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Cost-benefit assessment framework for robotics-driven inspection of floating offshore wind farms

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Abstract

Operations and maintenance (O&M) of floating offshore wind farms (FOWFs) poses various challenges in terms of greater distances from the shore, harsher weather conditions, and restricted mobility options. Robotic systems have the potential to automate some parts of the O&M leading to continuous feature-rich data acquisition, operational efficiency, along with health and safety improvements. There remains a gap in assessing the techno-economic feasibility of robotics in the FOWF sector. This paper investigates the costs and benefits of incorporating robotics into the O&M of a FOWF. A bottom-up cost model is used to estimate the costs for a proposed multi-robot platform (MRP). The MRP houses unmanned aerial vehicle (UAV) and remotely operated vehicle (ROV) to conduct the inspection of specific FOWF components. Emphasis is laid on the most conducive O&M activities for robotization and the associated technical and cost aspects. The simulation is conducted in Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT), where the metrics of incurred operational expenditure (OPEX) and the inspection time are calculated and compared with those of a baseline case consisting of crew transfer vessels, rope-access technicians, and divers. Results show that the MRP can reduce the inspection time incurred, but this reduction has dependency on the efficacy of the robotic system and the associated parameterization e.g., cost elements and the inspection rates. Conversely, the increased MRP day rate results in a higher annualized OPEX. Residual risk is calculated to assess the net benefit of incorporating the MRP. Furthermore, sensitivity analysis is conducted to find the key parameters influencing the OPEX and the inspection time variation. A key output of this work is a robust and realistic framework which can be used for the cost-benefit assessment of future MRP systems for specific FOWF activities.

KEYWORDS
cost estimation, floating offshore wind farm, operations and maintenance, robotics, WOMBAT

Abbreviations: ASV, autonomous surface vessel; CAPEX, capital expenditure; CTV, crew transfer vessel; FOWF, floating offshore wind farm; LCOE, levelized cost of energy; MRP, multi-robot platform; O&M, operations and maintenance; OPEX, operational expenditure; ROV, remotely operated vehicle; UAV, unmanned aerial vehicle, VLOS, visual line of sight; WOMBAT, Windfarm Operations and Maintenance cost-Benefit Analysis Tool.

1 | INTRODUCTION

The development of offshore wind energy has continued to expand over the last couple of decades.[1] In particular, the focus has been shifting towards floating offshore wind farms (FOWFs) wherein the benefits of greater capture of the wind resource and water depth along with lower carbon footprint can be reaped.[2] Floating offshore wind energy, still in its infancy, has a core place in the green energy transition, and a host of pressing challenges are being addressed by researchers to aid its wide-scale adoption. One such challenge is to improve the operational efficiency of FOWF components and to reduce the associated costs of operations and maintenance (O&M).[3] O&M costs can account for over 29.5% of the total lifecycle costs of a FOWF.[4] FOWF components such as turbine blades, tower, floating platform, array, and export cables are subjected to varying and extreme loads during the course of their operation. This leads to reduced structural integrity of the component, which, if not inspected and rectified in due time, can result in failure and a subsequent loss of power production. Furthermore, deeper waters and harsh weather conditions can hinder the inspection activities especially where rope-access technicians and divers need to be involved, making it more time- and cost-intensive. It is also pertinent to mention that the costs associated with inspection activities can have a direct impact on the levelized cost of energy (LCOE), while the downtime incurred affects the annualized energy production (AEP). Hence, there is an opportunity for automation and robotics-based inspection of FOWFs with the goal of improving the operational efficiency, while also reducing the downtime and the costs incurred.[5] Furthermore, these robotic systems can reduce the need for manual inspections, therefore minimizing human risk, and collect and stream continuous high-quality data for better decision-making.[6] As FOWFs continue to grow in size and scale, robotics-based inspection could become increasingly attractive not only to ensure the reliability and safety of offshore assets but also due to economies of scale and projected shortages of competent O&M labor. While many robotic systems in the offshore oil and gas operations have been in operation,[7–9] their usage in the offshore wind farm industry has been relatively explored less. Previous studies in this domain have focused on exploring robotics-based inspection from various angles. For instance, Netland et al[10] have proposed the use of a robot inside the nacelle. The proposed robot moves on a rail and is able to conduct inspection with high-resolution camera, thermal sensor, and microphones. Simulation results show that the remote inspection leads to increased time- and production-based availability and a lower cost of energy. Such turbine-mounted robots, while assisting remote inspection, have limitations in terms of navigating certain parts of the internal turbine due to their limited range of motion and maneuverability. Furthermore, they may have limited payload capacity and flexibility in carrying diverse equipment and attaining feature-rich inspection data.[11]

The use of unmanned aerial vehicles (UAVs) for inspecting wind turbines has gained traction in recent years[12,13]. The turbine blades are prone to damage over the course of the project lifecycle. Timely inspection using UAVs can lead to early detection and maintenance that can increase the assets' lifecycle.[14] UAV-assisted videography can lead to identification and classification of damages and can determine the structural integrity of the asset.[15] The coordinated control of multiple UAVs and route optimization[16] can lead to a reduction in the inspection time of turbine blades. A cost estimation for a drone service provider is provided by Kabbabe Poleo et al,[17] where it is shown that using drones for inspecting offshore wind farms can result in cost reduction of up to 70%, when compared with that of a rope-access case. Furthermore, revenue lost due to downtime is reduced by up to 90%. For the subsea components of the offshore wind farms, remotely operated vehicles (ROVs) have been in commercial operations with an aim to reduce the need for time-intensive diving operations, improve inspection efficiency, and reduce downtime.[18–20] Based on site- and task-specific mobility and reliability considerations, ROVs can either be tethered to the launching vessel or untethered, where they can autonomously navigate underwater, inspect the asset, and return to the vessel for retrieval. Different classes of offshore ROVs exist ranging from low-cost observation class to advanced ROVs with increased automation, manipulation and cable burial capabilities.[21] In the case of a FOWF, the most relevant use-case is observation and work-class ROVs with visual sensors and light intervention capability for inspection of mooring lines, array cables, export cables, and turbine foundations. An extensive survey on the technical feasibility of ROVs is presented by McLean et al.[22] The development of a prototype ROV designed to be launched from an autonomous surface vessel (ASV) is presented by Gray et al.[23] Similarly, the hydrodynamic modeling and control strategy for an ROV that is launched from an ASV is presented by Zhao et al[24] where the feasibility for such a cooperative system is established. ROVs have also been shown to cost less and reduce deployment time for the inspection of wave energy converters as compared with that of the diver-assisted methods.[25]

While significant research has focused on the control, sensing, and data communication from UAVs and ROVs, there is a need to develop a framework to conduct cost-benefit assessment in order to analyze the financial implications of incorporating robotic systems in the floating offshore wind energy sector. Previous studies in this domain have focused on the feasibility of singular systems,[17,25] but there remains a gap in assessing the cost-benefit impact of incorporating a multi-robot platform (MRP) in a large-scale FOWF environment. To this end, the objective of this work is to develop a cost-benefit assessment framework to estimate the cost of an MRP and assess its impact on the operational expenditure (OPEX) and key performance metrics of a FOWF. The proposed MRP consists of a commercially available UAV and ROV with the functionality of inspecting assets on the turbine and underwater, respectively.

