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Cost benefit analysis of mothership concept and investigation of optimum chartering strategy for offshore wind farms

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Abstract

The focus of this research is the cost benefit analysis of the mothership concept and the investigation of the optimum chartering strategy, which brings financial and operational benefits. This is achieved by performing operational simulations in the offshore wind operational expenditure and logistics planning tool StrathOW-OM, which is developed by the University of Strathclyde and commercial partner organisations. In this paper, a fixed accommodation platform concept, two mothership concepts and different vessel chartering periods are simulated. The simulation results are compared with a base case scenario, in which the O&M activities are performed through a conventional onshore base. The simulation results show that significant travel time is spent in far offshore, if only a single conventional onshore base is utilised in the operations. Among different vessel chartering periods (continuous, only summer months, only winter months or combination of summer months and winter months), October-December is identified as the most critical period for chartering a mothership.

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Keywords: Mothership; Offshore Wind; Operation and Maintenance; Charter Rate; Crew Transfer Vessel; Accessibility; Simulation

1. Introduction

In order to capture stronger winds and take advantage of larger areas, forthcoming projects are planned in deeper waters and located further from shore. This situation provides better power productivity; on the other hand, it introduces financial and operational risks. In far offshore, typical distance of more than 50 nautical miles (nmi),

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challenging climate conditions limit the operability and the accessibility of the maintenance vessels significantly. Furthermore, if significant time is spent in transit between the offshore wind farm and the operation and maintenance (O&M) port, this negatively impacts the number of maintenance tasks that can be carried out [1]. In addition, safety restrictions dictate that the maintenance activities can only be performed when there is sufficient daylight at the offshore wind farm [2]. Due to the fact that the length of days in winter is relatively short in the regions that the forthcoming offshore wind farm projects are planned such as UK, Germany, Norway, and Denmark, the restriction of starting maintenance activity after the sun rises decreases the operational window significantly in a regular maintenance day [3]. These major difficulties reduce the power production and increase the financial risks of the operating offshore wind farms.

A mothership, which is a large vessel that can accommodate multiple crew transfer vessels alongside, can provide a possible solution for operators. By considering a mothership in the O&M fleet, the reaction time to failures can be minimised; thus the availability of the offshore wind farm can be maximised [4]. Furthermore, fuel costs can be decreased by eliminating vessel transit between the O&M port and the offshore wind farm. Despite these advantages, a robust financial case has not been made to consider motherships in O&M fleets. This is because a mothership requires a large capital investment, and the cost-benefit of considering a mothership in the maintenance fleet has not been investigated in a comprehensive way. Furthermore, knowledge related to mothership operational practice is limited in the context of offshore wind O&M. Different chartering and operating strategies will have to be investigated in order to optimise offshore wind O&M activities.

In this context, the focus of this research is the cost benefit analysis of the mothership concept and the investigation of optimum chartering practise, which brings the highest financial and operational benefits. This is achieved by performing operational simulations in the offshore wind operational expenditure and logistics planning tool StrathOW-OM, which is developed by the University of Strathclyde and commercial partner organisations. StrathOW-OM examines climate parameters in the offshore wind farm location, size and operational characteristics of the maintenance fleet, and the failure rates of the turbine components. In section 2, the StrathOW-OM tool is introduced and the simulation logic is provided. A case study is performed in section 3 and the results of this case study are demonstrated in section 4. In section 5, concluding remarks of the study are presented.

2. Methodology

The developed methodology is divided into three main sections: Inputs, Simulations, and Outputs. Fig. 1 shows the flowchart of the developed methodology illustrating the information flow between different sections. The Inputs section is the stage where information about a case is defined and this specific information is delivered to the Simulations section. Thereafter, the case is analysed within specific sub-sections and the operational simulations are performed. The results of the operational simulations are aggregated in the Outputs section and final results are presented. In the following sections details are provided related to each section.

2.1. Inputs

The climate inputs in the developed methodology [5, 6] comprise of historical wind speed, wave height, wave period observations, probability of good visibility, and duration of daylight values collected from a specific location. The vessel specifications and O&M fleet configuration comprise of crew transfer vessel (CTV), helicopter, jack-up vessel, and mothership inputs. Wind farm/turbine inputs are the number of wind turbines, the power production values for associated wind speed values, and the time dependent failure rates of the turbine components. Furthermore, hub height from sea level is required to extrapolate wind speeds from observation height to hub height. From the O&M costs point of view, vessel charter, technician, crew, mobilisation, fuel, and fixed costs (provisions, insurance, overheads, etc.) are considered within the methodology.

