Offshore Logistics: Scenario Planning and Installation Modeling of Floating Offshore Wind Projects

Esperanza Susana Torres[1]
EPSRC and NERC Industrial Centre for Doctoral
Training in Offshore Renewable Energy (IDCORE),
Graduate School of Engineering,
The University of Edinburgh,
Edinburgh EH9 3FB, UK
e-mail: e.s.torres@ed.ac.uk

Philipp R. Thies
Department of Engineering,
Faculty of Environment, Science and Economy;
Renewable Energy Group,
University of Exeter,
Penryn Campus, Treliever Road,
Penryn TR10 9FE, UK
e-mail: p.r.thies@exeter.ac.uk

Mark Lawless
JBA Consulting,
1 Broughton Park, Skipton,
North Yorkshire BD23 3FD, UK
e-mail: mark.lawless@jbaconsulting.com

The offshore installation, logistics, and commissioning activities are currently estimated to make up 20% to 30% of the capital expenditures (CAPEX) of offshore wind projects. Technical and geographical factors affect both the CAPEX during construction and the installation schedule, such as a lack of supporting port infrastructure, the availability of specialized vessels, the distance from the wind farm to shore, accessibility, water depths, and seabed conditions. In addition, there are significant risks during the construction phase, such as uncertain durations due to the sensitivity of marine operations to weather conditions. Identifying supply chain requirements is critical in the early stages of project planning in order to avoid time delays and cost overruns during the transport and installation process. This study explores and analyzes the logistic requirements and installation methods of a floating offshore wind (FOW) technology. Using an advanced forecasting and decision support tool, realistic case scenarios are simulated at a variety of potential sites for FOW deployment across the UK. Technical risks associated with installation strategies are identified and classified. The results provide a comparison of key installation performance indicators of each case scenario (e.g., installation rate per wind turbine, weather downtime). This study is of interest to researchers, offshore wind project developers, service providers, and other key stakeholders seeking to optimize planning and logistics to drive down CAPEX costs, reduce the construction downtime, and minimize risks during marine operations. [DOI: 10.1115/1.4056882]

Keywords: floating offshore wind, installation, planning marine operations, logistics, weather window analysis, offshore engineering

1 Introduction

Over the past decade, offshore wind turbine technology has progressed to high-capacity models between 7 MW and 15 MW, with rotor diameter over 200 m, and blades beyond 100 m. Several fixed-bottom support structures are available for shallow and medium water depths up to 60 m. The most common are monopile, gravity-based, and jacket structures. In addition, there are floating substructure designs that allow wind turbines to operate at depths greater than 60 m, such as spar-buoy [1] and semi-submersible concepts.[2]

Offshore renewable technologies will play a key role in the world's future transition to clean energy. There are upcoming offshore wind auctions globally and project pipelines to reduce fossil fuel dependency. For instance, the European Union has an ambition to build over 110 GW of offshore wind by 2030 and more than 400 GW by 2050 to achieve the net-zero carbon emissions [2,3]. The United States has also committed to reach 30 GW of installed offshore wind capacity by 2030, which is a substantial increase from the present 42 MW [4].

Between 2020 and 2020, the world's installed capacity of offshore wind increased by nearly 21% from 29.1 GW to 35 GW. The average power rating of new offshore wind turbines was 8.5 MW, with an average distance from shore of 52 km and 44 m of water depth [5,6].

The worldwide floating offshore wind (FOW) capacity is predicted to grow from 132 MW today to 54 GW by 2030. At the end of 2021, the United Kingdom's installed FOW capacity reached 80 MW and the UK's Government has set a target to build 1 GW of floating wind power by 2030 [7].

There are significant lessons learned from offshore fixed-foundation wind projects that can be implemented in the development of floating wind arrays with respect to installation procedures and construction logistics. Examples of these are specially designed offshore installation and maintenance vessels, and crew transfer methods [8].

However, large-scale deployment in the offshore wind industry is still facing challenges, such as constraints in the supply chain in terms of logistics, vessel availability, and port infrastructure [9,10]. As offshore wind projects shift from demonstration to pre-commercial scale and the wind turbine size increases, the distance to shore and the availability of suitable ports and specialized installation vessels could be a barrier for the development and construction of offshore wind projects. For instance, there were only nine vessels in the world capable of supporting the installation of wind turbines greater than 10 MW in 2020 [11]. In addition, there are significant risks during the construction phase, such as uncertain durations due to the sensitivity of marine operations to weather conditions.

This paper explores and evaluates the logistic requirements and installation methods of a namely semi-submersible floating wind platform technology. The main approaches discussed are as follows:

(i) Delivery and subsequent storage of floating platforms and turbine components to the nearest port prior to installation,
(ii) full assembly of wind turbine components with mounting on a floating platform at the quayside,

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[1] Corresponding author.

[2] https://www.oceanwinds.com

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(iii) finally, towing the floater-turbine to site and connecting to a pre-laid mooring system.

In order to identify and classify technical risks associated with installation strategies, realistic case scenarios are simulated at a variety of potential sites for FOW deployment across the UK, using an advanced forecasting and decision support tool. Considering the main operations that are required to perform the transport and installation of major components, such as the floating platforms, a sensitivity analysis is carried out to identify the governing parameters for the marine logistics issues and to quantify their impact on a construction schedule. For instance, the impact of the vessel selection, its cargo capacity, and availability are analyzed.

The remainder of the paper is structured as follows: An overview of the modeling approach to simulate the construction process of a floating offshore wind farm is presented in Sec. 2. A case study is implemented in Sec. 3 and the results are presented in Sec. 4, providing a comparison of the average total time to complete each phase of the offshore construction process. A discussion of key installation performance indicators is given in Sec. 5. Finally, this article concludes with a summary of key findings.

2 Methodology

This research proposes a simulation modeling approach to analyze FOW installation methods and logistics strategies.

The methodology for this paper involves using the ForeCoast® Marine software,[3] an advanced metocean planning and forecasting tool, to model and simulate the transport and installation (T&I) phase of complex offshore wind projects. It considers key activities, operations, and resources needed to complete the build, which are represented at a high level, including mobilization, load-out, offshore transport, assembly, structures and turbines installation, inter-array and offshore export cable laying, testing and commissioning.

This section summarizes the offshore transport and installation strategy as well as the model assumptions and constraints to simulate the construction process. A semi-submersible floating offshore wind platform (FOWP)[4] is assumed as technology solution for the development of early-commercial scale FOW projects (of circa 300–350 MW [12]).

2.1 Offshore Transport and Installation Sequence. The major stages and execution order of T&I of a semi-submersible floating offshore wind turbine (FOWT) are set out in Fig. 1.

There are interdependencies among activities, which define either which activity has to be finished before another one can be started (known as "finish-to-start" dependency) or which activities can start and run in parallel (known as "start-to-start" dependency).