This paper is organized as follows: Section 2 describes the methodology employed in this study which includes the cost estimation for the MRP and the details of the O&M model. Section 3 presents the application of the cost estimation to a FOWF. The results obtained from the O&M model simulation are discussed in Section 4 along with the sensitivity analysis and the correlation matrix. This is followed by the conclusion in Section 5.

2 | METHODOLOGY

This section outlines the methodology employed in this study, beginning with an introduction to the cost estimation of robotics-based inspection of a FOWF. The operational cost of an MRP that could inspect different components of a FOWF is estimated. This cost is then taken as an input for an O&M cost model where different inspection scenarios are simulated for the lifecycle of the FOWF, which forms the basis of our work. Next, the simulation methodology is described followed by a formulation of the residual risk curve.

2.1 | Cost estimation

There exists different methods in literature to estimate costs for various offshore operations.[26,27] The top-down method, also known as analogous or parametric estimation, relies on historical data and comparisons with similar operations to derive an approximate cost estimate. In contrast, the bottom-up method involves breaking down an operation into smaller, manageable tasks or components followed by estimating costs at the task or component level. The former method is advantageous for providing quick and preliminary cost estimates, while the latter estimation is preferred for detailed and precise cost analysis. In this work, a combination of both methods is utilized wherein top-down costs of equipment have been estimated from the available data while bottom-up cost modeling is utilized in order to capture the various cost elements of an MRP inspecting a FOWF.

Recently, various conceptualizations of an MRP have been proposed in literature and industrial discourse with a focus towards their systems design, engineering, and commercial adoption.[28] In order to inspect different components of the FOWF, the proposed MRP in this work consists of a UAV with remote communication capability, and an ROV with tethered access to the MRP for effective and safe deployment. The UAV would inspect the blades and rotor hub on the turbine with a high-definition camera and a thermal sensor. The ROV would conduct inspection of the foundation, mooring lines, array, and export cables with videography. This is to mimic a simplified inspection scenario for the main components of a FOWF. The MRP serves as a hub, centralizing the inspection process by storing the acquired data onboard. It is assumed that the MRP is equipped with collision avoidance system, emergency shut-down mechanism, and fail-safe protocols. A visual illustration of such a scenario is shown in Figure 1.

A generalized formulation of the LCOE is stated in Equation (1) where r stands for the specified interest rate. t and n denote the time interval and the lifetime of the FOWF, respectively. The relevant metrics to be assessed are the OPEX and AEP. While the capital expenditure (CAPEX) pertains to the procurement and the installation of different components of the FOWF, the OPEX along with the AEP need to be forecasted for the total lifecycle of the FOWF and hence are dependent on the forecasting variables.

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \tag{1}$$

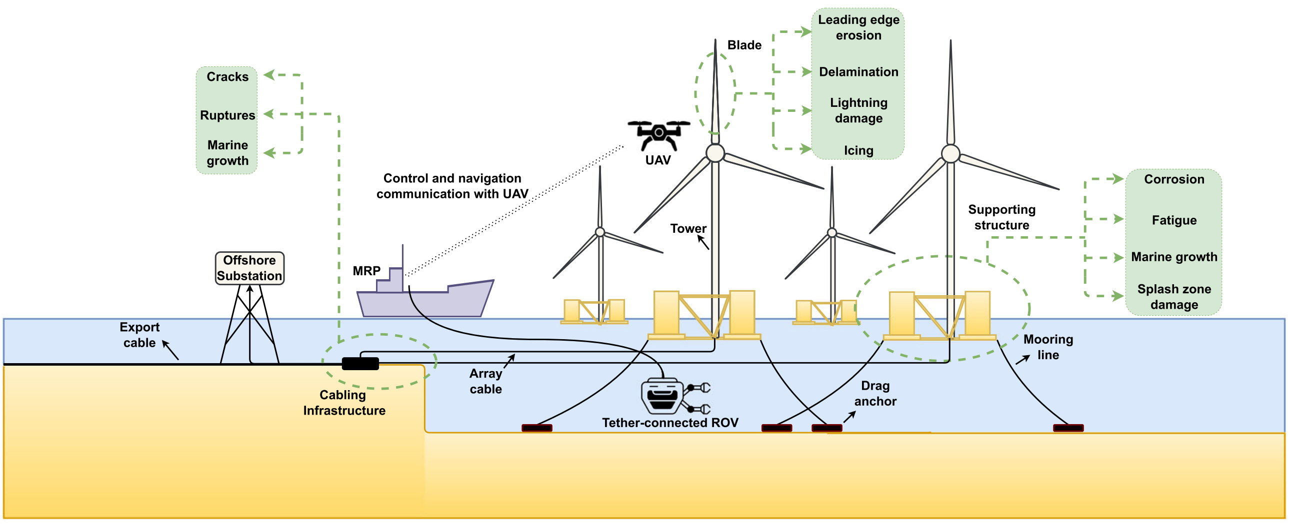

FIGURE 1 Illustration of the multi-robot platform based inspection of a floating offshore wind farm (FOWF). Typical damages on the FOWF components are exhibited in green blocks.

The OPEX consists of cost-contributing factors during the operational phase of the wind farm, where it primarily relates to the day rate of the vessel hired and any equipment needed to do the inspection, repairs, or replacement. In order to estimate the day rate of the MRP, contributing factors need to be defined that would be representative of the actual costs incurred during the inspection of the FOWF components. The formulation of the day rate for the MRP is shown by Equation (2):

$$Day\ rate = \sum_{k=1}^{m} (wf, eq, scd)k \tag{2}$$

where wf, eq, and scd stands for workforce, equipment, and secondary costs, respectively. k is the time unit pertaining to the duration of inspecting a certain component. These variables are further discussed below.

