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Comparison of Operation and Maintenance of Floating 14 MW Turbines and Twin 10 MW Turbines

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Turbine ratings in the past decade have grown unexpectedly fast. In 2021, Siemens Gamesa and GE revealed their new 14 MW turbine models, and it is predicted that this is not yet the rating limit that turbines can reach. Increased turbine ratings can also be achieved by putting two turbines on a single foundation. This study analyzes how operation and maintenance (O&M) would differ if a floating wind farm had twin 10 MW turbines installed on each substructure, instead of a single 14 MW turbine. This study demonstrates how the strategic O&M simulation tool COMPASS *can be used to perform this comparison. Assumptions regarding the O&M of twin turbines were estimated with the major floating twin turbine developer Hexicon AB. This study analyzed four cases—a case with 35 twin 10 MW turbines, and three cases with 50 single 14 MW turbines—to understand the potential effect of increased consumable costs, spare part lead times, and maintenance durations. All cases had the same wind farm capacity of 700 MW. The results show that O&M for cases with single turbines is at least 4.5% more expensive than the case with twin turbines. The case with twin turbines also resulted in a higher availability than any other case. Additionally, results showed that operational expenditure (OPEX) for the cases with single turbines is at least 6.0% higher in scenarios with single turbines than in the twin turbine scenario. The biggest cost contributors to the difference between scenarios were craft costs, particularly cable laying vessels and tugs. Due to the higher number of cables required for the scenario with single turbines, there is more frequent mobilization of cable vessels for cable repairs.* [DOI: 10.1115/1.4062413]

Keywords: operation and maintenance, twin turbines, floating wind, spare part availability, net-zero energy, offshore engineering, offshore safety and reliability, operations and maintenance of components, plant operations, maintenance, engineering, modifications, and life cycle, reliability of offshore structures and pipelines, renewable energy, scenarios, simulation, wind energy, wind turbines

1 Introduction

The size of offshore wind turbines has been growing rapidly in the last decade. The maximum turbine rating of fully commissioned offshore wind turbines in the UK is 9.6 MW at the time of writing [1]. Siemens Gamesa and GE have separately launched 14 MW wind turbines in 2021 and the next year Vestas announced their new 15 MW wind turbine. Even 15 MW is not likely to be the limit of what a turbine rating can reach. Turbine component costs and sizes change with turbine rating, and the costs of blades increase not linearly but exponentially [2]. The current heavy lift vessel market is not yet ready for such a sharp increase in size and weight of the turbines too. This introduces a challenge not only for construction but also for the operation and maintenance (O&M) of these turbines. Is it practical to keep increasing the turbine rating or is it better to achieve the same turbine rating by installing twin turbines on a single platform? This work investigates the difference between single and twin turbines from the perspective of O&M. Spare part lead times and costs, maintenance frequencies and durations are all expected to be affected by an increase in turbine rating. This study uses the Offshore Renewable Energy (ORE) Catapult's O&M simulation tool COMPASS to analyze the effects of these differences on key performance indicators (KPIs) such as cost, time availability, energy availability, and vessel usage. A recent study modeled the O&M of multi-rotor systems using the Strathclyde University offshore wind operational expenditure (OPEX) model and attempted to find an optimal crew transfer vessel (CTV) fleet for a farm with 1, 10, and 40 multi-rotor systems [3]. There were, however, few drawbacks of that work. First, the multi-rotor system was modeled as two turbines put in the same location, meaning they are not seen as a single asset by simulation software. In reality, there will be components that multiple rotors will share, such as a foundation or a transformer, so it is important to model the synergy between rotors and shared components.

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Second, the work only includes unscheduled minor repairs, however in reality, unscheduled works may occur together with scheduled works as well as minor failures that can happen together with major failures. For a thorough analysis, all types of maintenance activities should be considered. Third, the multi-rotor system with 45 rotors looked at in that work, has not been tested in the lab and hence has a technology readiness level 3 or below. Because the concept presented in that study is in the research state, it may still undergo alternations to the design and the way that multi-rotor system operates may change as well. Additionally, their work also uses only CTVs, which would need to return to port every time the shift of personnel finishes, and no other vessels are taken into account. Lastly, their work assumes that in the case of a failure on one turbine, the other turbines stay operational, this may not always be the case for other multi-rotor turbine designs. The current study describes the use of COMPASS for simulating twin turbines and shows how it addresses the drawbacks of existing research. This work then compares the O&M of twin turbines and single turbines using COMPASS.