To simplify the model, related installation tasks are grouped into six work packages. Figure 2 illustrates the work package (WP) precedence assumed for this study, establishing the priority of each activity within the offshore T&I project. Each node represents a construction WP, which comprises a sequence of activities and resources described at a high level in Secs. 2.3–2.8.

2.2 General Assumptions for Offshore Transport and Installation Modeling. To assess the overall T&I time of a FOW project, following are the assumptions and requirements considered:

- Offshore pre-installation activities, such as surveys and site preparation, have been ignored for the purpose of this analysis.
- Cable landfall and grid connection activities are considered out of scope.
- Due to a lack of details of installation costs, T&I cost analysis has not been included in the model.

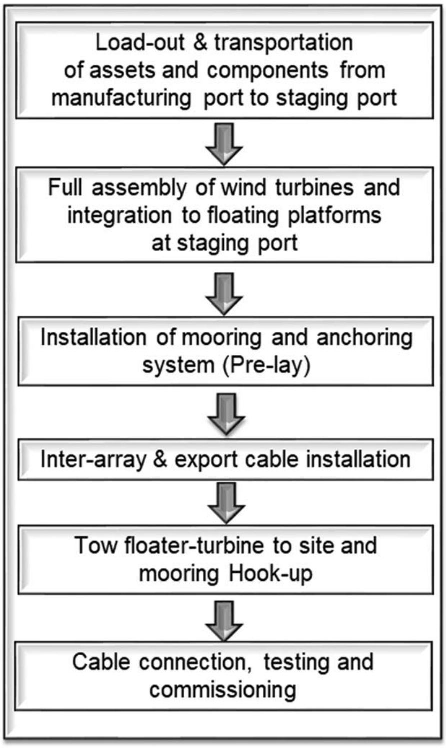

Fig. 1 High level of the offshore transport and installation sequence

- A construction/assembly land area, referred to as "staging port," is located close to the offshore wind farm site and is used to temporarily store, laydown, and assemble of wind farm components.

All wind turbine components (tower sections, nacelle, hub, and blades), anchoring and mooring components, array and export cables, and offshore substation (topside), are delivered from their respective manufacturer to the staging port. Neither production duration, nor transport activities have been considered in this study. It is assumed that all these components are already at the staging area prior to the offshore installation.

- The production of the floating structures is carried out on a land area, referred to as "manufacturing port." It is assumed that there are no spatial restrictions at the manufacture yard.
- A quay area available at the staging port allows a maximum of four floater-turbine units fully assembled and integrated at the same time.
- The offshore T&I starts at the manufacturing port once the fabrication of the floating platforms is completed, they are pre-assembled and ready to be loaded and delivered by a heavy transport vessel (HTV) to the staging port.
- The offshore T&I ends when the last floating wind turbine is commissioned.

2.3 Load-Out and Transport of Floating Platforms. Briefly, the floating structure load-out and transport method, after manufacturing and pre-assembly at fabrication yard, is as follows:

Starting point: FOWP manufacturing port

(1) Quay equipment and transport vessels mobilization.
(2) FOWP load-out onto a semi-submersible HTV.
(3) Sea-fastening.
(4) Transport on HTV, towed from the manufacturer's port to the wind farm staging port.
(5) FOWP float-off operation; the floating unit is released from HTV into the water at the staging port (quay space).

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[3] https://www.forecoastmarine.com
[4] https://www.principlepower.com/windfloat

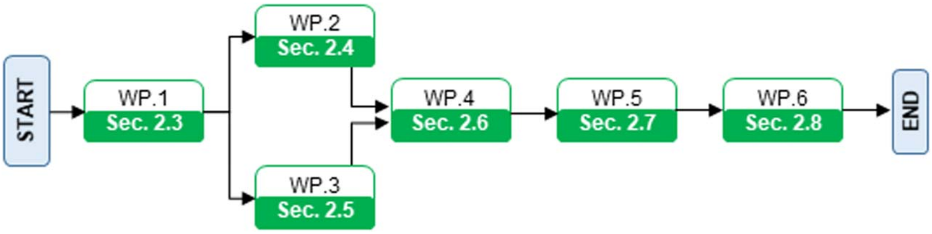

Fig. 2 Project installation process diagram

Fig. 3 Load-out and transport of floating platforms: (*a*) manufacturing port, platform load-out, (*b*) transporting platform by semi-sub HTV, tow to wind turbine staging port (Image source: Ref. [13]), and (c) float-off operation, the platform unit is released into the water at the staging port

(6) HTV towed back to manufacture yard to carry out the loading of the next FOWP.
(7) Tasks 2–6 are repeated until all floating platforms have been loaded out and transported from the manufacturing yard to the staging port.
(8) HTV demobilization.

A dry transport strategy for the floating structures is carried out by a semi-submersible HTV towed out to the project staging port by an anchor-handling tug vessel (AHT). In this analysis, an HTV can transport just one floater at a time, as shown in Fig. 3.[5] Once all floaters have been transported to the wind farm's assembly area, the load-out, and transport of floating platforms work package is completed.

To execute the load-out and transport operations safely, the sea state parameters and operational limits of the offshore transport vessels are summarized in Table 1 (based on Refs. [14,15]).

Table 1 Metocean limits for key transport operations (modeling assumptions)

Operation	H_s (m)	T_p (s)	U_{10} (m/s)	V_C (m/s)
Load-out	<1.0	<8	<10	<0.5
Float-off HTV	<0.5	<7	<10	<0.5
Towing operation	<2.5	<8	<15	<0.5

Transport Vessel	**Tug vessel**	**HTV**[a]
Vessel speed unloaded (knots)	10	[b]
Towing speed (knots)	5	[b]
Wave limit unloaded, H_s (m)	3	5
Wind limit unloaded, U_{10} (m/s)	20	20

[a] Semi-submersible heavy transport vessel with no propulsion.
[b] Tug vessel is assumed to tow the HTV.

2.4 Mooring System Installation (Pre-Lay). The next stage in the installation process is the pre-laying of the mooring system. Assuming that each floating wind turbine is anchored to the seabed, using drag-embedment anchors in conjunction with catenary mooring lines, the following is the pre-lay procedure:

Starting point: Staging port

(1) Installation vessel mobilization.
(2) Load-out of anchors and moorings onto an AHT. It is assumed that the AHT vessel has the capacity of carrying the mooring and anchors for five turbines at a time.
(3) AHT transits to wind farm site.
(4) AHT vessel positions at a FOWT target location.
(5) Pre-lay the anchors and mooring pre-tension.
(6) Repeat steps 4 and 5 for the other FOWT mooring systems until vessel deck is empty.
(7) AHT returns to staging port to pick up the next anchors and mooring systems.
(8) Steps 2–7 are repeated until all anchors and mooring lines have been placed on each wind turbine installation site.
(9) AHT transits to staging port.

The pre-lay operation is performed by an anchor-handling tug vessel supported by a remotely operated vehicle (ROV). It is completed when all mooring and anchors have been pre-installed at each FOWT target location.

