (3rd iteration)

1 **Site characteristics and FOWT characteristics determine the critical loading. A good overview of operational vs. idling wind and wave conditions can help determine critical load cases, which can significantly reduce the necessary simulation effort.**

Current design standards for FOWTs recommend running a full set of Ultimate Limit State (ULS) and Fatigue Limit State (FLS) DLCs which test the response of the FOWT to extreme and repeated loads respectively. This represents a significant number of simulations, computational time and amount of data generated. An example of this is the DLC 1.6 (extreme operational case, power production)[21] which considers 2 different water levels, 6 random seeds, 11 different wind speeds, 12 wave directions and 12 different angles for wave/wind misalignment, totaling 19,008 combinations.

It is possible to reduce the number of simulations, without reducing the accuracy of the results, by identifying the critical design driving load cases. These critical load cases are a function of both the site characteristics (e.g., wind and wave speed and direction under the normal and extreme conditions) and the characteristics of FOWT and platform.

For ULS analysis, during conceptual design analyses, different sensitivity analyses should be run to determine the design driving loads and select the appropriate simulations for the final design step and certification of design loads. Table 5 summarises the ways in which the number of ULS simulations could be reduced at the pre-FEED stage.

[21] IEC numbering for DLC naming is used in this report. More information available from: https://www.iec.ch/homepage

Table 5: Means of reducing the number of simulations in ULS.

	Means of reducing the number of simulations in ULS
Site directionality	Using refined wave and/or wind direction bins (or sectors) in the dominant direction and coarse bins in other directions. Discarding some directions in non-dominant sectors (while remaining conservative for the design of all mooring lines).
Wind-wave misalignment	Wind, wave and current directionality and wind-wave misalignment: Aligned environment does not always lead to the maximum FOWT responses.
Approximate aerodynamic load	For DLCs with variating wind speeds, computational effort can be focused around: • Considering rated wind speeds for which thrust loads are expected to be the largest, • taking highest wind speeds for which largest significant wave heights are expected
System Symmetry	Using the geometrical symmetry and mooring layout can help reduce the number of directions.
Peak Periods	A sensitivity analysis with respect to wave peak periods is advisable for FOWTs to understand which wave periods tend to be critical for the platform's behaviour and loads.
Model fidelities	In order to decrease the computational burden, the model fidelity for load analysis at different phases of the project can also be adapted.

To reduce the number of fatigue load case simulations, a representative and conservative set of conditions must be identified. These must characterise the environment for fatigue analysis while keeping the number of conditions limited, in order to restrict the computational cost and time. In this study, sensitivity analyses were conducted to help select important DLCs and parameters by floater type.

2 **Loading characteristics vary significantly among the different FOWT types (barge, semi-submersible, spar, Tension Leg Platform (TLP)).**

The project team carried out a sensitivity analysis to determine the most critical responses of the FOWT. The response characterisation can help to select critical load cases and the most suitable numerical models to calculate an accurate coupled response. It gives an important overview of which environmental conditions are critical to the FOWT. This analysis was carried out on a generic 15MW wind turbine with reference designs for barge, semi-submersible, spar and TLP platforms.[22]

The sensitivity studies carried out as part of the pre-FEED were:

- Sensitivity to Normal Wind Model (NWM) / Extreme Wind Model (EWM) wind loads,
- Sensitivity to normal, severe, and extreme sea state (NSS, SSS and ESS) wave loads.

[22] Reference Floating Wind Designs and Scenarios, delivered by Ramboll for the Floating Wind JIP, 2021.

Table 6 provides a summary of the critical loads for some components for each of the four floater reference designs at a pre-defined site with 'harsh' metocean conditions.[23] The full analysis was carried out for the rotor, tower, platform and mooring components. The table is filled by analysing the loads (not stresses) for each component under wind and wave conditions and identifying wind or waves (or both) as the reason for the highest loads. A clear categorisation of the driving source of loading (wind or waves) can be made for most of the FOWT components, particularly for the ULS simulations. This categorisation is highly sensitive to the site conditions.

Table 6: Maximum loads per component for each of the FOWT types (TLP, spar, semi-submersible, barge) rooted to the causing environmental loads for the harsh site.