Two wind farms are considered in this study: a farm with twin (TW) 10 MW turbines and a farm with single (SL) 14 MW turbines, where both farms would have the same total installed capacity. Floating semi-submersible substructures are assumed in both wind farms. Assumptions used in this study were consulted with the major floating wind twin turbine developer Hexicon AB which has recently been allocated a contract for difference [4]. There are a handful of studies which have analyzed the O&M of floating wind farms before [5], however none of them modeled twin turbines. There is also very limited and conflicting information about tow-to-port operation constraints. Inputs related to tow-to-port operations were consulted with Hexicon AB and are published here. COMPASS has been previously used to model a floating wind farm that uses a jack-up vessel for major maintenance activities [6]. Recent developments in the tool have allowed modeling of tow-to-port operations for major maintenance. Previous work has demonstrated the use of O&M simulation tools for assessing the two-to-port strategy, however at the time of writing, there are no simulation tools other than COMPASS that can model tow-to-port operations of multi-rotor floating turbines.

2 Materials and Methods

2.1 COMPASS Tool Overview. COMPASS is a strategic O&M simulation tool. It can model the full lifetime of a wind farm and estimate KPIs associated with its operation. COMPASS breaks down a full lifetime of a farm into a series of 1 h time-steps. For example, 1 year of farm operation would be modeled as 8760 time-steps in COMPASS. At certain time-steps (defined in the inputs), COMPASS can generate events such as "turbine failure occurred," "turbine maintenance started," "service operation vessel (SOV) is picking up personnel from a turbine," and other events. Multiple events can also occur at the same time-step. COMPASS will then look for means required to act on these events. For example, if an event is a turbine component failure, then the simulation tool will look for available vessels, personnel, and spare parts to repair or replace that component. In the case of multiple failures on a single asset, COMPASS will combine the activities together where possible (according to the vessel requirements and capacities). Each turbine, cable, and substation is seen as assets in COMPASS, a twin turbine is also computed as a single asset. COMPASS will check if there is a suitable weather window to perform activities and will then calculate KPIs at each time-step: time availability, energy availability, energy output, breakdown of O&M costs (fixed costs, crafts, consumables, equipment, personnel), and vessel and personnel usage. COMPASS will then output the final result once all time-steps have been computed.

COMPASS is a stochastic tool with random events modeled based on historical failure data. Due to this nature of COMPASS, the results are obtained from an average of multiple simulations. The results of this study were calculated based on 30 simulations for each case. A previous study has demonstrated the importance of running multiple simulations and explained the convergence analysis [6], the study has demonstrated that running 20 simulations is enough to bring the error in O&M cost results below 2%.

2.2 Floating Turbine Modeling in COMPASS. As mentioned, a previous study has used COMPASS to model O&M of a floating wind farm assuming all major replacements would be performed by a jack-up vessel at site [6]. In the case of major maintenance activities, the Kincardine and Hywind Scotland wind farms plan tow-to-port and tow-to-shallow operations respectively [7,8]. Hexicon AB is currently also assuming tow-to-port operations for major maintenance, however other options are considered too, e.g., using a heavy lift vessel. Recent COMPASS developments have allowed the modeling of tow-to-port operations, minor changes in COMPASS in the future can also allow for modeling of tow-to-shallow operations. Tow-to-shallow operations are similar to tow-to-port, where a turbine would be towed to shallow waters and a jack-up vessel would then be used to perform any major maintenance.

During tow-to-port operations, COMPASS distinguishes between four asset states:

- Awaiting repair
- Towing to port
- Undergoing maintenance
- Waiting for tow back
- Tow to site

In the "awaiting repair" and "waiting for tow back" states, the tool will wait (i.e., iterate through time-steps) until there is a suitable weather window for a towing operation, it will also wait for a vessel availability if a lead time for a vessel is specified. Towing operation assumptions are shown in Table 1. When a turbine is in port, it is assumed there are no weather limitations for its maintenance.

In case of major component replacement, there will be an associated spare part lead time. The countdown for availability of that spare part starts when a failure happens and is independent of the proceeding activities. The countdown will start when a failure occurs and can continue even when an asset is in port which means there may be some waiting time in port associated with spare part unavailability until a turbine can undergo maintenance.

2.3 Twin 10 MW Turbine Modeling in COMPASS. This section provides information collected from a discussion with Hexicon AB and is valuable for accurate O&M modeling. It also gives an overview of what assumptions were made in COMPASS.