2.1.1 | Workforce costs

The workforce cost element consists of the salaries of the MRP operators and constitutes a major part of the total cost along with that of the MRP infrastructure. For this work, it is envisaged that the MRP would be based at an offshore support base in the vicinity of the FOWF from where it would transit to the turbine for inspection. The role of the operators would be to launch the UAV and ROV from the offshore support base along with acquisition and processing of the inspection data.

Estimating the workforce costs for offshore vessels can be achieved using various methods, each with its advantages and limitations. One commonly used method is the traditional "labor day rate", which calculates the cost per operator per day worked. Another approach is the use of "fixed pricing", which involves a fixed price for the entire team of operators for a specified period, regardless of the number of days worked. Additionally, some researchers have proposed a "task-based pricing" method, which accounts for the different tasks and activities performed by the operators during their shift. In this work, fixed pricing in terms of monthly salaries of the MRP operators is utilized where a fixed number of workforce comes as part of the MRP and remains available for the duration of the inspection. As offshore operations are typically longer in duration owing to the weather window availability, hence, fixed pricing mechanism can be utilized to hire MRP and conduct the inspection tasks during a certain period of the year.

2.1.2 | Equipment costs

The equipment costs relate to the UAVs, ROVs, and their subsystems such as sensors and spare parts. The UAV consists of an RGB and a thermal camera with which it would be able to scan the turbine blades. It would have remote communication capability where the operator of the MRP would fly it from the offshore support base. The ROV would be tethered to the MRP while inspecting the foundation, mooring lines, and cabling infrastructure.

While most of the relevant cost data from actual operations are confidential, estimation is done based on the available literature, commercial quotations, and expert elicitation. The readily available models of UAV and ROV, with visual inspection functionality, have been selected as listed in Table 1.

2.1.3 | Secondary costs

The secondary costs include soft costs such as administration, consumables, and insurance costs. While these are dependent upon the type of equipment utilized and the specific inspection scenarios, an estimation based on annual contract length is conducted using the available data.[29] Furthermore, indirect costs to the tune of 10% of the total operating costs have been included to account for any additional expenditure. A breakdown of the total cost estimation is shown in Table 1.

2.2 | O&M model

There exists different O&M models in literature[32] with a focus on understanding the underlying O&M mechanism along with using such models as decision-making tools to arrive at the right design choices. In this work, WOMBAT (Windfarm Operations and Maintenance cost-Benefit Analysis Tool)[33] is used as the O&M tool to simulate the lifecycle of the FOWF. WOMBAT is a discrete-event simulation tool with the function to analyze the O&M phase of a wind farm from a technical and financial viewpoint. It has high component-level granularity, where the *repair manager*

TABLE 1 Estimation of the day rate for the multi-robot platform (MRP).

Cost element	Cost ($)	Notes
UAV	8000	Based on the quote of a DJI™ Matrice 300 UAV
Thermal sensor for UAV	600	Based on the quote of a FLIR™ thermal camera
ROV	55,000	Based on the quote of a VideoRay™ Pro4 ROV
Workforce	375,000	Based on 2020 nominal U.S. salary rate[a]
MRP soft costs[b]	150,000	Estimated from Kaiser et al[30] and Ioannou et al.[29]
Other consumables	50,000	Adjusted from Kabbabe Poleo et al.[17]
Total operating cost	638,600	Sum of the preceding costs
Anticipated revenue	159,650	Revenue rate of 25% for the O&M operator
Indirect costs	63,860	10% of the total operating cost
MRP vessel infrastructure	2500	Day rate of the vessel excluding any capital costs, adjusted from *Guide to a Floating Offshore Wind Farm*[31]
Estimated MRP day rate	5815	Calculated for 260 annual working days

Abbreviations: MRP, multi-robot platform; ROV, remotely operated vehicle; UAV, unmanned aerial vehicle.
[a]A workforce of 5 MRP operators is assumed with 75,000$ annual rate per person.
[b]Including administration costs.

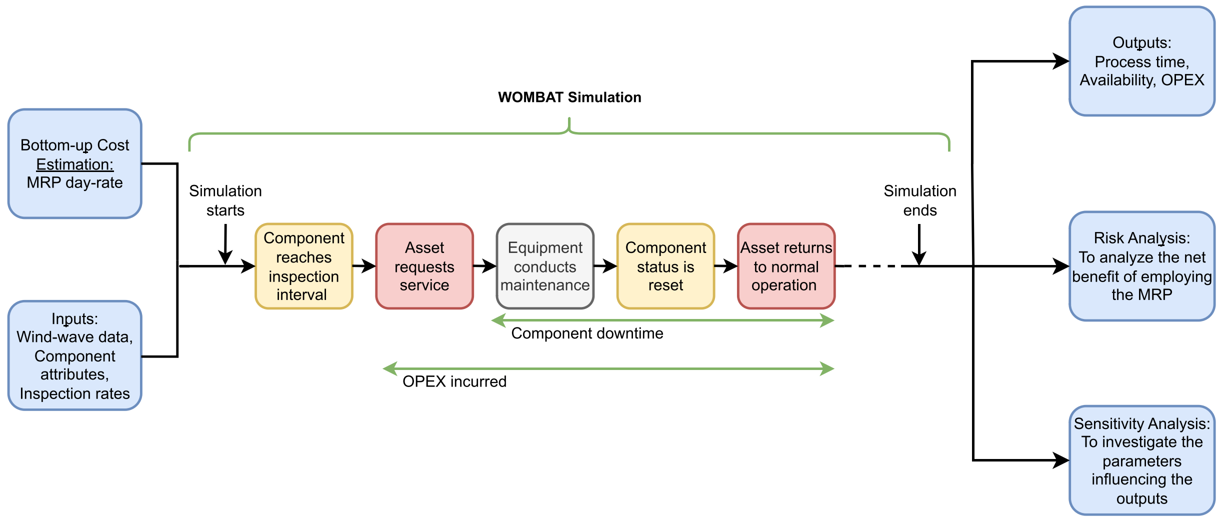

FIGURE 2 Illustration of the operations and maintenance (O&M) model methodology. Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) simulation details adjusted from Hammond et al.[33]

assigns equipment such as MRP or crew transfer vessel (CTV) based on the failure rates and maintenance intervals of a specific component. The way the simulation runs is that when a component sends request for inspection then the time needed to reach the site and the time needed to conduct the inspection is calculated. If this time falls within the next weather window availability, then the inspection is conducted. If not, then the MRP waits until the weather window becomes available. This is done in order to make sure that the vessel does not have to go back to the port in the middle of the inspection. Furthermore, after conducting one inspection, the loop for the next component inspection is run again to find the next weather window availability. The weather window availability can affect the accrued costs and process time of an inspection task. An illustration of the complete simulation methodology employed in this work is shown in Figure 2 and is detailed in the steps below:

1) Day rate of the MRP is estimated based on bottom-up cost modeling.
2) Parameters pertaining to the FOWF site, inspection components, and the MRP are added as inputs into the WOMBAT model.
3) After initialization, the simulation is run based on the site-specific wind-wave time series.
4) When an inspection interval is reached, a request is passed by the asset to the *repair manager*. The *repair manager* sends on the MRP which conducts inspection conditional to the weather window availability. After the inspection is completed, the component returns to the normal operation.
5) The outputs in terms of OPEX and process time are calculated for postprocessing.

6) The steps 1 to 5 are repeated for the baseline case, and the difference in the logged outputs is determined.
7) Next, sensitivity analysis is conducted by varying the key parameters in step 2, and the resultant effect on OPEX and process time is analyzed.

2.3 | Residual risk

The cost-benefit ramifications of the MRP are further assessed by calculating the residual risk, which is defined as follows:

$$R_r = P(L_b - L_{MRP}) - C_o \tag{3}$$

where P relates to probability of attaining a certain value of OPEX. The values are defined as L_b and L_{MRP} where the former pertains to the baseline OPEX and the latter is the OPEX incurred by the MRP. In general, the risk is defined as the product of probability and consequence. Here, the consequence is defined as the OPEX incurred while the probability takes into account the inherent uncertainty of the OPEX estimation from the WOMBAT simulation and hence gives a broader indication into the feasibility of incorporating MRP for the inspection as compared with the baseline manned inspection. C_o is the operating cost of the MRP which is the product of day rate of the MRP and the total number of yearly working days excluding the inspection days. In Equation (3), the residual risk is defined in a way that the MRP is a net benefit if the residual risk is positive and vice versa.

3 | APPLICATION TO A FOWF

The cost estimation presented in this work is applied to a hypothetical FOWF located off the West coast of Ireland. The West coast has been mapped extensively and computations have shown that it incurs the lowest LCOE for floating offshore wind as compared to that of the other Irish coasts.[34] The hourly wind-wave data for the site are obtained from Copernicus ERA5 database.[35] The specification of the proposed 1.5GW FOWF is listed in Table 2 where the IEA 15MW turbine has been selected as the reference.[36] In order to analyze the O&M phase of the FOWF, inspection time and duration for the selected components need to be specified. Typically, the O&M contractor sets a schedule for one or two inspections per year. By increasing the frequency of inspections, unplanned repairs can be minimized. However, planning for more frequent inspections based on fixed time intervals or a specific reliability threshold may entail higher expenses.[37] In this study, we consider the annual inspection of five components namely: (a) wind turbine blades, (b) supporting structure which includes the foundation and the splash zone, (c) mooring lines, (d) array cables, and (e) export cables. The UAV launched by the MRP would inspect the blades, while the observation-class ROV would inspect the remaining subsea components. The inspection is restricted to visually capture the external surface of the components and store the imaging and videography data onboard. The time required to inspect a certain component is included in the simulation where the initial values are taken from the available data[17,25] which are then varied in the sensitivity analysis to make the findings more robust. Failure rates and resource requirements for 350 offshore wind turbines have been presented in Carroll et al,[38] where three different O&M operations have been highlighted: minor and major repair and major replacement which gives an overview of the costs and time duration associated with conducting component-wise O&M tasks. In this work, only annual inspection of these components has been considered as it includes the most relevant activities that could be replaced by the proposed MRP.

The baseline scenario is represented by inspecting the components by rope-access technicians and divers from a CTV. Different reference studies on the validation of O&M tools have detailed the cost estimation of CTVs.[40] The initial day rate of the CTV is obtained from the recently published *Guide to a Floating Offshore Wind Farm*[31] which amounts to be £2000. This is converted into dollars with a base conversion rate of 2023, and the day rate of the technicians and divers is added to it. For the CTV, a total of eight crew members are considered for one inspection operation. The final day rate for the CTV is estimated to be $4100. The selected values pertaining to the inspection and the WOMBAT simulation parameters are listed in Table 3.

4 | RESULTS

Table 4 corresponds to the incurred inspection-based OPEX during the lifecycle of the FOWF which increases by 51.1% in the case of utilizing three MRPs as compared with that of the baseline case. A value of 4200.28$ per MW per year is obtained which includes inspection of the five components of the FOWF. On the other hand, this leads to a 58.3% improvement in the time-to-completion which pertains to the total number of hours from the time of inspection request by a component to the time-of-completion of the inspection. The OPEX reduces by 50.6% if only one MRP is utilized, but this leads to a slightly higher time-to-completion, that is, an increment of 17.2%. This is due to fact that a single MRP has

TABLE 2 Specification of the FOWF.

Description	Value
FOWF location	West Coast, IE
FOWF size	1.5 GW
Project lifecycle	20 years
Number of turbines	100
WT model	IEA 15MW RWT
WT rated power	15 MW
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
WT rotor diameter	240 m
WT rated wind speed	10.6 m/s
Floating platform	DeepCwind[39]
Floating platform type	Semisubmersible
Number of mooring lines	3
Unstretched mooring line length	835.5 m[39]
Water depth	200 m

Abbreviation: FOWF, floating offshore wind farm; WT, wind turbine.

TABLE 3 WOMBAT simulation input parameters.