Component	Platform	Operational (FLS)		Extreme (ULS)	
		Wind (NWM)	Wave (NSS)	Wind (EWM)	Wave (SSS/ESS)
Rotor	TLP		■		■
	Spar	■		■	■
	Semi-Sub	■		■	
	Barge	■		■	
Tower	TLP	■	■		■
	Spar	■	■	■	
	Semi-Sub	■	■	■	
	Barge	■	■		■

For FLS conditions, the categorisation of load origin depends on the mean wind speed and thus the sea state. For the assessed conditions, wind is driving the majority of the load response in lower sea states, whilst waves are driving most of the load response for higher sea states (this is why some components have both wind and wave shaded in Table 6). However, some components and FOWT types are less sensitive to wave loads than others. This holds especially for the rotor loads of the FOWTs with catenary mooring, whereas the TLP rotor suffers significantly from wave loads, transmitted through the tower.

3

Efficient pre-FEED modelling can accelerate numerical design. If wind loads do not drive a component's loads, a generic wind turbine model can be used.

A hydro-elastic finite element (FE) model can be used to calculate global natural frequencies with sufficient accuracy for the pre-FEED stage. The FE model includes elasticity of the tower and the floating substructure and still-water hydrodynamics. In this study, Ansys Mechanical and OrcaFlex software were used successfully to calculate these data points. The advantage of this type of modelling, as opposed to coupled aero-hydro-servo-elastic modelling,[24] is its simplicity with the only necessary parameters being hydrodynamic coefficients and structural beam properties.

[23] The key parameters for the "harsh" metocean conditions modelled here are introduced in section 3.1 of the Access and Availability section.

[24] Aero-hydro-servo-elastic modelling includes aerodynamics, hydrodynamics, structural dynamics, control and mooring line dynamics.

Sensitivity studies can be carried out quickly using a hydro-elastic FE modal analysis approach. An example analysis in this study was varying of wall thickness of the equivalent beams of the substructure to understand the sensitivity of the derivation of equivalent beams. The results showed that natural frequencies are not primarily driven by wall thicknesses but rather by mass distribution and diameters.

4 **The wind turbine controller has a significant effect on fatigue loading for most components, including the mooring lines. The effect depends on the control features enabled. Suboptimal tuning can impair design loads.**

The controller has a significant effect on all floaters with clear differences between floater types. For this study three different controllers of the open-source ROSCO framework were activated in OpenFAST simulations with co-directional loading to test their impact on the stability of the turbine:

1. The high-bandwidth controller resulted partly in unstable behaviour as it reduced the fore-aft (forward and backward) damping and triggered large fore-aft motion responses.
2. The low-bandwidth controller results in large rotor speed and power fluctuations, which neither the electrical equipment, nor the rotor blades are likely to be able to withstand.
3. The constant torque controller with high bandwidth results in the most stable overall dynamics.

In summary, the controller is highly relevant for the fatigue loading of all components of the FOWT. The variation of loads for different controller tunings is significant, not only for rotor loads but also for tower, floater and mooring loads. This holds especially for the FOWTs with catenary mooring lines and to a lesser extent for the TLP. Thus, it is important to obtain a potentially simplified but fully parameterised controller, which adapts itself automatically to a FOWT (model-based controller design). A parameterisable model-based controller helps to quickly tune it for load reduction of critical components and also adapt it over time to design changes.

5 **Clarity about how wind turbine and floater designers work together and couple their software is necessary at the start of the project. The development of universal coupling software could have a high potential to streamline this process.**

An integrated modelling strategy requires a WTD and FD to agree a process to share modelling outputs and develop a strategy to couple the modelling of the wind turbine and platform. At the moment, the WTD is normally responsible for coupled simulations during the integrated load analysis due to confidentiality (around wind turbine generator (WTG) data and controller) and because the WTG type certificate is associated with a software tool used for WTG dynamic analysis. Moreover, for compatibility reasons, FDs are frequently required to adapt their engineering process to be compatible with the WTD's preferred tools. A more open way of collaborating in order to allow more optimized FOWT systems within coupled, integrated simulation environments (idealised strategy below) would streamline the design process.

Choosing an appropriate modelling strategy to deliver an integrated loads assessment will depend on a number of factors including the tools proposed by the FDs and WTDs and the considered design stage. The main strategies for communication and exchange of data, that have been seen in practice in the industry include:

- **Idealised strategy with tool couplings or integrated tool:** In this strategy, a single aero-hydro-servo-elastic model is used by both WTD and FD using either one integrated single tool or coupled tools, for global loads analysis and dimensioning of the main components. It allows an integrated system view for a globally optimal design: all components are modelled with high-fidelity modelling.