The Hexicon AB floating structure will have two turbines installed on two corners of a semi-submersible structure with a single-point mooring system connected at the third corner (see Fig. 1). Hexicon AB's mooring system consists of eight hybrid (nylon and chain) mooring lines connected to a swiveling turret. In deeper sites, Hexicon AB is planning to utilize tension legs, however for this study, an assumption of catenary hybrid moorings with drag anchors is used. The single-point mooring system allows the whole structure with twin turbines to rotate according to the wind direction. The structure would then stop rotating once a balance between forces acting on each turbine is reached. In this concept, the turbine yaw system would only be activated for a start-off of a turbine but not required afterward. Due to this mechanism, if one turbine fails, both turbines will stop operating; this means that

Table 1 Tow-to-port operation assumptions

Condition	Number of tugs	Speed	Wave height	Lead time
Loaded	2	5 knots	1.5 m	10 days
Unloaded		17 knots	3 m	

Fig. 1 Hexicon AB twin turbine concept

the whole assembly cannot be in the state where one turbine is operating whilst the other is not. It was decided to not include the yaw system failures in the inputs of O&M of twin turbines. It is expected that due to the low frequency of usage of the yaw system, its failure rate will be minimal.

The flowchart shown in Fig. 2 explains how twin turbine maintenance is modeled in COMPASS. Unlike another study mentioned in Sec. 1, COMPASS models twin turbines as a single asset (as a united structure) rather that two turbines put in the same location. This allows turbines to have shared components, such as dynamic cables or semi-submersible structures. Unlike the discussed study, COMPASS also has more than one option for the dependency between turbine failures. The preferred option can be picked by a user depending on what type of system they are modeling. COMPASS turbine setting “One Off All Off” defined as TRUE will cause all turbines to switch off in case of a failure, the same option set as FALSE will let the other turbines in the system continue operation in the event of a failure. COMPASS assumes that personnel arrived by a maintenance vessel can walk between turbines to continue planned maintenance, hence service vessel does not need to move between turbines. Planned maintenance activities are automatically combined for the twin turbines. In the case that large parts are required, that cannot be carried safely by personnel, a vessel would need to change its position. COMPASS however assumes that any tasks on an asset can be combined irrespective of the spare parts involved.

2.4 10 MW and 14 MW Turbine Operation and Maintenance Assumptions. In both scenarios, planned maintenance and minor unplanned maintenance will be carried out using an SOV that would be positioned in the vicinity of the farm. SOV weather limits are assumed to be the same as in the previous study [6]. Every two weeks an SOV will return to port to refuel.

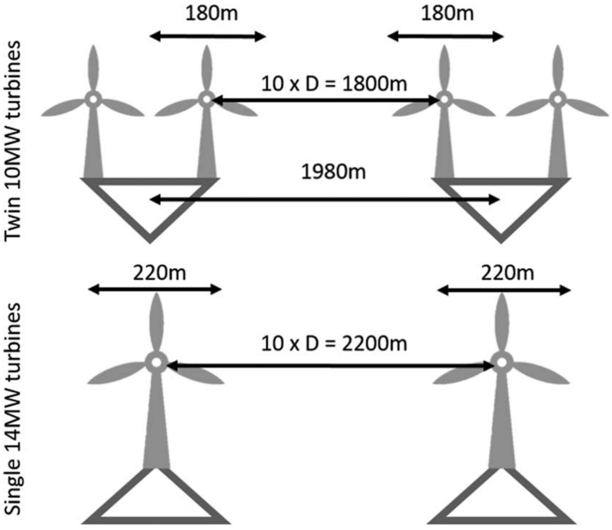

Fig. 3 Distances between turbines and foundations

Mooring configuration and number are not a focus of this study, therefore both scenarios assume the same number and type of mooring lines and anchors.

The same location is assumed in both scenarios, but with different layouts. Wake effects will be stronger between 14 MW turbines due to larger turbine diameter than for 10 MW turbines. Although wake effects are not modeled in COMPASS, the distances between turbines are expected to affect the transit times between turbines. Distance between turbines was assumed to be ten times the rotor diameter. The assumed rotor diameters for 10 MW and 14 MW turbines were 180 m and 220 m respectively. Distance between 10 MW turbine rotors considering the assumptions made, would be expected to be 1.8 km (10 rotor diameters), however the distance between the centers of twin turbine foundations should be about 180 m bigger (1.98 km) considering that there are two turbines and not one, this calculation is demonstrated in Fig. 3. Therefore the distance between foundations for twin turbines is rounded to 2 km and between single 14 MW turbines it is calculated as 2.2 km.