Fig. 1. The developed methodology

2.2. Simulations

It is rare that the climate data will present exactly the same observations/measurements in the following years. Therefore, it is important to generate alternative climate dataset by also preserving the characteristics of the original dataset. The developed model has the capability of generating synthetic wind speed, wave height and wave period time series using a Multivariate Auto-Regressive (MAR) model, developed from the methodology in [7, 8]. The key characteristics of mean and variance as well as annual distribution, access window duration periods and temporal correlation are preserved as well as the relationship between wind and wave conditions.

In heavy seas, waves cause additional resistance on the vessel hull. The most accurate method to calculate additional resistance due to waves is model testing. Alternatively, Jinkine and Ferdinande [9] developed an empirical formulation for predicting the added resistance. Due to the fact that time-step approach is utilised in the simulations, wave height and wave period values in each time-step are different, which creates variation in added resistance and eventually total resistance of the vessels. In this study the power and thrust of the vessels are kept constant and vessel speed changes with the influence of added resistance. In order to calculate the speed loss in each time-step under the condition of constant power and thrust, the formulations derived by Berlekom, et al. [10] and Berlekom [11] are utilised.

The wind turbine system failure process is implemented using the methodology developed by Billinton [12]. Each wind turbine is modelled as a series of subsystems, for which a probability of ‘moving from an operating state to a failed or reduced operating state’ is envisaged. The probability of shifting states is governed by the component reliability, which is the probability that the component performs satisfactorily for the specified time interval t. In this context, the failure rates $f(t)$, which are determined from observed annual failure rates in operational history and expert judgement, are utilised to calculate the reliability of the turbine components.

In the operational simulations, all the information from previous blocks is collected and O&M activities are simulated on daily basis. After identifying a failure, the O&M technicians are allocated to the wind turbine, if the current weather conditions are within the turbine access limits as defined in the model inputs. If these conditions are not met, the O&M technicians stay at the O&M port and the turbine remains out of service.

2.3. Outputs

The methodology provides major outputs such as availability, power production, vessel utilisation, mean time to repair values, and cost attributes in order to support the decision making process. The generic principle of the outputs sections is to calculate each output specifically for each simulation and then average these outputs when all the simulations are completed. Since multiple simulations are run in order to cover all possible situations such as bad weather and good weather years, high number and low number of failures, etc., the outputs associated with each scenario will vary. By running a sufficiently large number of simulations, the average results will converge to a final value and the variability across simulations will provide a measure of uncertainty. The key outputs for this study are wind farm availability, crew transfer vessel (CTV) travel time, CTV utilisation, distribution of total mothership cost, and total O&M cost/MWh.

2.4. Mothership model

For the mothership, the following three concepts have been modelled;

(A) A fixed accommodation platform concept: The O&M vessels can moor alongside, minimal operating cost is expected, but significant capital investment is required.
(B) A floating hotel mothership concept: The O&M vessels can moor alongside, the mothership can be chartered for long-term or short-term/seasonal.
(C) A pro-active mothership concept: The O&M vessel can moor alongside, daughter crafts on-board also provide additional support. The mothership can be chartered for long-term or short-term/seasonal.

The explanation of mothership inputs are listed in Table 2. These inputs are considered within the simulation logic depending on the selected concept in the analyses. For instance, ‘operational speed’ is not considered for the fixed accommodation platform concept. Likewise, ‘Capital Expenditure (CAPEX)’ is not considered for the floating hotel and pro-active mothership concepts. For presentation purposes, the three concepts above are symbolised by ‘A’, ‘B’, ‘C’ in Table 2, respectively.