- **Strategy A:** In this strategy, the WTD uses coupled tools for the complete FOWT modelling and is in charge of running the simulations, but the hydrodynamics and mooring lines modelling is simplified by the FD to reduce the computational time. To compensate for this simplification, the FD re-models the FOWT with a more advanced model in an ocean engineering tool, using inputs from the coupled model. This means that the FD re-runs the DLCs relevant to the floater and mooring system designs (but not necessarily the full DLC list).

- **Strategy B:** For this modelling strategy, the WTD and the FD use different software tools and models for the analysis, checking, and design of their respective FOWT component. This is often the case when hydrodynamic and moorings functionalities of the WTD's tool are not considered sufficiently advanced by the FD. To bring the two models together, either:
    - The FD re-models the FOWT with a more advanced ocean engineering tool that integrates the turbine. This means that the FD re-runs all the DLCs relevant to the floater and mooring and has to accurately model the WTG for this; or
    - Run tool couplings instead of an integrated tool.

In terms of mapping these strategies onto the specific tools used by WTDs and FDs, the project team identified many possible combinations. The stakeholder engagement carried out later on in the study indicated that a limited number of tools are actually used by WTDs and FDs, showing some convergence of industry practice. Some of these tools are known to have demonstrated their compatibility, however further improvements to interfacing software tools for floater and wind turbine designers are achievable and have a clear potential to streamline the modelling process.

6 **The load transfer approach from global to local simulation models must be determined at the beginning of a project in order to avoid delays through an incompatibility of methods. Developing a standardised process would be beneficial.**

Having identified the modelling strategy outlined above, the process of transferring outputs from one model (the global FOWT model) to another model (of the FOWT components, such as the tower or floater) must also be determined. These models are long to build, run and process and it can be difficult to run a time domain analysis on these models given the numerous time stamps and limited computational power. Industry practices regarding the use of results from integrated analysis for floater structural design are not yet standardised.

There are various paths that one can follow to transfer internal floater forces and moments output from the integrated coupled model, via structure models (FE models/analytical models) to get stresses that are relevant for the structural checks. A number of these were identified and illustrated as part of the outputs of this study. It is important for these load path options between the integrated model and the structural checks models to be defined. As such, the integrated model must provide the relevant starting point to these load paths and comply with the requirements of global modelling. The modelling strategy and modelling tools should not be selected before the load paths have been defined.

5.3. Innovation/technology needs

The research carried out during this study highlighted current practices for carrying out an integrated loads assessment for floating offshore wind and developed best practice guidelines to streamline this process. In addition, during the study several areas of interest, which would merit further development, were identified.

1 **Development of an open-source tool for binning of metocean conditions and generation of simulations list would benefit the industry.**

When considering the modelling conditions for a FOWT, many parameters including wave period, wave direction, significant wave height, wind speed and direction should be taken into account (with current velocity and direction also optional). This would require the time series of at least 5 parameters to establish the FLS DLCs list. As such, binning and lumping of metocean data becomes necessary. Existing guidelines and standards do not describe a clear process on how to do this.

Developing an open-source tool for binning of metocean conditions and generation of simulations would provide a common ground for integrated modelling to the project parties.

2 **Development of a generic Dynamic Link Library (DLL) for coupling aeroelastic tools from WTDs with ocean engineering tools from FDs.**

Dynamic coupling of the WTDs tool with the FDs tool seems to be the best way to ensure compatibility. This would increase ability of wind turbine designers and floater designers to jointly perform integrated analysis whilst using the wind turbine designers aeroelastic tool that is related to the WTG type certificate. A coupling DLL has to take into account the nature of the equations of motion of both models (by FD and WTG).

3 **Apply recent research on sensor placement strategies to gather data on FOWTs to validate modelling software tools.**

To-date, software tool validation has been mostly based on code-to-code comparison or comparing model code with results from small-scale experiments. With more floating wind farms being installed, there is the opportunity to conduct a large-scale validation exercise across multiple modelling tools.

The more innovative floating substructures are, the more important the validation of the software used in the design process becomes. Current innovations which require full validation of software include: single-point mooring concepts with turret, tower-less concepts (three struts replacing tower), suspended keels, synthetic moorings, non-redundant design approaches and advances controllers.

Such new features are usually implemented in state-of-the-art software tools and their functionality is proven in scaled experiments using a selected number of FOWTs. For this to happen, these FOWTs must be fitted with sensors in the correct positions. The types of sensors required are accelerometers for capturing motion, and strain gauges on structural elements, capturing elastic deformations. Also, differential Global Positioning System (GPS) sensors are relevant to capture rigid-body motions.