Despite the increase in distance, the frequency and duration of maintenance activities for cables are kept the same for both scenarios. Turbine and approximated cable layouts for the two scenarios are shown in Figs. 4 and 5. Unlike other O&M simulation tools, COMPASS takes into account cable layout and checks if any failure has caused disconnection of any turbine from a substation (onshore or offshore). This is particularly important for this study because, although the capacities of the two farms are the same, the number of cables will be higher in the case with 14 MW turbines.

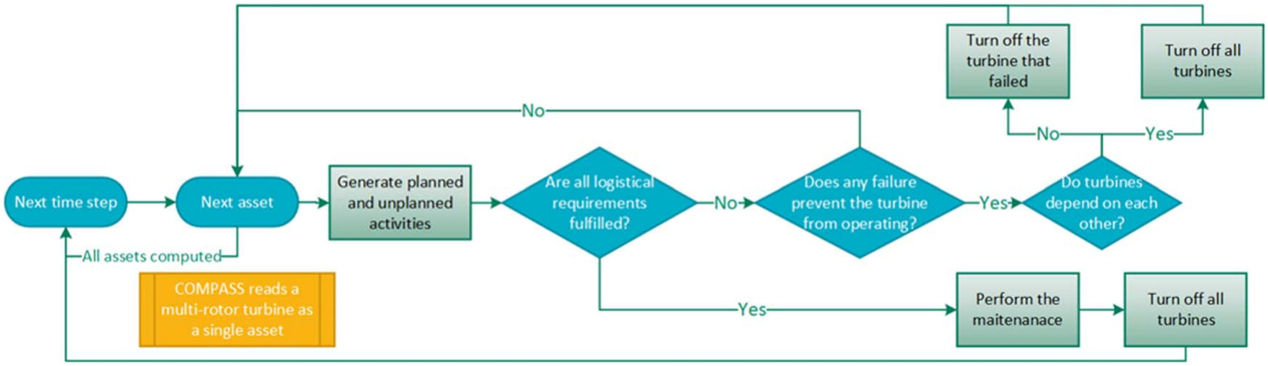

Fig. 2 Simplified flowchart showing the simulation logic for twin turbine maintenance

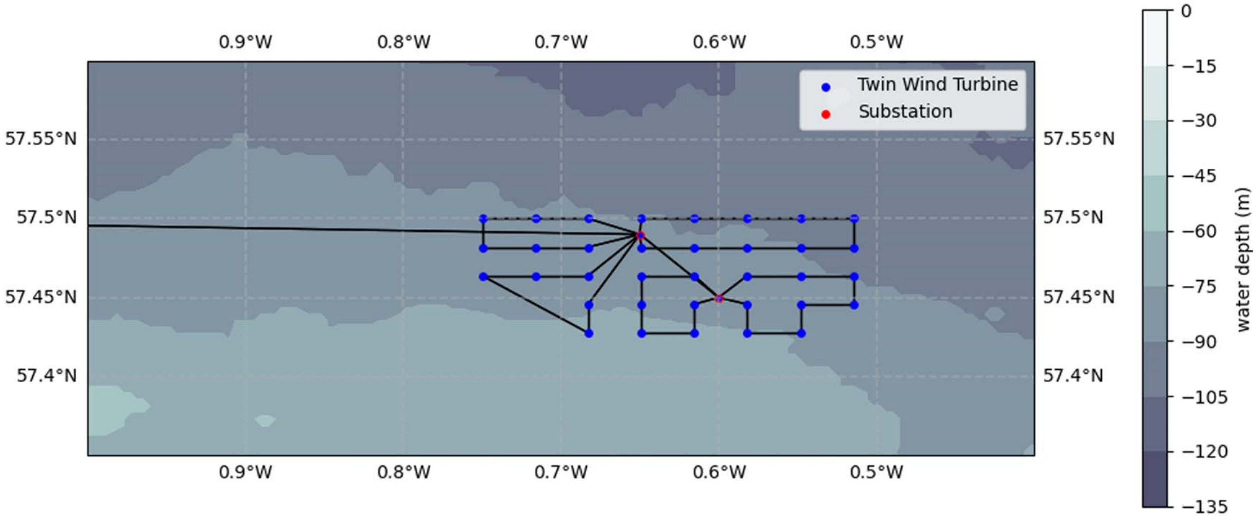

Fig. 4 Floating wind farm layout with 35 twin 10 MW turbines

Peterhead port is assumed to be the O&M port in both cases; this port will provide harbor for any maintenance vessels and space for a floating structure in the case of a tow-to-port operation. Weather data time series were extracted from ERA5 weather reanalysis dataset for the nearest point to the site with coordinates 57.5 deg N, 0.75 deg W. The time period extracted from ERA5 was 1995–2019, which makes 25 years of weather data, which is an assumed lifetime of a wind farm. COMPASS then uses wind data to calculate the power output, and wave data to calculate available weather windows for vessels. Table 2 provides the overview of the farm characteristics used in this study.