Description	Units	CTV	MRP	Notes
Start year	-	1996	1996	Start year of the simulation (inclusive)
End year	-	2015	2015	Final year of the simulation (inclusive)
Work day start	AM	07:00	07:00	Starting hour for a typical work shift (inclusive)
Work day end	PM	19:00	19:00	Ending hour for a typical work shift (inclusive)
Inflation rate	%	1	1	Varied between 0.5 and 2
Significant wave height	m	2.5	2.5	Maximum wave height for safe operations
Maximum operating wind speed	m/s	20	20	Maximum wind speed limit for safe operations
Number of crew	-	8	5	These values are taken for preliminary day rate estimation. These are further increased by 35% in the sensitivity analysis.
Time required to inspect components	-			Adjusted from Remouit et al[25] and Kabbabe Poleo et al.[17] Varied by $\pm$ 50% in the sensitivity analysis.
Blades	hr	3	0.75	
Supporting structure	hr	3	0.75	
Array cables	hr	4.5	1	
Export cable	hr	4.5	1	
Mooring lines	hr	3	1	

Abbreviations: CTV, crew transfer vessel; MRP, multi-robot platform; WOMBAT, Windfarm Operations and Maintenance cost-Benefit Analysis Tool.

to conduct inspection of each component on a first-in-first-out basis as compared with multiple MRPs which can transit to multiple sites as the requests come in. The OPEX breakdown, as shown in Figure 3, shows that inspection of the blades and mooring lines constitutes a major proportion of the OPEX, while inspection of the supporting structures, array, and export cables is not as costly. It is pertinent to mention here that only *inspection* of the components is simulated in this study, and hence, this OPEX is not reflective of major repairs and expensive replacements of components that could correspond to that of an actual FOWF.

Figure 4 shows the residual risk curve where it can be seen that the MRP is a net benefit up until the probability of 0.73 which is the breakeven point. If we reduce the day rate by 20% then this breakeven point moves further to the right to the value of 0.57, which is depicted by the blue line in the plot. This shows that the residual risk increases for lower values of the MRP day rates which means that further net benefit can be attained if any of the values of the cost elements in Table 1 are to reduce. This bodes well for the future developments in this domain where

TABLE 4 OPEX and time-to-completion variation between baseline and MRP cases.

Metric	Baseline (3 CTVs)	MRPs (3)	MRPs (1)
OPEX ($/MW/year)	2779.83	4200.28	1373.11
OPEX variation	-	+51.1%	−50.6%
Time-to-completion variation	-	−58.3%	+17.2%

Abbreviations: CTV, crew transfer vessel; MRP, multi-robot platform; OPEX, operational expenditure.

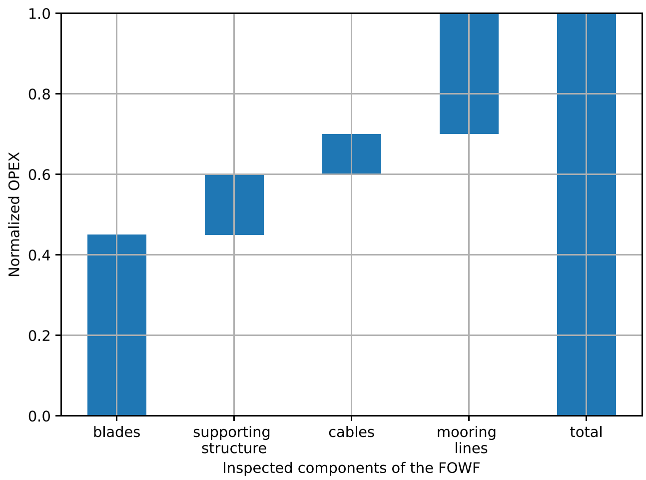

FIGURE 3 Component-wise operational expenditure (OPEX) breakdown. The category "cables" include both array and export cables.

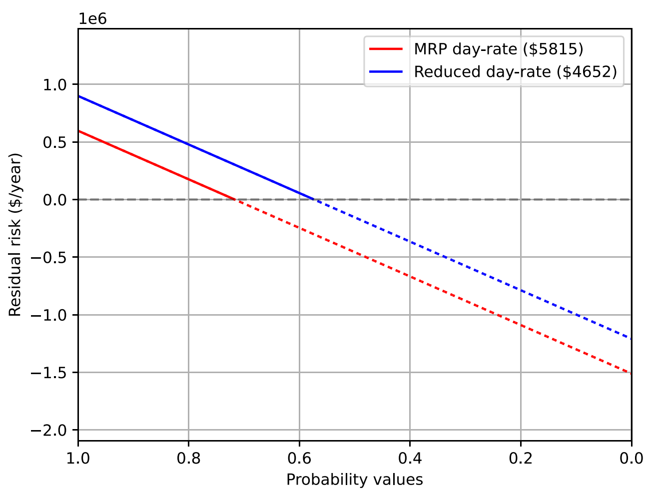

FIGURE 4 Residual risk plot. The dashed and dotted lines show the range where the multi-robot platform (MRP) is a net positive and a net negative investment, respectively.

innovation leading to further depreciation in the prices of robotic systems and the associated vessel costs can make the MRP a net positive investment.

Results can differ based on the choice of cost parameters in Table 1. In this work, a simplified scenario with the most readily available cost elements is chosen, but there remains possibility of extending the bottom-up model by including more detailed cost elements. Furthermore, the increase in OPEX also corresponds to higher CAPEX incurred on the type and functionality of the selected UAV and ROV. In future, this CAPEX could decrease with the advent of systems with higher technology readiness levels (TRLs) and economies of scale, which can result in further improvement in the metrics of OPEX and time-to-completion.

4.1 | Sensitivity analysis

The sensitivity analysis represents a crucial aspect of evaluating the impact of variations in the different parameters on key performance metrics, that is, inspection-based OPEX and the time-to-completion. In the depicted graph in Figure 5, OPEX ($/MW/year) is plotted on the *x*-axis, while inflation rate, MRP day rate, design life, port distance, and the number of MRPs are displayed on the *y*-axis. This is done to assess the effect on OPEX by varying the key parameters. For instance, a 35% increase in the MRP day rate, from a baseline value of $5815 to $7850.25, results in more than $1500/MW/year increase in OPEX. Similarly, an increase in the number of MRPs from an initial value of 3 to 12 leads to a drastic rise in the OPEX. It is pertinent to mention that this rise is not proportional as more components are inspected in a shorter duration of time by utilizing the weather window availability which reduces the number of transit days needed. On the other hand, prolonging the design life from 20 to 25 years corresponds to a relatively minor increase in the OPEX. It can be seen that the number of MRPs, day rate, and the inflation rate have the largest impact on the OPEX. This shows that the cost elements associated with the MRP account for a significant proportion of the overall increase in the inspection-based OPEX.

Similarly, Figure 6 shows the sensitivity analysis results for the time-to-completion metric. It can be seen that the number of MRPs is indirectly proportional to the time-to-completion metric. This means that an increase in the number of MRPs can result in quicker inspection but this comes at an expense of higher OPEX, as shown in Figure 5. Further reduction in time-to-completion can be attained by reducing the inspection time of components. The mobilization time also results in an increase in the metric, while the port distance has a relatively minor effect on the time-to-completion.