For FOWTs, the approaches of fixed-bottom foundations for mechanical load monitoring can be partially adopted. As for jackets and monopiles, the dominant elastic modes have to be identified and the sensors placed such that the locations of largest deformations are well captured by accelerometers. Augmentation of structural sensors with digital twins is also advisable for FOWTs, due to some inaccessible components, which are impractical to instrument with sensors on the market.

Figure 16 shows a possible sensor placement strategy for a semi-submersible FOWT. The objectives of the strategy cover:

- Measurement of structural sectional forces via strain gauges at
    - Blade-root
    - Yaw bearing
    - Tower-base (bolted flange connection)
    - Joints of tubular members, pontoons (covering Vortex-Induced Vibration (VIV))
    - Midpoints of tubular members, pontoons
    - Vicinity of mooring line attachment point to reconstruct mooring tensions
    - Heave plates (radial loads)
- Measurement of modal deformations via accelerometers at midpoints and endpoints of elastic members: struts, tower, blades

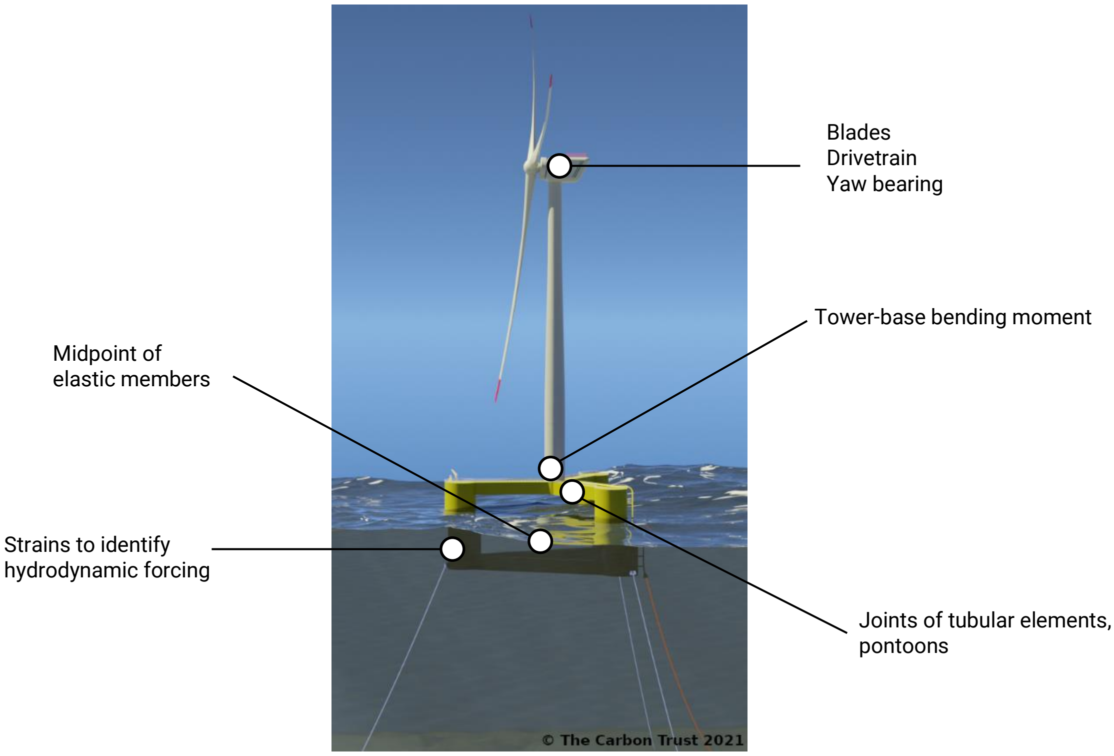

Figure 16: Example FOWT showing potential placement of mechanical sensors - strain gauges and accelerometers (Carbon Trust).

6. Projects for phase V

PROJECT 1

Fabrication, infrastructure and logistics

Contractor: Arup

Challenge:

To date, floating wind farms developed have been of a small scale compared to bottom fixed offshore wind farms that exceed 1 GW in capacity. In future, large scale floating wind farms are expected, and this will bring challenges to fabrication, infrastructure, and logistics. Constraints may include facilities for steel and concrete fabrication; port facilities for assembly and storage; launching facilities; transport of large equipment; and local content requirements

Figure 17: Floating foundation fabrication (Navantia)

Project Overview:

The project aim is to understand the common infrastructure requirements for floating wind projects in order that port authorities can understand investment requirements, and developers and fabricators have a framework for port selection.