The power curve for a 10 MW turbine was taken from the NREL database [9]. To model a 14 MW turbine power curve, the 10 MW turbine power curve was scaled such that cut-in, cut-out, and rated wind speeds are same for both 10 MW and 14 MW turbines. Resulting power curves are shown in Fig. 6.

According to Kincardine project plan for operation and maintenance [7], the planning assumptions for a 2 MW and a 9.5 MW turbine are same: 6 days scheduled maintenance and 10 days unscheduled maintenance per year on average. This means that there is no expectation that failure rates would change depending on turbine rating. One of the findings of the latest System Performance, Availability and Reliability Trend Analysis (SPARTA) Portfolio Review 2020/2021 contradicts this assumption [10]. SPARTA results show that the number of forced outages increases with the turbine rating. According to SPARTA, the turbines rated below 3.6 MW, between 3.6 MW and 5 MW, and above 5 MW experience almost the same number of forced outages per megawatt per month. There may be other factors influencing these results, such as weather and the early failures of turbines. It is also not clear what amount of these forced outages have been caused by actual failures and what amount required only a manual reset of a turbine without any intervention. There is also no information about whether the number of major replacement operations increases with turbine rating. SPARTA is however the most reliable source of reliability data for offshore wind, at the time of writing. It is the only database that is continually collecting data from over 1500 offshore wind turbines, reaching the rating of 8 MW. Considering the latest SPARTA findings, minor and medium failure rates were scaled linearly with turbine rating, i.e., they were assumed to be 40% more frequent for 14 MW turbines than at 10 MW turbines, however future work should analyze SPARTA results in more detail. Major repair and replacement rates were kept the same for 10 MW and 14 MW turbines. This study also assumes the same unplanned maintenance frequency for 10 MW and 14 MW turbines. Due to the sensitivity of this data, failure rates and maintenance

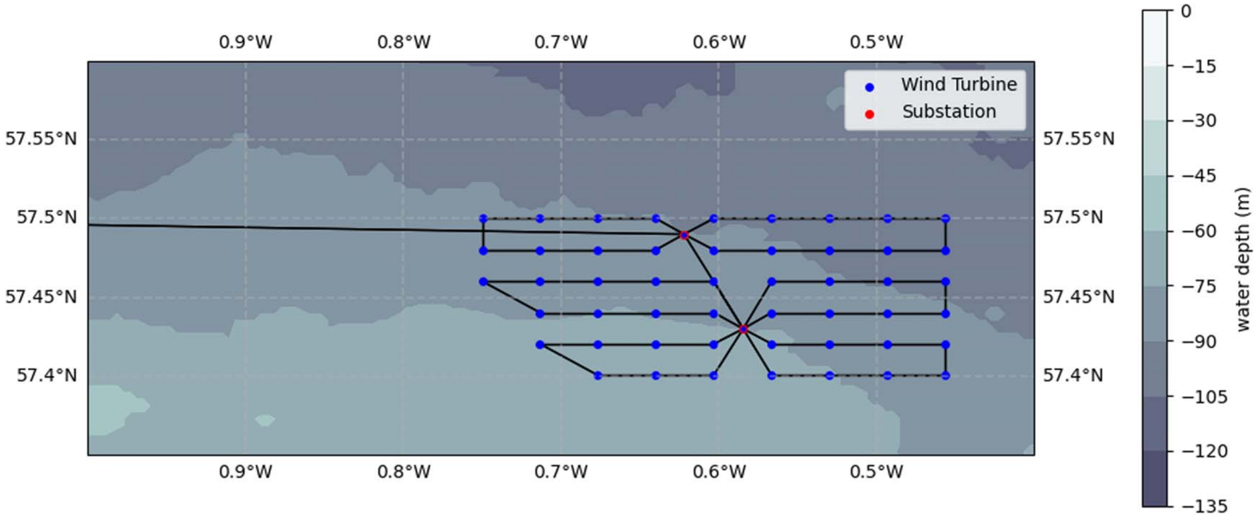

Fig. 5 Floating wind farm layout with 50 single 14 MW turbines

Table 2 Characteristics of the 700 MW floating wind farm

Parameter	Value
Farm capacity (in all cases)	700 MW
Number of turbines	35 (twin turbines) or 50 (single turbines)
O&M port	Peterhead
Weather data	ERA5 (57.5 deg N, 0.75 deg W)
Distance to port	70 km