2.5 Cable Laying. The offshore cable installation activities can commence at the same time that the mooring system installation starts. The inter-array dynamic cable will connect the wind turbines to each other and to the offshore substation. The offshore export cable will connect the offshore substation to the landfall point (onshore transition joint).

The cable installation work package requires a dedicated cable lay vessel (CLV) supported by an ROV. Below is the cable installation process:

Starting point: Staging port

(1) Cable lay vessel mobilization.
(2) Load-out of export cables onto a CLV.
(3) CLV transits to FOWT installation site.
(4) Pre-lay export cables.
(5) CLV return to staging port to pick up the inter-array cables.
(6) CLV transit to the installation site.
(7) Pre-lay inter-array cable at each FOWT target location.
(8) CLV transit to staging port.

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[5] Image sources of Fig. 3(*a*): https://www.principlepower.com/windfloat and Fig. 3(*c*): https://www.mammoet.com/news/Mammoet-completes-load-out-of-five-floating-wind-platforms-for-the-Kincardine-Offshore-Wind-Farm

2.6 Floating Offshore Substation Installation.

There are no floating substations in the offshore wind industry to date. According to offshore renewable energy market information,[6] only one floating substation prototype demo, with a rated power of 25 MVA and 22 kV/66 kV step-up voltage, was installed in 2013 and decommissioned in 2021, the Fukushima FORWARD floating offshore wind farm demonstration project.

However, for long-distance FOW projects (i.e., more than 50 km from onshore grid connection point), one offshore substation (topside) is considered to reduce power losses and transmission costs. It is assumed in this study a semi-submersible concept to install the topside, which is attached to the seafloor using anchors and mooring lines in the same manner as a FOWT.

An AHT is considered to execute the towing of the floating substation from the staging port to the final offshore installation site. The main steps in the offshore substation installation are as follows:

Starting point: Staging port—Quayside

1. Lifting offshore topside onto floating platform.
2. AHT begins towing to the offshore installation site.
3. Floater is hooked-up to the pre-installed mooring system.
4. Connection to the pre-laid export and array cables.
5. AHT returns to staging port.

When the offshore substation installation is completed, the AHT returns to the staging port to start the FOWT installation work package.

2.7 Floating Offshore Wind Turbine Installation.

The FOWT installation work package includes: full wind turbine assembly and floating platform integration at quayside, towing to final offshore installation site, and floater-turbine mooring hook-up and power cable connection. The wind turbines are fully assembled at the quayside (staging port), and mounted on the top of a floating platform. The assembly includes lifting operations of the main components onto FOWP: tower sections, nacelle, and three blades, as illustrated in Fig. 4.[7]

Once the floater-turbine is towed to the installation site, the structure is hooked-up to the mooring system and connected to the power cable. These operations are monitored by ROV.

The offshore wind turbine sequential installation is listed here:

Starting point: Staging port—Quayside

1. Wind turbine and tower assembly on top of FOWP using onshore cranes (Fig. 4).
2. AHT begins towing the fully assembled floater-turbine to installation site (as shown in Fig. 5[8]).
3. Floater is hooked-up to the pre-installed mooring system.
4. Connection to the pre-laid power cable.
5. AHT returns to staging port to carry out the towing of the next floater-turbine (tow out one at a time).
6. Steps 1–5 are repeated until all FOWTs have been placed and connected on each wind turbine target site.
7. AHT demobilization.

To perform the marine operations under safe conditions, Table 2 presents the weather tolerance thresholds on site.

2.8 Final Commissioning.

The final stage in the T&I process is the commissioning of the floating wind turbines. Using a service operation vessel (SOV) to transport technicians to FOWT, the commissioning sequence is as follows:

Starting point: Staging port

1. SOV mobilization.
2. SOV transits to the offshore wind turbine site.
3. Transfer technicians from SOV to FOWT.
4. Perform commissioning tests on wind turbine.
5. Transfer technicians from FOWT to SOV.
6. SOV moves to next FOWT.
7. Steps 3–6 are repeated until all wind turbines have been commissioned.
8. SOV demobilization.

Fig. 4 Wind turbine assembly and integration at staging port

Fig. 5 Tow to installation site

Table 2 Metocean limits for key installation operations (modeling assumptions)

Operation	H_s (m)	T_p (s)	U_{10} (m/s)	V_C (m/s)
Lifting WTG components (assembly at quayside)	<1.0	<7	<10	<0.5
Anchors and mooring pre-lay	<2.0	<8	<20	<0.5
Cable laying	<3.5	<8	<15	<0.5
Mooring hook-up	<1.5	<7	<10	<0.25
Cable connection	<1.5	<7	<15	<0.25
Technician transfer (commissioning)	<3.0	<8	<10	—

When the last FOWT is tested and commissioned, the final operation is the SOV demobilization, which ends the offshore T&I phase of the project.

The duration of each operation (i.e., an estimated number of hours needed to finish an activity excluding a contingency time) has been estimated based on industry trends, lessons learned, press releases, published literature, and open data. The minimum length of weather window (accessibility) required to complete each operation has been defined following British standard BS-ISO-29400 [16] and the DNV-ST-N001 guidelines for marine operations [17,18].

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[6] www.4coffshore.com

[7] Image source of Fig. 4: https://www.principlepower.com/projects/kincardine-offshore-wind-farm

[8] Image source of Fig. 5: https://www.oceanwinds.com

Fig. 6 Location of assembly ports (staging port) and floating offshore wind farms for case study (for illustrative purpose only)

A summary of sea state parameters and operational limits of the offshore installation vessels, assumed for this work, is provided in Table 7, Appendix A.

3 Case Study

3.1 Scenario Definition. Based on ORE Catapult technical reports [19] and [20], three potential zones for FOW large-scale deployment are considered across the UK: North East coast of Scotland, North East coast of England, and the Celtic Sea on the South West coast of Wales. The construction port during the offshore installation phase is selected based on the identification of existing suitable areas for investment in port infrastructure, as presented by Refs. [21–23]: the port of Nigg in Scotland, the port of Blyth in England, and the port of Milford Haven in Wales.

For the three selected wind-farm locations, Fig. 6 indicates the distance to assembly port in kilometers and the average water depth in meters. A summary of site characteristics is presented in Table 6,[9] Appendix A.

As base case scenario, a hypothetical 300 MW capacity wind farm consisting of 30 10 MW wind turbines—with a spacing of 1.9 km between them—and semi-submersible three-column floating platform is selected for all analyses in each location. The Port of Ferrol in Spain is assumed as manufacturing facility for the floating structures (inspired by Kincardine and WindFloat Atlantic offshore wind projects[10]). A floating offshore substation is assumed to connect the wind farm to an onshore substation using subsea cables (export cables).

A simulation-based analysis is carried out at each zone. The installation strategies described in Sec. 2 are applied for comparing the impact of weather and sea conditions on the offshore T&I timeline. The results are presented in Sec. 4.