4.2 | Correlation matrix

The correlation matrix analysis is a powerful statistical tool that measures the strength and direction of linear relationships between multiple variables, in this case OPEX and the MRP attributes. It is essential to conduct such an analysis to identify potential patterns, dependencies, and redundancies, which can help improve efficiency, reduce costs, and optimize overall operations. The correlation matrix for a selected number of parameters is shown in Figure 7.

Starting from the top left, a negative correlation can be seen between the number of MRPs and the time-to-completion. This relates to the fact that a large number of MRPs can conduct inspection in a shorter duration of time. A positive correlation of 1 between OPEX and MRPs implies that an increase in the number of MRPs typically corresponds with a higher OPEX which is a function of the day rate of the MRP. Similarly, the positive correlation of 0.88 between task completion rate and MRPs indicates that a higher number of MRPs is associated with increased task completion rate. This corresponds to the monthly average tasks completed which reduces if the number of MRPs are reduced where some of the

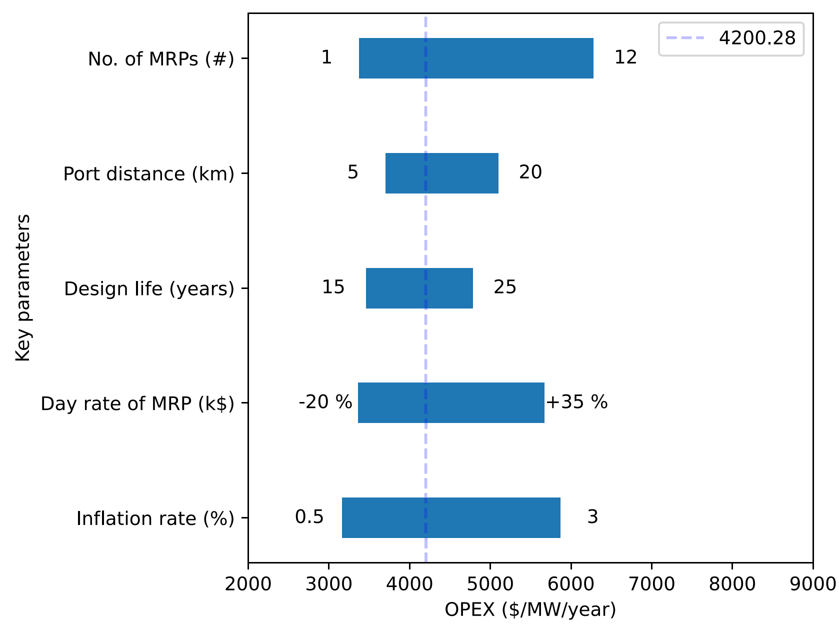

FIGURE 5 Sensitivity analysis for the operational expenditure (OPEX) metric. The dashed line shows the preliminary OPEX which is selected as the reference for the sensitivity analysis.

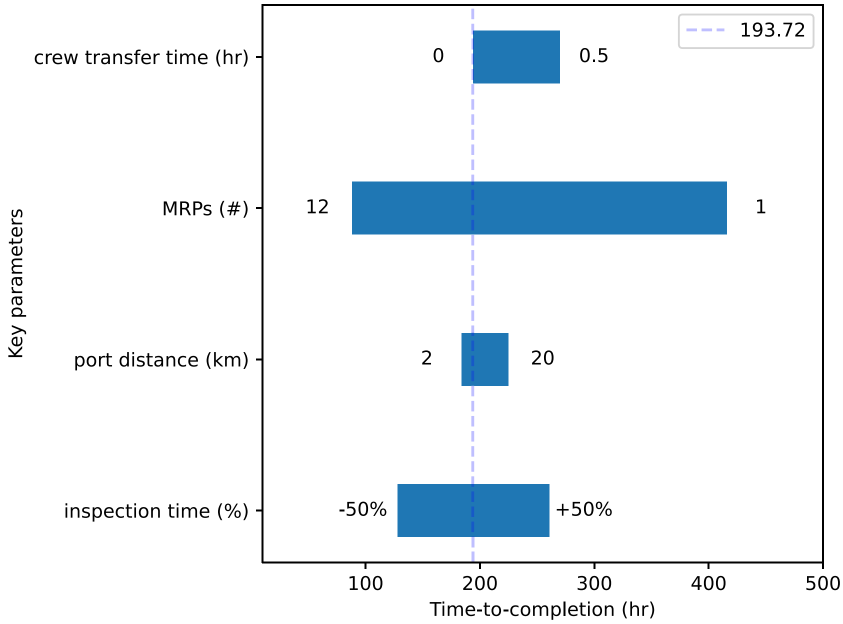

FIGURE 6 Sensitivity analysis for the time-to-completion metric. The dashed line shows the preliminary time-to-completion which is selected as the reference for the sensitivity analysis.

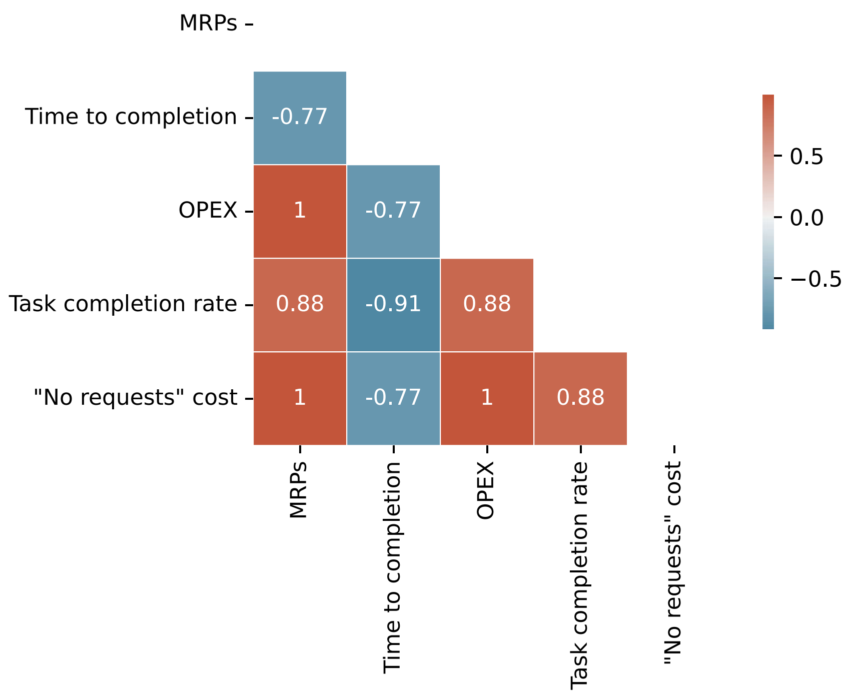

FIGURE 7 Correlation matrix of five key parameters. The red colors correspond to a positive correlation, and the blue colors correspond to a negative correlation.

tasks initiated in one month are completed in the next month. This also highlights the operational benefits of increasing the number of MRPs but at the expense of a corresponding increase in OPEX.