This will build on previous projects completed to understand key fabrication, infrastructure and logistical constraints towards building large scale floating wind farms and to ensure that infrastructure constraints do not prevent floating wind deployment.

In addition, market engagement with technology providers and key ports will add gravitas and industry support to conclusions.

PROJECT 2

Moorings redundancy, reliability and integrity

Contractor: AMOG Consulting Group

Collaborating with Sowento, PEAK Wind, Offspring LTD

Challenge:

Mooring systems are a crucial component of a floating offshore wind installation. However, there is currently a high level of uncertainty surrounding floating specific mooring systems in terms of project risk and lifetime cost. This can be attributed to reliability and failure rates that have been based upon other sectors such as oil & gas or the more general marine sector. These indicate a high likelihood of failure within a system which in turn calls for redundancy and/or large conservatism to be put in place regarding project risk, CAPEX and subsequent OPEX. Increasing conservatism can have a negative impact upon the commercial performance of a project, particularly on larger sites.

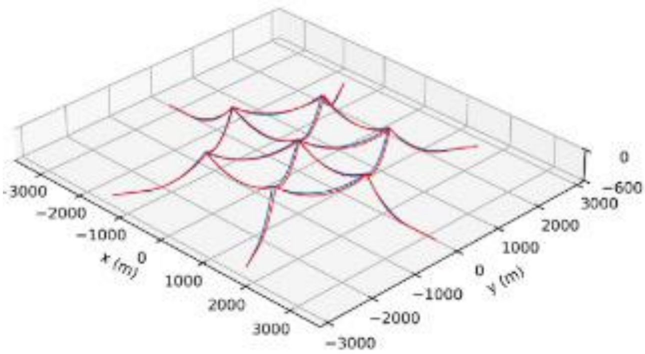

Figure 18: three-dimensional nonlinear model (Hall et al, Ocean Engineering)

Project Overview:

Building on previous projects using a qualitative approach this project will create a mooring line definition by investigating if the route cause failures within O&G and other sectors should be applied to floating offshore wind as well as looking to understand the best ways that the industry can correctly capture and quantify potential floating wind-specific failure within project planning.

In addition, this project will also investigate potential alternative solutions such as synthetic moorings systems and LRDs, to understand if the potential risk of failure can be reduced by offering a comparison with traditional mooring systems in turn optimised mooring designs reducing the level or risk and consequence.

Lastly, this project aims to: increase clarity around the definition of ‘redundancy’ in relation to a typical 3-line mooring system, understand how mooring line redundancy is affected when considering an integrated mooring platform and WTG design.

Finally, it seeks to compare, assess, and potentially challenge the standards used in floating wind, particularly; ABS, DNV and BV floating specific standards., offering guidelines and recommendations for the industry.

PROJECT 3

Major component exchange with self-hoisting cranes

Contractor: Offshore Wind Consultants and WavEc

Challenge:

Figure 19: Mammoet WTM 100 Wind Turbine Maintenance Crane (Mammoet)

Currently the exchange of major turbine components for floating wind turbines is seen to be an expensive and challenging operation. The most viable method of undertaking major component exchange in waters too deep for conventional jack-up vessels is to tow a floating wind platform to port for the exchange to take place or utilize expensive semi-submersible heavy lift vessels. The major advantage of using self-hoisting and climbing cranes is that they overcome the relative motion challenge by being fixed to the floating turbine. In addition, because the final crane height is provided by the turbine structure rather than a heavy lift vessel, smaller less expensive vessels can be used. However, there are several challenges associated with turbine-mounted cranes, including: the logistical challenge of transferring the crane between the service vessel and turbine, the need to assemble and disassemble the crane system on each turbine requiring maintenance, and the need for turbine modifications such as strong points and tower reinforcement.

Project Overview:

This project builds upon findings of the Floating Wind JIP Phase 3 Heavy Lift Maintenance on site (HLM) with the aim to develop a greater understanding of the different technology options surrounding major component exchange, specifically self-hoisting cranes and climbing cranes. It will provide an opportunity for engagement with both the wind turbine manufacturers and climbing crane technology concept developers with the feasibility of concepts assessed in context to:

- Technology
- Risks
- Costs
- Operational requirements

The project will undertake a market review of self-hoisting and climbing crane concepts, shortlisting up to six concepts which will then be assessed in terms of their technical feasibility, risks and expected costs. It will enable solutions to be found regarding the on-site exchange of major WTG nacelle without using a tow to port strategy. The project will enable solutions to be found regarding the on-site exchange of major WTG nacelle components such as main bearings, gearboxes, transformers, as well as blades without using expensive large heavy-lift vessels requiring motion compensated cranes or towing a platform to port.