durations assumptions in COMPASS are not disclosed here, however they are derived from four sources: SPARTA [10], internal expertise, external expertise, and other sources [11]. Failure rates for submerged components are the same as in the previous study from the same authors of this paper [6]. In the context of O&M simulations, spare part lead time is sometimes mentioned in the literature but without any numerical data associated with it. The main reason behind waiting for component maintenance is often assumed to be weather window availability and vessel availability. Most recent sensitivity analysis studies have not included spare part lead time [12]. Consumables lead time in this study is defined as the time it takes from the moment the part is ordered to the moment when it arrives at the O&M base. The reason for avoiding the inclusion of spare part availability in O&M simulations is most likely the lack of available data on spare part lead times. The only two sources that were found are outdated and may not be relevant for the current generation of turbines. One study collated data from other sources [13] and resulted in spare parts under 10,530 EUR requiring 1–2 weeks of lead time and parts costing 100,000–113,000 EUR requiring 10 weeks of lead time. Another study consulted with wind farm developers [14]. According to that study, a replacement blade and a transformer would take 8 and 16 weeks of lead time respectively. Each of the other components would take 1 week. Differences in wind farm operator strategies result in high variability of spare part lead time estimations. Some farm operators will prefer to keep some spare parts at an O&M base, while others will decide against it due to the lack of storage space. Other operators may decide to get replenishments from a distribution center (e.g., Hull, UK). Lead time is also highly dependent on the market size and supply chain, some components may be only manufactured abroad. According to Hexicon AB, if a major component is not in the inventory it may take from three months to over a year to arrive and be ready for a replacement activity. Lead time depends on a set of factors, such as where a component is coming from, whether it is a major component, and whether there is a developed market for that component. According to ORE Catapult expertise, a transformer lead time would be around 6 weeks. Table 3 was constructed using the information above and shows the assumptions made in this study for 10 MW turbine components.

All component costs were scaled linearly with increase in power rating according to Ref. [15]. Equipment costs were scaled linearly too. Table 4 shows four scenarios that were simulated in this study. Case TW-2x10 represents a scenario with a farm with twin turbines rated at 10 MW each, cases named SL-14-0, SL-14-20, and SL-14-40 represent scenarios with a farm with single 14 MW turbines. TW-2x10 uses spare part lead time values provided in Table 3. It is assumed that maintenance durations and failure rates currently specified in COMPASS are applicable to 10 MW turbines. TW-2x10 case was taken as a base case for generating the inputs for 14 MW turbines. First, all inputs (failure rates, maintenance durations, vessel and crew requirements, etc.) were copied to make a new 14 MW scenario. Then consumables costs and failure rates were adjusted assuming a direct correlation between these parameters and the turbine rating, forming case SL-14-0. Spare part lead times and maintenance durations were then scaled by 20% and by 40% in cases SL-14-20 and SL-14-40 with respect to SL-14-0 case. It should be noted that, contrarily to the failure rates, the spare part lead times and maintenance durations scaling with rated power were not observed in SPARTA; this is an assumption aimed exclusively at a sensitivity analysis on these parameters.

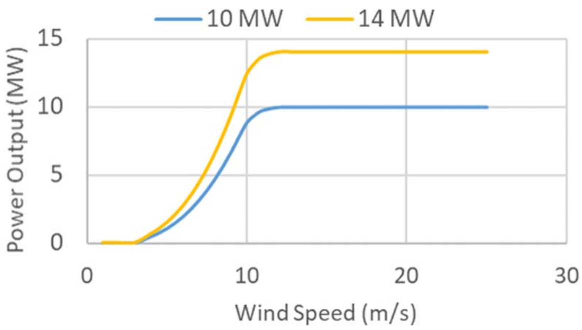

Fig. 6 Power curves for 10 MW and 14 MW turbines

Table 3 Spare part lead time assumptions

Spare part	Lead time
Blade	8 weeks
Transformer	6 weeks
Generator, gearbox	4 weeks
Others	1 week

Table 4 Differences between simulated cases

Case name	Failure rates[a]	Consumables costs	Consumables lead time and maintenance duration
TW-2x10	Base case	Base case	Base case
SL-14-0	40%	40%	0%
SL-14-20	40%	40%	20%
SL-14-40	40%	40%	40%

TW-2x10 represents a farm with twin 10 MW turbines and the rest represent farms with single 14 MW turbines.

[a] Only minor and medium repair rates were scaled.