Lastly, there is a strong positive correlation between number of MRPs and the "no requests" cost, which pertains to the cost incurred when the MRPs are available but there are no inspection tasks to be completed. This indicates that "no requests" costs can result in higher OPEX values when it is a function of the day rate which corresponds to a fixed number of working days simulated in this study. Instead of day rate, a fixed term inspection contract could result in a lower overhead in the "no requests" element.

In summary, the correlation matrix analysis unveils valuable insights into the relationships between inspection time, OPEX, and the MRP attributes. It suggests that efforts to minimize the day rate could lead to a lower OPEX, thereby improving MRP competitiveness. It also demonstrates that optimizing the number of MRPs can lead to both an increased task completion rate and decreased time-to-completion, which are critical factors for devising an optimal O&M strategy. By understanding these relationships and adjusting the parameters accordingly, decision-makers can optimize resource allocation and drive operational improvements.

5 | CONCLUSION

This study presents cost estimation for an offshore MRP and its impact on the OPEX and process time of inspecting specific components of a 1.5GW FOWF consisting of 100 turbines. The newly developed WOMBAT is employed as the O&M simulation tool. The outputs pertaining to various techno-economic performance metrics are analyzed and sensitivity analysis is conducted to identify the variables that have a key effect on these metrics. The analysis shows that there is a potential for inspection time reduction by the use of MRP. This reduction has dependency on the MRP attributes and the time taken by the UAV or ROV to conduct inspection. Considering that incurred cost, inspection time, and data acquisition are the main enablers of adoption of the MRP, further refinement of cost estimation and its validation could pave way for wide-scale adoption of robotics in the floating wind energy sector. In future, the perceived CAPEX depreciation in prices of UAV and ROV could also result in lower values of the day rates.

In comparison with CTV-based inspection, the MRP incurs a higher OPEX of 51.1% but accumulates a lower time-to-completion rate by 58.3%. The OPEX reduces by 50.6% if only one MRP is used with a relatively lower increase of 17.2% in the time-to-completion metric. This shows that initially smaller number of MRPs could be utilized which would reduce the OPEX but at an expense of increased inspection duration. Sensitivity analysis shows that the variables including the number of MRPs, day rate, and the inflation rate have the highest impact on the OPEX. On the other hand, the number of MRPs and the component inspection duration have the highest impact on the overall time-to-completion. Furthermore, correlation analysis shows that transitioning from the industrial standard of specified annual working days to fixed term O&M contracts can reduce the OPEX as well.