3.2 Weather Data. In order to run time-domain simulations of marine operations and represent the metocean conditions at each wind farm location and construction port, site-specific weather time-series data is extracted from Copernicus Marine Service[11] and the ERA5 dataset[12] [24]. The metocean dataset contains time-series at hourly time-step resolution from Jan. 1, 1991 to Dec. 31, 2020 (30 years), which includes significant wave height H_s (in m), peak wave period T_p (in s), surface current speed V_c (in m/s), wind speed (in m/s) at 10 m and 100 m height above sea level (U_{10}, U_{100}).

As all T&I operations are limited by the metocean conditions at site, an initial analysis of the weather time-series shows the level of risk and site accessibility at each wind farm location (excluding downtime due to weather windows).

Based on a 30-year hindcast data, Fig. 7–10 provide a characterization of metocean conditions at each selected zone. Mean value and 90th percentile (P90) represent the monthly trends of H_s, T_p, V_c, and U_{10} over the observed period.

There is a clear pattern of sea state conditions during the winter and summer months at each location. From the data in Fig. 7, the mean H_s tends to be higher in the North East of Scotland compared to the other two locations. For instance, the observed mean H_s was 2.59 m during January with the 90th percentile of observations at 4.30 m. In contrast, for the same month in the North East of England and Celtic Sea locations, the mean H_s was 2.23 m and 2.28 m, respectively, with a corresponding P90 of 3.72 m and 3.88 m.

The wind speed (U_{10}, at 10 m above the mean sea level) follows the H_s seasonal variation, as shown in Fig. 9. The mean wind speed is greater than 9 m/s in the winter months, especially in the North East of Scotland location, where the mean U_{10} reached 10.6 m/s in January with 10% of the observations exceeding 15.88 m/s. Similarly, in the North East of England and Celtic Sea locations, the respective mean wind speed in January was 9.87 m/s with P90 of 14.72 m/s, and 9.88 m/s with P90 of 15.03 m/s.

Figure 11 displays the annual mean H_s (x-axis) between 1.0 m and 5.0 m, and its non-exceedance rate of occurrence (y-axis). For instance, for installation operations with a H_s limit of 1.5 m, such as mooring hook-up, there is a rate of not exceed of 0.46 in the North East of Scotland, 0.54 in the North East of England, and 0.57 in the Celtic Sea.

3.3 Transit Paths Between Manufacturing Port and Floating Offshore Wind Farm Staging Port. For each project site, to calculate the transit time of transport vessels (i.e., HTV and tug vessel) during the transport of floating semi-submersible structures, Fig. 12 illustrates the transit route assumed from the floating platform manufacturer yard to the offshore wind farm staging ports. The estimated distance is presented in Table 6, Appendix A. The vessel operational limits, including towing and unloaded transit speed, are as mentioned in Table 1.

4 Results

To assess the impact of weather and sea state conditions on the offshore T&I timeline of FOW projects, for each of the three case scenarios in Sec. 3, the transport and installation strategy discussed in Sec. 2 was simulated.

The downtime and the duration of offshore T&I operations were estimated using time-domain simulations for the site-specific metocean data time-series. At each time-step, the parameters to consider whether a planned marine operation can proceed are: (1) metocean weather thresholds, (2) operational limits, and (3) duration of each installation activity. The simulation allowed to identify suitable weather conditions, i.e., when operations can proceed, to complete each operation in sequence.

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[9] Kincardine Offshore Wind Farm: https://www.principlepower.com/projects/kincardine-offshore-wind-farm; Green Volt floating offshore wind project: https://www.flotationenergy.com/projects/green-volt

[10] https://www.oceanwinds.com, https://www.principlepower.com/windfloat, https://www.principlepower.com/projects/kincardine-offshore-wind-farm

[11] https://resources.marine.copernicus.eu/products

[12] https://cds.climate.copernicus.eu

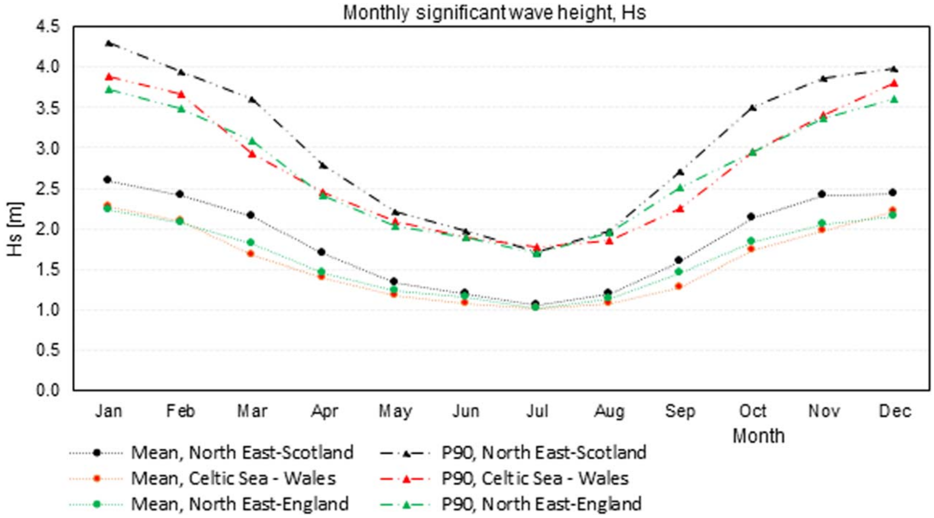

Fig. 7 Monthly mean and 90th percentile significant wave height statistics at site (over 30 years)

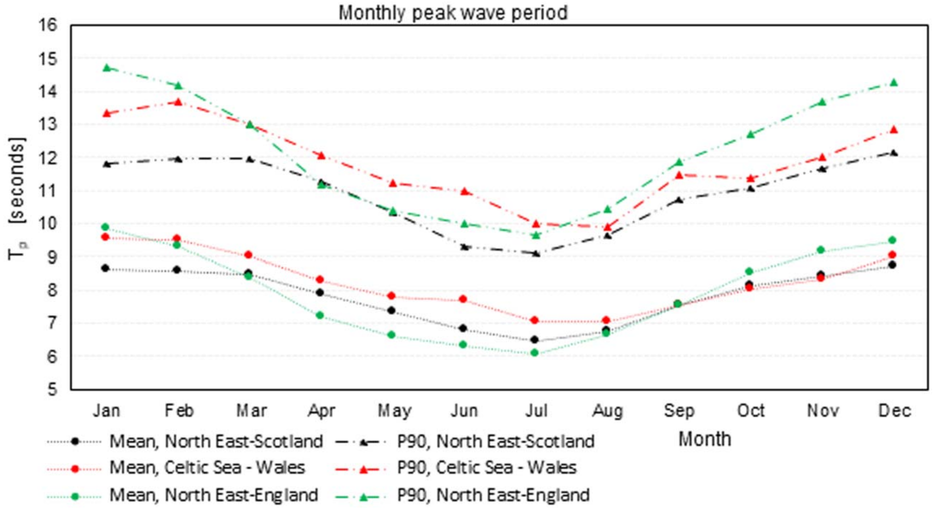

Fig. 8 Monthly mean and 90th percentile peak wave period statistics at site (over 30 years)