Table 2. Mothership inputs

Input Name	Concept	Explanation	Unit
Operational Speed	B - C	Speed at maximum continuous power	*knot*
Charter Type	B - C	Seasonal charter or continuous charter	*N/A*
Start Month	B – C	Start month of the seasonal charter (inclusive)	*N/A*
Final Month	B – C	Final month of the seasonal charter (inclusive)	*N/A*
Mothership endurance	B - C	Number of days that mothership can stay in offshore site	*day*
Time required to replenish	B - C	Number of working shifts required to replenish fuel, fresh water, provisions, etc.	*shift*
Fuel consumption (stationary)	B - C	Fuel consumption in stationary position	*mt/hour*
Fuel consumption (operational)	B - C	Fuel consumption in operational speed (between offshore wind farm and O&M port)	*mt/hour*
Number of crew	A - B - C	Number of qualified personnel to operate fixed platform/mothership continuously	*N/A*
Wind speed (survival)	B - C	Limiting wind speed at sea level (if exceeds mothership leaves site immediately)	*m/s*
Wave height (survival)	B - C	Limiting wave height (if exceeds mothership leaves site immediately)	*m*
Number of CTVs	A - B - C	Number of CTVs that can moor along mothership	*N/A*
CTV Endurance	A - B - C	Number of days that CTVs can stay in offshore site without sailing back to O&M port	*day*
Number of daughter crafts	C	Number of daughter crafts that mothership can accommodate on-board	*N/A*
CAPEX	A	CAPEX of fixed platform (including foundation, material, installation, and platform)	*£*
Charter rate	B - C	Charter rate of mothership (excluding crew, fuel, and operating costs)	*£/day*
Fuel cost	B - C	Fuel cost of mothership	*£/mt*
Fixed and operating costs	A - B - C	Fixed and operating costs of mothership (i.e. port, insurance, maintenance, provisions)	*£/year*

3. Case Study

A case study has been performed in order to capture the influence of the mothership on the offshore wind O&M activities and to identify the most favourable chartering strategy. In this context, an offshore wind farm, which consists of 150 3.6 MW turbines, was considered. The site is 50 nmi from the O&M port and the water depth of 250 m. It is common that offshore personnel are on duty in 14 consecutive shifts of 12 hours each followed by 14 days of rest [13], in which they remain in the payroll. Therefore, the personnel pool (crew and O&M technicians) and associated costs are required to be multiplied by two. 5 CTVs are operated in the site by 2 skippers each and it is assumed that all the three concepts are large enough to accommodate all the CTVs at the same time. In order to cover different variations in the results due to randomisation of the climate parameters and the variables in the Monte-Carlo simulation process, 100 simulations are used. The length of the simulations has been defined as 25 years to cover an entire life span of an offshore wind farm. 5% interest rate as in [14] is applied for net present value calculations associated with on-going costs and benefits.

3.1. Fixed accommodation platform concept

The weight of a 250 m jacked foundation is approximately 24,000 tons [15] and the manufacturing & installation cost is £3000/ton [16]; therefore, the foundation cost is calculated as £72M. The accommodation units and living quarters cost £20M [17]; thus, the CAPEX of the fixed accommodation platform is £92M. It is envisaged that 11 crew (2 able seamen, 1 bosun (experienced seaman), 1 electrician, 3 stewards, 2 cooks, and 2 officers) with average £40,000 annual salary can operate the fixed accommodation platform. By using the cost distribution in [18], £5M annual operating cost is envisaged for the fixed accommodation platform.

3.2. Floating hotel mothership and pro-active mothership concepts

These two concepts are essentially unique vessel concepts, in which crew and O&M technicians can be accommodated, also these vessels incorporate well-equipped workshops. The only difference envisaged between these two concepts is that the pro-active mothership has 3 daughter crafts on-board. In this respect, if there are still unattended turbines after all the CTVs are allocated in a repair day, these daughter crafts can be utilised. Due to very high CAPEX, it is envisaged that these mothership concepts are chartered for certain period of time. Due to more advanced design, it is assumed that pro-active mothership concept has higher charter rate than floating hotel concept. The mothership inputs are presented in Table 3. The charter rates with the associated charter types are adapted from [19, 20]. In addition, different O&M fleet configurations utilised in the simulations, are listed in Table 4. The horizontal axes of the figures in the results section refer to the configuration number in Table 4.