Such a cost-benefit framework can be used by the MRP operators or FOWF developers in order to assess and optimise the suitability of robotics based inspections. In future, conducting sensitivity analysis of the cost estimation variables by including O&M term contracts and analyzing its effect on the OPEX could result in attaining useful insights regarding the MRP use cases. The inherent flexibility of the WOMBAT tool could be leveraged to simulate a variety of FOWF scenarios and across a large parameter horizon in order to arrive at a generalized framework for the MRP cost estimation. Furthermore, extending this analysis by including major repairs, replacements, and CAPEX data resulting in a realistic value of the LCOE should make the results more resourceful, and representative of an actual FOWF.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Bilgili M, Alphan H. Global growth in offshore wind turbine technology. *Clean Technol Environ Policy*. 2022;24(7):2215-2227. https://doi.org/10.1007/s10098-022-02314-0
2. Bento N, Fontes M. Emergence of floating offshore wind energy: technology and industry. *Renew Sustain Energy Rev*. 2019;99(February 2018):66-82. https://doi.org/10.1016/j.rser.2018.09.035
3. Rinaldi G, Thies PR, Johanning L. Current status and future trends in the operation and maintenance of offshore wind turbines: a review. *Energies*. 2021;14(9):2484.
4. Stehly T, Beiter P, Duffy P. 2019 cost of wind energy review; 2020.
5. Khalid O, Hao G, Desmond C, Macdonald H, McAuliffe FD, Dooly G, Hu W. Applications of robotics in floating offshore wind farm operations and maintenance: literature review and trends. *Wind Energy*. 2022;25(11):1880-1899. https://doi.org/10.1002/we.2773
6. Mitchell D, Blanche J, Harper S, Lim T, Gupta R, Zaki O, Tang W, Robu V, Watson S, Flynn D. A review: challenges and opportunities for artificial intelligence and robotics in the offshore wind sector. *Energy and AI*. 2022;8:100146. https://doi.org/10.1016/j.egyai.2022.100146
7. Shukla A, Karki H. Application of robotics in onshore oil and gas industry—a review part I. *Robot Auton Syst*. 2016;75:490-507. https://doi.org/10.1016/j.robot.2015.09.012
8. Shukla A, Karki H. Application of robotics in offshore oil and gas industry—a review part II. *Robot Auton Syst*. 2016;75:508-524. https://doi.org/10.1016/j.robot.2015.09.013
9. Wen F, Pray J, McSweeney K, Gu H. Emerging inspection technologies—enabling remote surveys/inspections. Day 1 mon, may 06, 2019, OTC, https://doi.org/10.4043/29450-ms; 2019.
10. Netland O, Sperstad IB, Hofmann M, Skavhaug A. Cost-benefit evaluation of remote inspection of offshore wind farms by simulating the operation and maintenance phase. In: Energy procedia, Vol. 53. Elsevier B.V.; 2014:239-247. https://doi.org/10.1016/j.egypro.2014.07.233
11. Schmidt D, Berns K. Climbing robots for maintenance and inspections of vertical structures—a survey of design aspects and technologies. *Robot Auton Syst*. 2013;61:1288-1305. https://doi.org/10.1016/j.robot.2013.09.002
12. Pierce SG, Burnham KC, Zhang D, McDonald L, MacLeod CN, Dobie G, Summan R, McMahon D. Quantitative inspection of wind turbine blades using UAV deployed photogrammetry. In: 9th European Workshop on Structural Health Monitoring (EWHM 2018); 2018:1-12.
13. Schfer BE, Picchi D, Engelhardt T, Abel D. Multicopter unmanned aerial vehicle for automated inspection of wind turbines. In: 2016 24th Mediterranean Conference on Control and Automation (MED); 2016:244-249.
14. Nordin M, Sharma S, Khan A, Gianni M, Rajendran S, Sutton R. Collaborative unmanned vehicles for inspection, maintenance, and repairs of offshore wind turbines. *Drones*. 2022;6(6):137. https://doi.org/10.3390/drones6060137
15. Khadka A, Fick B, Afshar A, Tavakoli M, Baqersad J. Non-contact vibration monitoring of rotating wind turbines using a semi-autonomous UAV. *Mech Syst Sig Process*. 2020;138:106446. https://doi.org/10.1016/j.ymssp.2019.106446
16. Chung H-M, Maharjan S, Zhang Y, Eliassen F, Strunz K. Placement and routing optimization for automated inspection with UAVs: a study in offshore wind farm. *IEEE Trans Ind Inform*. 2021;17:3032-3043.
17. Kabbabe Poleo K, Crowther WJ, Barnes M. Estimating the impact of drone-based inspection on the levelised cost of electricity for offshore wind farms. *Results Eng*. 2021;9(October 2020):100201. https://doi.org/10.1016/j.rineng.2021.100201
18. Restivo A, Brune M. Removing marine growth using an ROV with cavitation technology. In: Offshore Technology Conference, Vol. 1; 2016:271-293. p. D011S006R005. OTC.
19. Fahrni L, Thies PR, Johanning L, Cowles J. Scope and feasibility of autonomous robotic subsea intervention systems for offshore inspection, maintenance and repair. 771–778; 2018.
20. Capocci R, Dooly G, Toal D. Offshore renewable energy systems: solutions for reduction in operational costs; 2017.
21. Schiaretti M, Chen L, Negenborn RR. Survey on autonomous surface vessels: part I—a new detailed definition of autonomy levels. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Vol. 10572 LNCS; 2017:219-233.
22. McLean DL, Parsons MJG, Gates AR, et al. Enhancing the scientific value of industry remotely operated vehicles (ROVs) in our oceans. *Front Marine Sci*. 2020;7:220.
23. Gray A, Schwartz E. Anglerfish: an ASV controlled ROV. https://www.mil.ufl.edu/publications/fcrar16/AndyGrayAngler-FishFCRAR2016,_May_03_2016.pdf, 105–110; 2016.
24. Zhao C, Thies P, Lars J, Cowles J. ROV launch and recovery from an unmanned autonomous surface vessel hydrodynamic modelling and system integration. *Ocean Eng*. 2021;232:109019. https://doi.org/10.1016/j.oceaneng.2021.109019
25. Rmouit F, Chatzigiannakou MA, Bender A, Temiz I, Sundberg J, Engstrm J. Deployment and maintenance of wave energy converters at the Lysekil research site: a comparative study on the use of divers and remotely-operated vehicles. *J Marine Sci Eng*. 2018;6:1-21.
26. Kaiser MJ. The role of factor and activity-based models in offshore operating cost estimation. *J Petrol Sci Eng*. 2019;174:1062-1092. https://doi.org/10.1016/j.petrol.2018.10.093
27. Gonzalez-Rodriguez AG. Review of offshore wind farm cost components. *Energy Sustain Develop*. 2017;37:10-19. https://doi.org/10.1016/j.esd.2016.12.001
28. Bernardini S, Jovan F, Jiang Z, Watson S, Moradi P, Richardson T, Sadeghian R, Sareh S. A multi-robot platform for the autonomous operation and maintenance of offshore wind farms blue sky ideas track. In: Autonomous Agents and Multi-Agent Systems (AAMAS), Vol. 2020; 2020:1696-1700.
29. Ioannou A, Angus A, Brennan F. A lifecycle techno-economic model of offshore wind energy for different entry and exit instances. *Appl Energy*. 2018;221:406-424. https://doi.org/10.1016/j.apenergy.2018.03.143
30. Kaiser MJ, Snyder BF. Modeling offshore wind installation vessel day-rates in the united states. *Maritime Econ Logist*. 2012;14:220-248.
31. Guide to a Floating Offshore Wind Farm. Wind farm costs. https://guidetofloatingoffshorewind.com/#, Accessed on 02/04/2023; 2023.
32. Welte TM, Sperstad IB, Halvorsen-Weare EE, Netland O, Nonås LM, Stålhane M. Operation and maintenance modelling. *Offshore Wind Energy Technology*: John Wiley & Sons, Ltd; 2018:269-303. https://doi.org/10.1002/9781119097808.ch7

33. Hammond R, Cooperman A. Windfarm operations and maintenance cost-benefit analysis tool (wombat). *Tech. Rep.*, National Renewable Energy Lab. (NREL); 2022. https://www.osti.gov/biblio/1894867
34. Martinez A, Iglesias G. Site selection of floating offshore wind through the levelised cost of energy: A case study in ireland. *Energy Convers Manag*. 2022;266:115802. https://doi.org/10.1016/j.enconman.2022.115802
35. Hersbach H, Bell B, Berrisford P, et al. The ERA5 global reanalysis. *Quart J Royal Meteorol Soc*. 2020;146(730):1999-2049. https://doi.org/10.1002/qj.3803
36. Gaertner E, Rinker J, Sethuraman L, et al. Definition of the IEA 15-megawatt offshore reference wind turbine. International Energy Agency, NREL/TP-75698, https://www.nrel.gov/docs/fy20osti/75698.pdf; 2020.
37. Asgarpour M, Dalsgaard Sorensen J. O&m modeling of offshore wind farms – state of the art and future developments. In: 2016 Annual Reliability and Maintainability Symposium (RAMS); 2016:1-6.
38. Carroll J, McDonald A, McMillan D. Failure rate, repair time and unscheduled o&m cost analysis of offshore wind turbines. *Wind Energy*. 2013;2013:1-20.
39. Robertson A, Jonkman J, Masciola M, Song H, Goupee A, Coulling A, Luan C. Definition of the semisubmersible floating system for phase II of OC4. *Tech. Rep.*, Office of Scientific and Technical Information (OSTI); 2014. https://doi.org/10.2172/1155123
40. Dinwoodie I, McMillan D. Testing the robustness of optimal vessel fleet selection for operation and maintenance of offshore wind farms. *Ocean Eng*. 2017;145:334-343.

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