PROJECT 4

Stick building of turbines on site

Contractor: Heerema Engineering Solutions

Challenge:

Floaters are typically installed in an area with a water depth in excess of 70 meters. Which for the majority of the floating wind projects eliminates the option to install WTGs by means of a Jack up. Floating wind turbine generators (WTGs) can be assembled both at port, or at the wind farm site, as is common practice for bottom-fixed offshore wind. However all current commercial floating sites have currently been installed in port rather than on site. There are a number of potential benefits in performing on-site assembly as this will remove restrictions around harbour water depth and the complexities of towing of assembled WTG's to a site location. Currently, the decision on the assembly location is affected by several factors, including the foundation type and the port specifications.

Figure 20: Kincardine 9.5MW turbine installation (Principle Power)

Project Overview:

The aim of the project is to identify and assess the innovative methods to permit WTG assembly at floating offshore wind farm sites. The project will identify enabling technologies that allow for WTG assembly on-site and define required operational procedures for stick-building on site. It will also set the frame and limitations for on-site assembly and identify potential major showstoppers. It will bring about a greater understanding of the different installation methods that can be used for floating WTGs in context to their versatility and potential to reduce costs. Through developing greater installation options this will help to reduce port facility and availability bottlenecks as well as constraints around water depth for different floating foundation concepts.

PROJECT 5

Dynamic cable failure rates

Contractor: Offshore Wind Consultants Ltd & Exeter University

Challenge:

Dynamic Cables for floating offshore wind applications are constantly exposed to many dynamic environmental loadings. As a consequence, they are subjected to mechanical stresses throughout their technical life. Understanding the failure mechanism of these products is critical to address future optimised design solutions and standards. Further understanding of data collection requirements for future floating wind development and dynamic cable modelling and/or testing is necessary to allow the floating wind industry to have a standard process when working with dynamic cables, leading to a greater understanding of lifetime and design costs and potential cost reductions.

Figure 21: Cable thermal degradation (PeakWind)

Project Overview:

The project aims to identify failure modes of dynamic cables and includes existing examples and root causes of where failures have occurred on dynamic cables based on the offshore wind and related industries. This will be achieved by creating a detailed state-of-the-art market survey with key stakeholder engagement and technology analysis of the offshore wind and related industries. Assessment of this will be used to determine significant failure modes and rates for integrated solutions of dynamic export and array cables for floating wind applications. The out puts of this work will provide failure rates for dynamic cables to be used for OPEX calculations in floating wind farm development; standardise test methods for dynamic cables; standardise fatigue modelling methods for dynamic cables, providing a basis of cable failure calculations which is crucial when estimating operational cost, insurance, and advising on final investment decisions.

PROJECT 6

High voltage and electrical equipment fatigue

Contractor: Petrofac

Challenge:

With the future development of large scale floating wind turbine arrays, higher voltages (HV) and floating substations will be required to reduce losses and interconnect in deeper water locations where bottom fixed substations will not be feasible. A major area for concern is electrical fatigue caused by the dynamic motions in harsh environments between wind turbines and floating substations and on the floating substations themselves. To date limited studies have been performed on the electrical equipment requirements for floating substation and WTGs, and more understanding is required on the parameters impacting it during the entire lifetime of service.

Project Overview:

Base on previous CT studies and reviewing of other HV electrical equipment and standards in key offshore markets, this project aims to benefit the floating offshore wind industry by providing a basis of feasibility for the application of electrical components in floating wind, identifying the associated risks and costs incurred by:

Obtaining a greater understanding of fatigue analysis of high voltage electrical equipment in floating structures, by identification of relevant forces and weak points of electrical equipment sensitive to acceleration stress.

Figure 22: BorWin Gamma offshore platform, German North Sea (Petrofac)

Making specific recommendations on what changes should be made to standards to accommodate for the installation of HV equipment in floating applications and should account for all relevant requirements in:

- Reliability
- Safety
- Fault levels

Finally offering advice and strategies on potential design changes required and a type-test program for floating wind applications.

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