Table 3. Mothership inputs

Input Name	Value	Input Name	Start Month	Final Month	Value	Daily Charter Rate	
						B	C
Operational Speed	8.5 knots	Charter Type - Continuous	N/A	N/A	25 years	£25,000	£30,000
Mothership endurance	30 days	Charter Type - Seasonal	January	June	6 months	£35,000	£40,000
Time required to replenish	2 shifts	Charter Type - Seasonal	April	September	6 months	£35,000	£40,000
Fuel consumption (stationary)	1.51 mt/hour	Charter Type - Seasonal	July	December	6 months	£35,000	£40,000
Fuel consumption (operational)	3.025 mt/hour	Charter Type - Seasonal	October	March	6 months	£35,000	£40,000
Number of crew	22	Charter Type - Seasonal	January	March	3 months	£45,000	£50,000
Wind speed (survival)	36.1 m/s	Charter Type - Seasonal	April	June	3 months	£45,000	£50,000
Wave height (survival)	7 m	Charter Type - Seasonal	July	September	3 months	£45,000	£50,000
Number of CTVs	5	Charter Type - Seasonal	October	December	3 months	£45,000	£50,000
Fuel cost	£550/mt						
Fixed and operating costs	£5M/year						

Table 4. Simulated O&M fleet configurations

No	Configuration	Charter Type	Start Month	Final Month	Period	Daughter craft	No	Configuration	Charter Type	Start Month	Final Month	Period	Daughter craft
1	No mothership	N/A	N/A	N/A	N/A	N/A	-	-	-	-	-		-
2	Fixed platform	N/A	N/A	N/A	25 years	N/A	-	-	-	-	-		-
3	With mothership	Continuous	N/A	N/A	25 years	N/A	12	With mothership	Continuous	N/A	N/A	25 years	3
4	With mothership	Seasonal	Jan	Jun	6 months	N/A	13	With mothership	Seasonal	Jan	Jun	6 months	3
5	With mothership	Seasonal	Apr	Sep	6 months	N/A	14	With mothership	Seasonal	Apr	Sep	6 months	3
6	With mothership	Seasonal	Jul	Dec	6 months	N/A	15	With mothership	Seasonal	Jul	Dec	6 months	3
7	With mothership	Seasonal	Oct	Mar	6 months	N/A	16	With mothership	Seasonal	Oct	Mar	6 months	3
8	With mothership	Seasonal	Jan	Mar	3 months	N/A	17	With mothership	Seasonal	Jan	Mar	3 months	3
9	With mothership	Seasonal	Apr	Jun	3 months	N/A	18	With mothership	Seasonal	Apr	Jun	3 months	3
10	With mothership	Seasonal	Jul	Sep	3 months	N/A	19	With mothership	Seasonal	Jul	Sep	3 months	3
11	With mothership	Seasonal	Oct	Dec	3 months	N/A	20	With mothership	Seasonal	Oct	Dec	3 months	3

4. Results

Fig. 2 shows the wind farm availability, CTV travel time, and average CTV utilisation. Due to randomisation of the climate parameters, variability is observed in the wind farm availability, which is shown by the box-plots. The average availability within each configuration is presented by the blue markers on the box-plots. In general, the average availability values are grouped in three areas (low-average-high), which are separated by the dotted red lines. The fixed accommodation platform concept has the biggest potential to improve the average availability. Similarly, the floating hotel mothership and the pro-active mothership concepts can increase the average availability up to 91%. However, extra operational restrictions (i.e. endurance limit) - which are not applicable for the fixed accommodation platform - limit the number of days in operation. The values below 75% average availability are the configurations (seasonal), which do not bring a significant benefit from availability point of view. The common point among these configurations (no. 5, 9, 10, 14, 18, 19) is the charter season. In these configurations, the mothership is chartered between April and September, in which the climate is expected to be calmer than other months. Due to extra daughter crafts on-board, the pro-active mothership concept provides better average availability than the floating hotel mothership concept. The July-December and October-March periods for 6 months seasonal charter, and the October-December period for 3 months seasonal charter are identified as the most favourable seasonal charter periods from an availability point of view. In these 3 alternatives, October-December is the common period, in which the climate is expected to be challenging and the accessibility is expected to be the lowest.