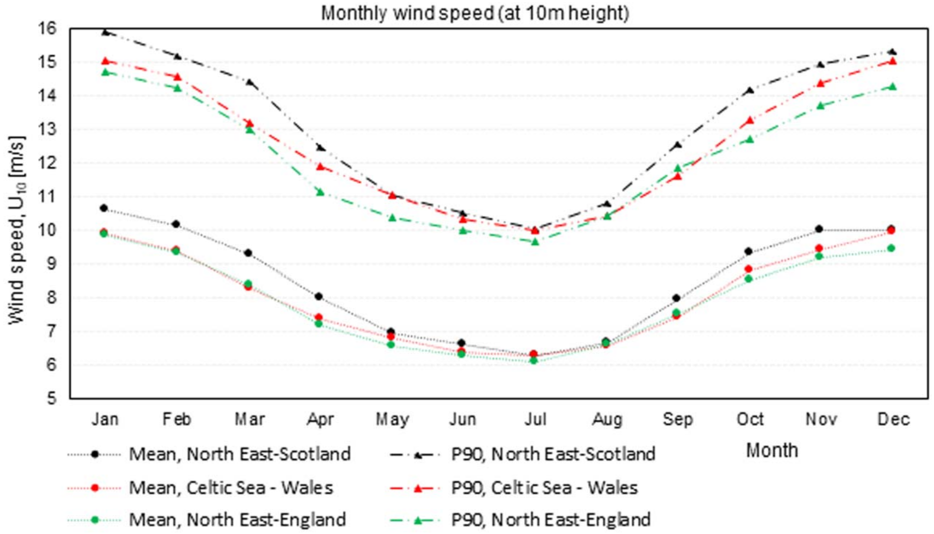

Fig. 9 Monthly mean and 90th percentile wind speed statistics at site (over 30 years)

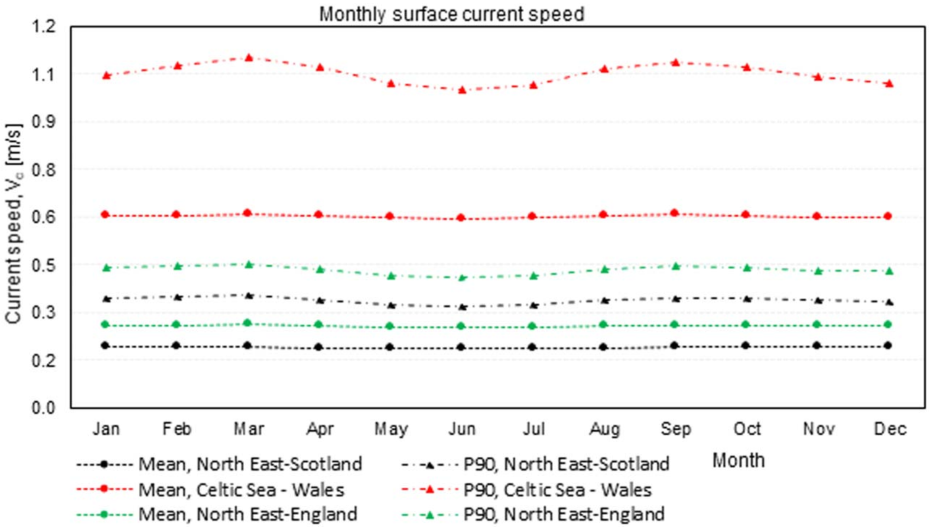

Fig. 10 Monthly mean and 90th percentile current speed statistics at site (over 30 years)

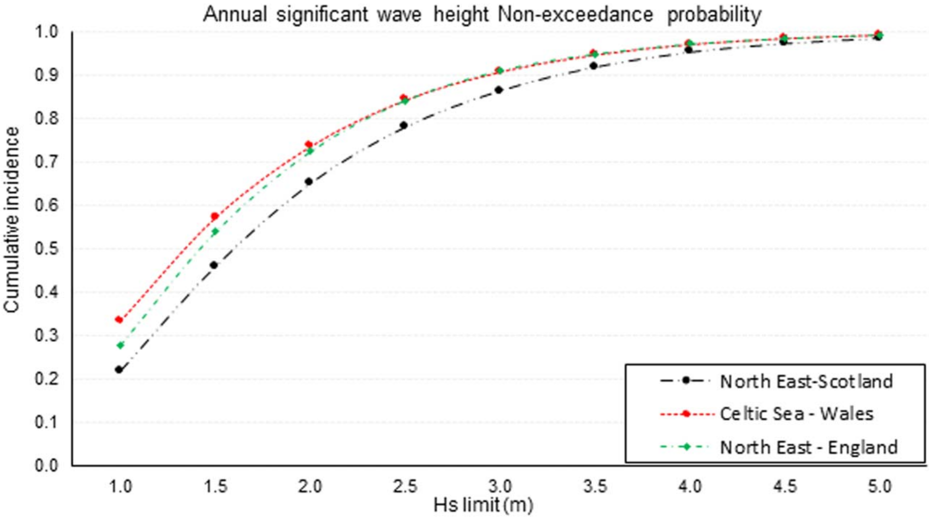

Fig. 11 Mean annual non-exceedance probability of significant wave height at site (over 30 years)

The simulation was performed starting on the first day of each month and repeated for each of the 30 years in the metocean dataset described in Sec. 3.2. The mean value, P10 and P90 percentiles were selected to analyze both the estimated overall T&I project duration and the length of each installation WP.

This section outlines the outcomes and the most relevant installation performance indicators, such as overall offshore T&I duration, ratio of weather and logistical downtime, and WP installation ratio per FOWT. Weather downtime refers to the time where the metocean conditions are not favorable to execute the T&I operations—metocean conditions over operational thresholds for each vessel or operation—resulting in unplanned stoppages in the offshore installation process. For instance, lifting operations for the assembly of wind turbines at quayside cannot be performed if the wind speed is over 10 m/s, as defined in Table 2.

Logistical downtime refers to unplanned interruptions of offshore installation cycles due to resource unavailability, independent of the metocean conditions. Random failures on a vessel, pausing of turbine-floater integration activities due to lifting equipment breaking down or limited quayside storage capacity, as previously described in Sec. 2.2, are examples of logistical downtime.

4.1 Overall Transport and Installation Project Duration.

The overall T&I duration indicates the total time in days required to complete the project. It is quantified from the start time of the first activity to the end time of the last activity. Following the installation process diagram in Fig. 2, the overall T&I duration includes floating platform load-out operations, travel time to the construction/assembly port, the duration of all installation work packages, and waiting times for favorable weather conditions (weather windows).