3 Results and Discussion

Results from the 30 simulations of each scenario described in Table 4 are summarized in Fig. 7 and Table 5. Different KPIs exist that can be used to compare O&M scenarios and strategies. Common KPIs are O&M costs and availability of a farm. Total O&M costs are provided in £ million in Table 6. Table 5 provides the annual O&M costs (£/kW) calculated by dividing the total costs by the lifetime of a farm and the installed capacity in kW. Time and energy availabilities resulting from each scenario are given in Fig. 7 together with annual O&M costs. OPEX was then calculated to assess both the costs and the energy production in a single KPI rather than assess these outputs separately. Table 5 provides the OPEX calculated via dividing the total O&M costs (given in Table 6) by the total energy output in each scenario (annual energy output from Table 5 multiplied by 25 years, the lifetime of a farm).

As can be seen in Fig. 7, cases SL-14-0, SL-14-20, and SL-14-40 (i.e., single 14 MW turbine cases) are all more expensive in terms of O&M costs (£/kW) than the case with twin 10 MW turbines, with the lowest difference of 4.5% and the highest difference 5.3% compared to TW-2x10. The highest time availability output out of all scenarios is 91.7% which also belongs to the twin turbine case

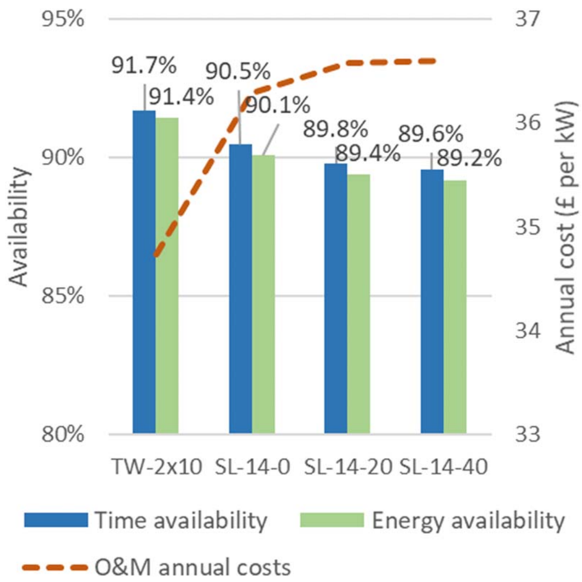

Fig. 7 Availability and cost results of the simulated scenarios

Table 5 Annual O&M cost and energy output for each of four scenarios and the resulting OPEX

	TW-2x10	SL-14-0	SL-14-20	SL-14-40
Annual O&M cost (£/kW)	34.7	36.3	36.6	36.6
Annual energy output (MWh)	3671	3616	3589	3581
OPEX (£/kWh)	6.62	7.02	7.13	7.15

TW-2x10. If OPEX is compared, then the difference is even greater, with the minimum of 6.0% difference between SL-14 cases and the TW-2x10 case, favoring the latter. O&M costs and OPEX presented in Tables 5 and 6 do not include the quayside costs, however following paragraphs will discuss the impact of the quayside costs on this comparison.

Additionally, Table 6 provides the breakdown of the total O&M costs. From the breakdown of costs presented in Table 6, it can be seen that the biggest contributor to these differences is craft costs. In all cases, fixed costs make the biggest portion of O&M costs, followed by craft, personnel, consumables, and equipment costs.

As was expected, cases SL-14-20 and SL-14-40 are more expensive than SL-14-0 due to the increase in lead time and maintenance duration. This study found that a 20% increase in consumables lead time and maintenance duration caused a 1.6% increase in OPEX compared to SL-14-0 case. Interestingly, 40% increase in the same parameters caused a 1.9% increase in OPEX which means that the change is not directly proportional to the increase in lead times and maintenance times. Similarly, time availability decreased from 90.5% in case SL-14-0 to 89.8% in case SL-14-20 but then further decreased to only 89.6% in case SL-14-40. Longer maintenance times require more waiting for a suitable weather window. During this waiting time, other failures may happen on other turbines. When a suitable weather window is found, activities would be done in a bundle hence resulting in more effective maintenance operations and vessel usage. This effect could explain the unexpectedly small difference between SL-14 case results, however additional analysis would be required to investigate this in more depth.