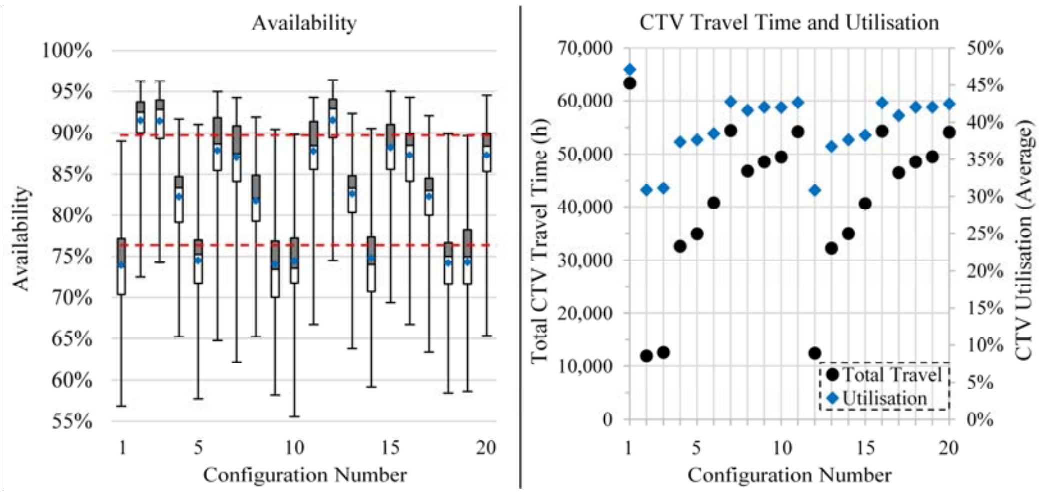

Fig. 2. Wind farm availability, CTV travels and average utilisation

Although the average availability values are established as the final results of the entire analysis, variations are observed within each simulation result, which is associated with the relatively random behaviour of climate parameters and failures. In the configuration no. 1, 90% availability can be observed if the climate is calm and if the number of failures are low. On the other hand, if the climate is rough and if the number of failures are high in a particular simulation, the availability can drop to below 60%. The uncertainty observed in the configurations no. 2, 3 and 12 is considerably lower than the uncertainty observed in the other configurations, in which the availability varies between 75% and 95%. It is more favourable to observe lower uncertainty, because the financial and operational risks can be quantified more accurately. Therefore, considering a fixed accommodation platform at the wind farm site or a continuous mothership charter can increase the average availability of the wind farm more than any other seasonal mothership configuration, but also these configurations can decrease the associated risks by limiting the uncertainty.

When the CTV travel time and average utilisation values are evaluated, it can be seen that the lowest values are identified when the fixed accommodation platform and the vessel concepts under continuous charter are considered in the O&M fleet. The difference among the CTV travel time values proves that the time spent between the O&M port and the wind farm is considerably higher than the time spend within the wind farm. Since the period, which CTVs travel within the wind farm is relatively short, the number of CTVs needs to be allocated is lower for the same number of failures. Therefore, the number of CTVs allocated in a single shift is lower for the configurations no. 2, 3, and 12, which results in relatively low average utilisation. Although it is outside scope of this study, the size of the CTV fleet can be decreased in order to get the maximum benefit from each CTV and minimise cost.

Fig. 3 shows the distribution of total mothership cost and the change in the total O&M cost/MWh. The total O&M cost comprises charter cost, OEM cost, technician cost, crew cost, fuel cost, fixed costs, port operations, wind farm insurance and lost revenue. Since a mothership is not considered in configuration no. 1, there is no mothership cost associated. Similarly, charter and fuel costs are not considered for the fixed accommodation platform concept. The cost values presented in Fig. 3 are associated with the averaged simulation results. Therefore, the uncertainty in cost values is not presented in this study. From cost distribution part of Fig. 3, it can clearly be seen that the charter cost has the highest proportion in all configurations. The proportion of the charter cost to the total mothership cost increases, when the charter period decreases. On average, the charter cost, fuel cost, crew cost, and fixed cost account for 62%, 17%, 7%, and 14% of the total mothership cost, respectively.