Arranging the results by the project starting month, Fig. 13 shows the seasonal variability in the calculated overall T&I duration based on 30 years of hindcast data. On the bar plot, the bar height represents the expected mean value for each site. The displayed error bars represent the P10 and P90 non-exceedance values.

Considering the long distance for the transport of the semi-submersible FOWP from the manufacture port to the wind farm assembly port, higher installation periods in the North East of Scotland and the North East of England are expected in comparison with the Celtic Sea zone, as presented in Table 3.

In each of the simulated cases, there is a significant difference between the base duration (without weather downtime) and the simulation outcomes, providing insights into project delay risk of

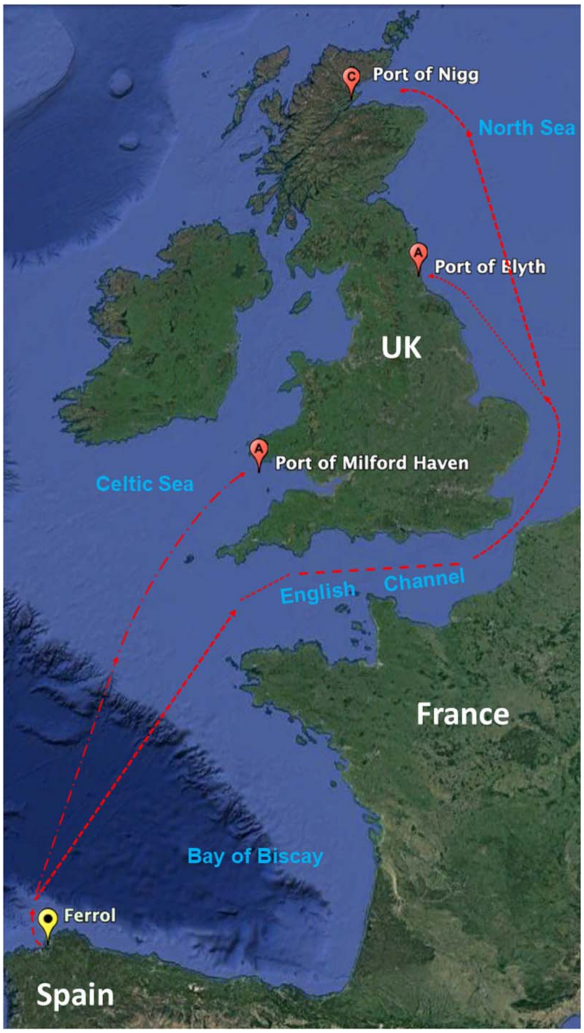

Fig. 12 Vessel transit routes from the floating platform fabrication yard to the offshore wind turbine assembly port (for illustrative purpose only)

during the entire offshore transport and installation phase. For instance, the estimated T&I duration for the North East of Scotland varies between 1032 days and 1358 days (i.e., 2.8 years to 3.7 years), compared to 635 days (i.e., 1.7 years) excluding downtime.

Table 3 Overall transport and installation mean, 10th and 90th percentile project duration statistics (averaged across all start months)

Duration quantile (days)	N.E. Scotland	Celtic Sea	N.E. England
P90	1358	878	1323
Mean	1232	808	1175
P10	1032	713	979
Overall base duration (excludes downtime)	635	353	521

The risk arises from potential unfavorable metocean conditions, i.e., weather downtime, and limited resource availability, i.e., logistical downtime. The fraction of weather and logistical downtime, as well as the operational time, related to the overall T&I project duration is presented in Fig. 14. As can be seen, between 39% and 43% of the project duration are delays attributed to adverse weather conditions, while 5% and 9% of the time spent in the overall T&I is due to logistical downtime.

Mooring hook-up of the floating platform, is one of the most critical and weather-sensitive offshore operations during the FOWT installation. As it requires the support of ROVs to complete such task, it shall take place in relatively low waves and slow currents as indicated in Table 2.

A small variation in the safe operating limits may impact the total project timeline. For instance, Table 4 summarizes the effect of increasing the wind speed limit from 10 m/s to 15 m/s for the load-out of floating platforms and rising the H_s threshold from 2.5 m to 3.0 m for the towing operations to staging port (refer to Table 1, Sec. 2.3, for initial values). A reduction in the overall T&I duration was noted in each of the three case scenarios: from 1358 days to 1086 days (i.e., 3.7 years to 2.97 years) in the North East of Scotland, from 878 days to 767 days (i.e., 2.4 years to 2.1 years) in the Celtic Sea, and from 1323 days to 1040 days (i.e., 3.62 years to 2.85 years) in the North East of England, as maximum values.

The outcomes of the installation work packages described in Secs. 2.3, 2.7, and 2.8, are summarized in Tables 8–10, Appendix B, respectively.

4.2 Key Performance Installation Indicators. To measure the performance of the installation strategy at each location, key performance indicators (KPIs) are presented in the following, with a summary shown in Table 5 and Fig. 15:

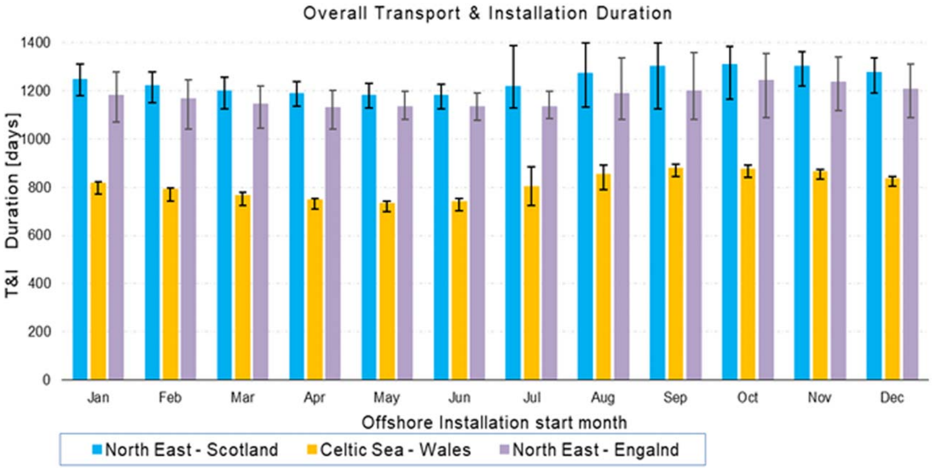

Fig. 13 Overall transport and installation project duration, changing the project start date

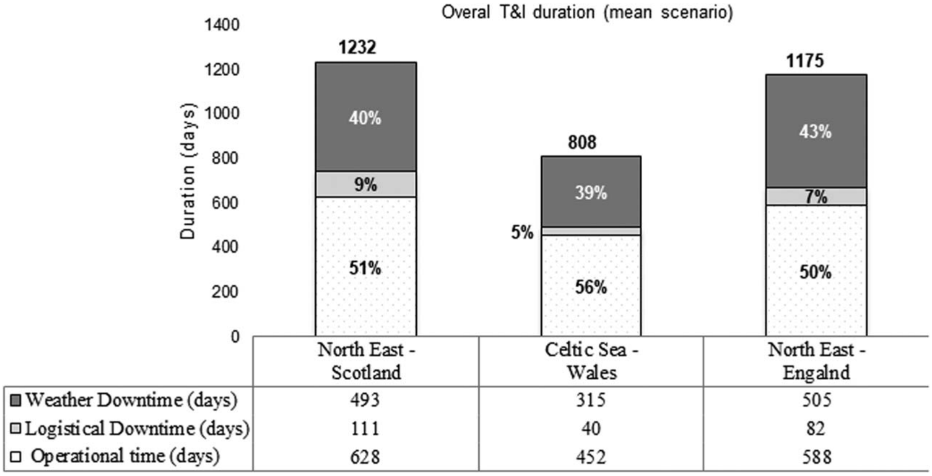

Fig. 14 Transport and installation project downtime and operational time, mean scenario (averaged across all start months)

Table 4 Overall transport and installation mean, 10th and 90th percentile project duration statistics (increasing U_{10} threshold from 10 m/s to 15 m/s and H_s from 2.5 m to 3.0 m, for load-out and transport of floating platforms)

Duration quantile (days)	N.E. Scotland	Celtic Sea	N.E. England
P90	1086	767	1040
Mean	1044	688	967
P10	976	644	881
Overall base duration (excludes downtime)	635	353	521

- *Total T&I project duration, in days*: the average number of days to complete the offshore transport and installation phase at each project location.
- *Total T&I project delays, in days*: the average total project downtime, including weather and logistical downtime.
- *Construction time per FOWT, in days/FOWT*: the overall T&I project duration is divided by the number of FOWT, to represent the average number of days required to install one floating offshore wind turbine at each project location.
- *Construction delay per FOWT, in days/FOWT*: the total project delays are divided by the number of FOWT, to represent the risk of project timeline delay.
- *Work package installation ratio per FOWT, in days/FOWT*: the expected duration of each installation work package is divided by the number of FOWT. This indicator illustrates the average number of days per FOWT required to complete each work package.

It is clear that the distances from FOWP manufacture port to the staging port and from the staging port to the project site, as well as the metocean conditions, have a significant impact on the overall construction time per FOWT. It is expected to take about 41 days/FOWT in the North East of Scotland, 39 days/FOWT in the North East of England, and 27 days/FOWT in the Celtic Sea, to complete the offshore T&I per turbine. There is a difference between North East of Scotland and Celtic Sea locations of more than 12 days/FOWT to complete the T&I phase.

There is a potential risk of delays in the construction time per wind turbine of around 20 days/FOWT, in the North East of Scotland and North East of England. The risk of construction delays is expected to be more than 11 days/FOWT in the Celtic Sea.

5 Discussion

This study is based on justified assumptions, such as number of wind turbines, asset geographic location, metocean conditions, as well as transit routes, installation sequence, duration of the operations, and vessel operational threshold limits—vessel speed, significant wave height (H_s), wave period (T_p), current speed (V_c), and wind speed (U_{10}).

For each of the three project site scenarios described in Table 6, Appendix A, overall transport and installation duration of the offshore wind farm was calculated using these assumptions, including expected weather and logistic delays, as shown in Fig. 14.

This modeling approach provides insight into the logistics challenges during the transport and installation phase to deliver large-scale floating offshore wind deployment in UK waters. The presented results focus on the installation phase only. A full feasibility study for any FOWT installation will also have to consider the energy yield [25], i.e., expected revenue profile, and operation and maintenance cost throughout the lifetime of the wind farm. A similar simulation and optimization process will have to be carried out for O&M strategies [26].

Table 5 Estimated installation performance indicators, mean scenario

Installation KPI	N.E. Scotland	Celtic Sea	N.E. England
Distance to shore (km)	185	60	85
Total T&I project duration (days)	1232	808	1175
Total T&I project delays (days)	604	356	587
Construction time per FOWT (days/FOWT)	41	27	39
Construction delay per FOWT (days/FOWT)	20	11.8	19.5
Work package installation ratios per FOWT			
Load-out and transport of floating platforms ratio per FOWT (days/FOWT)	29.1	18.6	27.5
Floating offshore wind turbine installation ratio per WT (days/FOWT)	3.86	1.73	3.84
Commissioning ratio per FOWT (days/FOWT)	1.93	1.37	1.92

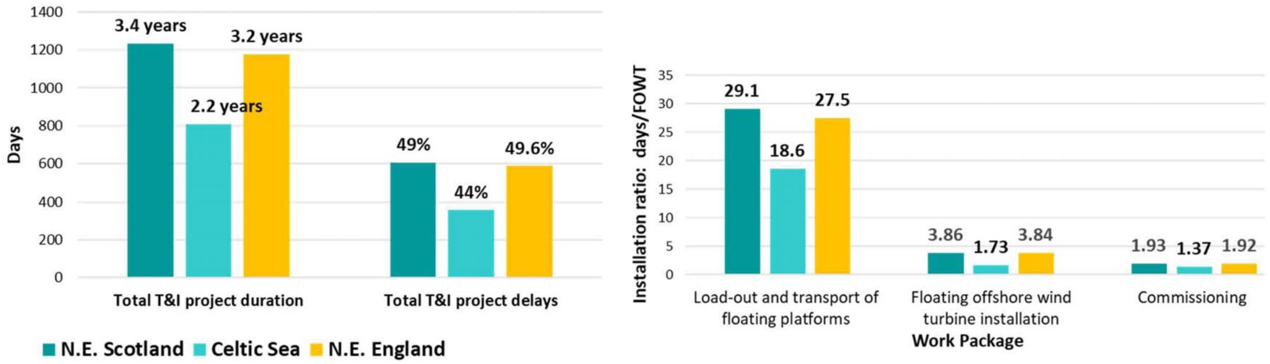

Fig. 15 Work package installation ratios per FOWT (mean scenario)

The presented modeling also depends heavily on the availability and suitability of ports to assemble the platform and turbine [27]. This includes aspects such as availability of suitable quay access and port water depth, laydown areas, and lift capability. These shore-based dependencies need to be planned in detail and are likely to present bottlenecks, if the envisaged FOWT installations are taking place without additional port infrastructure investments.

In general, it should be noted that there is not much public information regarding the installation of FOW projects. There are a few demonstration projects, primarily for spar and semi-sub floating platforms. Hence the presented results should be interpreted as relative values that can aid the scenario-modeling and decision-making for different sites, installation strategies, and vessel/port capabilities. Although the simulations have not yet been validated against a complete project installation, the study provides important awareness of the logistics, planning, and key drivers for the planned large-scale installation of floating wind energy projects.

6 Conclusion

FOW technology offers opportunities to advance the installation of offshore wind turbines into deeper waters and further from the coast (e.g., between 60 m and 1000 m deep, more than 50 km distance from shore). This will also unlock areas where the waters are deep close to shore, such as in California and Oregon, in the west coast of the United States, Spain, Taiwan, or Japan.