Total O&M cost/MWh is selected for the final comparison, because it reflects the level of financial benefit (production increase) and loss (cost increase) achieved through considering mothership in the O&M fleet. The configurations are evaluated relative to the configuration no. 1 (£54.3/MWh), in which a mothership is not considered. Despite the absence of mothership associated costs, the total O&M cost/MWh value is considerably high in the configuration no. 1. This is related to significantly low power production. The configurations, which the average availability values do not show a significant increase as in Fig. 2, present higher total O&M cost/MWh value than the base configuration. This is because, the increase in the total O&M cost is not compensated by the increase in the power production. In a similar manner, the financial benefit by considering a fixed platform or vessel concepts under continuous charter is not as high as the average availability increase. In these configurations, future economic risks also have to be born in mind. The configuration no. 11, which comprises of a jack-up vessels, 5 CTVs and a floating hotel mothership chartered between October and December, is identified as the most cost-effective configuration among seasonal charter alternatives. Although the average availability is 87% (the 6th highest) for configuration no. 11, the total O&M cost/MWh value decreased considerably (the 3rd lowest), just after configurations no. 2 and 3.

Nevertheless, the fixed accommodation platform concept is identified as the most favourable alternative. However, it should be highlighted that the most favourable alternative is significantly dependent on the climate, distance, water depth, failure rates, CTV fleet size, turbine capacity and wind farm size. For instance, the fixed accommodation platform can require excessive CAPEX in much deeper waters, in which the vessel concepts can be the most favourable alternative. It is also important to quantify the risks of considering mothership in the O&M fleet. Due to immaturity of these concepts, it cannot easily be done in the current operational environment. The offshore wind O&M sector will develop by the increase in turbine installations at far offshore locations, for which risk assessment can be done relatively easier in the future.

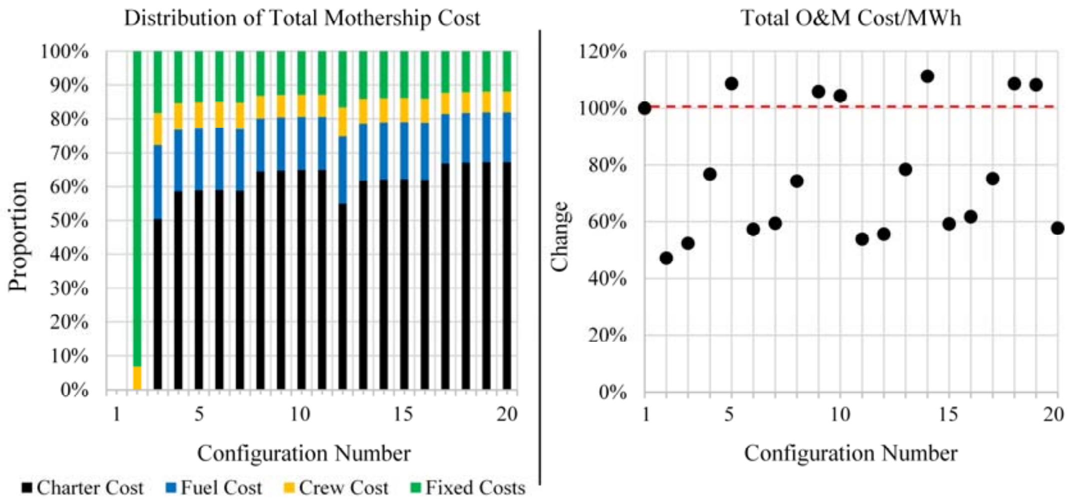

Fig. 3. Distribution of total mothership cost and Total O&M cost change

5. Conclusions

In this study, a model was introduced with the objectives of investigating the benefits of considering a mothership in the O&M fleet and identifying the most favourable chartering strategy, which brings financial and operational benefits. In order to assess the proposed model and to generate realistic results, the model was applied to a case study offshore wind farm. The results indicate that fixed accommodation platform and mothership can improve the performance of the offshore wind farms noticeably, since these assets minimise the transit time between offshore wind farm and O&M port, and therefore maximise the productive period in a working shift. In far offshore locations, conventional O&M strategies performed by conventional O&M vessels will not be cost-effective. Therefore, offshore wind operators will need to consider a mothership in their O&M fleets.

It is believed that another direction of further research can be the investigation of failure rate variability, daily charter rate, distance, wind farm size, and climate on the assessment of the mothership operations; so more accurate calculations can be performed. Furthermore, hybrid vessel chartering strategies can be necessary to sustain the power production in the future. Therefore, bespoke methodologies are required to be developed for very large offshore sites.

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