However, logistics challenges must be overcome, such as the availability of specialized heavy transport vessels and port infrastructure, to allow large-scale floating offshore wind deployment and meet the global renewable energy targets within the next decades.

This paper has presented a modeling approach to simulate the transport and installation logistics of floating offshore wind development, making a contribution to feasibility and early project planning analysis, to support future deployment of floating offshore wind. Even though three sites were identified for potential floating offshore wind deployment in UK waters, the model can be adjusted for assessment of port strategies, transport of components and installation methods, analysis of vessel strategies, and operational limits at any offshore wind farm potential locations.

The key findings drawn from this study are as follows:

- Simulation tools and installation modeling are useful during the planning stage of offshore wind project development to assist decision-making and identify possible risks. For instance, vessel operational and survival limits can be analyzed under different weather conditions in order to identify scenarios than could exceed tolerance limits and prepare contingency plans.
- One of the governing parameters that impact the overall T&I duration, is the logistical distances. Both the distance from the FOWP manufacture port to the staging port, and the distance from the staging port to the project site, are relevant for the transport of components method and installation vessel selection.
- Installation delays can be reduced, e.g., having either more vessels or manufacturing facilities located closer to project site.
- Any variation in the vessel operational limits could increase time delays or decrease installation time.
- Planning with delays and understand when and where bottlenecks could occur in the logistics and supply chain, can minimize potential risks of project over budget or complete after the scheduled end date.
- Currently, no port in the UK has the capacity to deliver all the processes required (from fabrication to installation) for large-commercial scale FOW deployment (up to 1GW by 2030).
- Major capital investment in FOW port infrastructure and supply chain development is required to meet the global renewable energy targets within the next decades.

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Conflict of Interest

The author(s) declare(s) that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

m = meter
H_s = significant wave height, m
T_p = peak wave period, s
U_{10} = wind speed, m/s, at 10 m height
U_{100} = wind speed, m/s, at 100 m height

V_C = surface current speed, m/s
km = kilometer
AHT = anchor-handling tug vessel
CAPEX = capital expenditures (£)
CLV = cable-laying vessel
FOW = floating offshore wind
FOWP = floating offshore wind platform
FOWT = floating offshore wind turbine
GW = gigawatt
HTV = heavy transport vessel
KPI = key performance indicator
MW = megawatt
MVA = mega-volt Ampere
O&M = operations and maintenance
ROV = remotely operated vehicle
SOV = service operation vessel
T&I = transport and installation
UK = United Kingdom
WP = work package
WT = wind turbine

Appendix A: Case Study Assumptions

See Tables 6 and 7.

Table 6 General site parameters (modeling assumptions)

Parameter/Location	Zone A[a]	Zone E[a]	Zone I[a]
Location	North Sea, North East of Scotland	Celtic Sea, West of Wales	North Sea, North East of England
Distance to construction/assembly port[b]	185 km	60 km	85 km
Construction/Assembly port[c]	Port of Nigg, Scotland	Milford Haven Port Authority, Wales	Port of Blyth, England
Floating foundation fabrication yard[d]	Ferrol, Spain	Ferrol, Spain	Ferrol, Spain
Foundation type (Floating)[d]	Semi-submersible platform	Semi-submersible platform	Semi-submersible platform
Distance from fabrication yard to assembly port[g]	∼2200 km	∼1010 km	∼1810 km
Mooring system[d] (per turbine)	Three mooring lines with catenary configuration	Three mooring lines with catenary configuration	Three mooring lines with catenary configuration
Mooring line radius	9 × water depth	9 × water depth	9 × water depth
Anchor type[d]	Drag embedded anchors	Drag embedded anchors	Drag embedded anchors
Turbine rated power (MW)[d,e]	10	10	10
Number of turbines	30	30	30
Wind-farm capacity (MW)[e,f]	300	300	300
Offshore substation (MW)	350	350	350
Dynamic inter-array cable[e]	66 kV AC	66 kV AC	66 kV AC
Export cable[e]	220 kV HVAC	220 kV HVAC	220 kV HVAC
Number of export cables	3	3	3
Average wind speed (m/s) (at 150 m height)[b]	11.20	10.65	10.1
Weather conditions	Harsh	Medium	Medium
Average water depth (m)[b]	97.5	115	95

[a] Indicative floating wind development zones based on ORE Catapult studies [19,20].
[b] Based on site parameters for development zones identified on ORE Catapult study [19].
[c] Port selection based on Refs. [21–23,31].
[d] Inspired by Kincardine floating wind farm, Scotland [28].
[e] Based on Green Volt floating offshore wind farm, Scotland [29] and NREL report [32].
[f] Based on Gwynt Glas Offshore Wind Farm, Celtic Sea [30].
[g] Estimated distance based on the transport routes illustrated in Fig. 12.

Table 7 Sea state parameters and operational limits of the offshore installation vessels (modeling assumptions)

Vessel type	CLV	AHT	SOV
Vessel speed unloaded (knots)	14	12	14
Vessel speed loaded (knots)	2	3	14
Wave limit unloaded, H_s (m)	10	5	10
Wave limit loaded, H_s (m)	3	2	3
Wave limit technician transfer, H_s (m)	—	—	3
Wind limit unloaded, U_{10} (m/s)	20	20	20
Wind limit loaded, U_{10} (m/s)	10	10	10
Wind limit—technician transfer, U_{10} (m/s)	—	—	10
Current speed limit—Hook-up operations (m/s)	—	<0.25	—

Appendix B: Simulation Outcomes: Installation Work Package Duration Statistics

See Tables 8–10.

Table 8 Load-out and transport of floating platforms mean (averaged across all start months), 10th and 90th percentile work package duration statistics

Duration quantile (days)	N.E. Scotland	Celtic Sea	N.E. England
P90	1005	646	962
Mean	874	560	825
P10	775	481	739
Base duration[a] (excludes downtime)	475	235	392

[a] Base duration (in days) refers to the estimated number of days required to complete the work package excluding weather restrictions—no weather downtime.

Table 9 Floating offshore wind turbine installation mean (averaged across all start months), 10th and 90th percentile work package duration statistics

Duration quantile (days)	N.E. Scotland	Celtic Sea	N.E. England
P90	144	61	139
Mean	116	52	115
P10	88	48	97
Base duration[a] (excludes downtime)	72	42	53

[a] Base duration (in days) refers to the estimated number of days required to complete the work package excluding weather restrictions—no weather downtime.

Table 10 Floating offshore wind turbine final commissioning mean (averaged across all start months), 10th and 90th percentile work package duration statistics

Duration quantile (days)	N.E. Scotland	Celtic Sea	N.E. England
P90	98	68	89
Mean	61	41	56
P10	41	28	36
Base duration[a] (excludes downtime)	23	16	18

[a] Base duration (in days) refers to the estimated number of days required to complete the work package excluding weather restrictions—no weather downtime.

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