Table 6 Total cost outputs from simulations of 25 years of farm O&M of each of four scenarios

	TW-2x10	SL-14-0	SL-14-20	SL-14-40
Fixed costs (£m)	285	285	285	285
Crafts cost (£m)	250	265	268	267
Equipment (£m)	1	1	1	1
Consumables (£m)	7	11	11	11
Personnel (£m)	65	73	76	77
Total O&M cost (£m)	608	635	640	640

Table 7 Logistical outputs from all simulations

	TW-2x10	SL-14-0	SL-14-20	SL-14-40
SOV usage (days/year)	32.8	40.4	40.0	40.1
Cable vessel (days/year)	1.0	1.3	1.5	1.5
Tug usage (days/year)	28.3	21.5	21.5	21.5
Quayside use (days/year)	20.8	16.5	18.2	19.5

A summary of the SOV, cable vessel, and tug vessel usage is provided in Table 7; these are the only vessels that are expected to affect the difference between scenarios. Tug vessel and cable vessel usage are the main reasons for differences between scenarios in terms of costs. Because major repair rates were kept the same for 10 MW and 14 MW turbines (due to the lack of information on how they scale), tug vessels in case TW-2x10 are used more often. Tug day rates, mobilization and demobilization rates are much lower that the rates for a cable vessel. All vessel cost assumptions in this study were taken from the COMPASS vessel database. Cable vessels in this database have 96 times higher mobilization cost than that of a single tug and 20 times higher day rate than that of a single tug. Cable vessels are used more often in cases with single 14 MW turbines (SL-14-0, SL-14-20, and SL-14-40). Despite it being used much less than a tug vessel, its total cost is much higher due to higher vessel rates. Because there are 59 cables in SL-14 cases compared to 43 in the TW-2x10 case, the likelihood of failures is higher and hence that is reflected in the craft cost output and the cable vessel usage output.

No information was found on what the quayside costs would be in case of a major repair in port and hence it was not included in the KPI comparison discussed earlier. Quayside costs would include the rental of the space and a crane for maintenance. COMPASS however tracks the quayside work time in terms of work days a year, these are shown in Table 7. From these outputs, a difference between twin turbine and single turbine case quayside use was calculated to be 4.3 days a year. Knowing the number of days the quayside would be used it is possible to solve Eq. (1) to find the quayside cost at which two scenarios TW-2x10 and SL-14-0 would break even.

$$\frac{D_{\mathrm{TW}} \times C_{\mathrm{QD}}}{E_{\mathrm{TW}}}+\frac{\sum C_{\mathrm{TW}}}{E_{\mathrm{TW}}}=\frac{\sum C_{\mathrm{SL}}}{E_{\mathrm{SL}}}+\frac{D_{\mathrm{SL}} \times C_{\mathrm{QD}}}{E_{\mathrm{SL}}} \qquad (1)$$

In Eq. (1), D_{TW} and D_{SL} are the number of days that the twin turbines and single turbines spent in port respectively, C_{QD} is the quayside rate per day (the unknown), E_{TW} and E_{SL} are the total energy outputs from the twin turbine and the single turbine scenarios respectively, $\sum C_{\mathrm{TW}}$ and $\sum C_{\mathrm{SL}}$ are the sums of total O&M costs for the twin turbine and single turbine scenarios respectively which include fixed costs, consumables and equipment costs, craft costs, and personnel costs and exclude quayside costs.

Solving Eq. (1) for C_{QD}, it was found that the quayside cost would need to be £371,500 per day for the TW-2x10 case to have the same OPEX as in the SL-14-0 case. This is at least three times higher than the charter rate of the most expensive vessel in the COMPASS database leading to a conclusion that it is unlikely that quayside costs would reach this value. This calculation also assumed the same quayside cost in both scenarios, however larger, 14 MW turbines may require a bigger, more expensive crane. Therefore, TW-2x10 remains a more favorable case in terms of O&M costs, time and energy availability, and most importantly, OPEX.

Future research should investigate in more detail how turbine component costs change with turbine rating. Turbine size does not scale linearly with turbine rating, therefore the assumption that component costs would scale linearly is an oversimplification. Despite that, it is not expected that consumables or equipment cost variation would significantly affect the O&M costs because the highest proportion of costs comes from fixed costs, vessel costs, and personnel costs. Similarly, cable failure frequency and maintenance durations were assumed the same for all cases, however greater cable length in cases SL-14-0, SL-14-20, and SL-14-40 may increase the likelihood of cable exposure and failure. At the same time, array cable used in the TW-2x10 case would be higher rated and hence would be more expensive to replace.

There is a general lack of information on spare part management, more research should be done to understand what spare parts can be stored in a local O&M base, how much time would different parts take to arrive if they are not in the inventory and what variables lead times depend on.

Tow-to-port operations require thorough logistical planning and involve a lot of risks. It is not yet clear if it is the best O&M strategy for floating wind turbines. Other options include using a heavy lift vessel, towing a turbine to shallow waters to perform maintenance with a jack-up vessel or even using modular crane systems that can be temporary installed on a turbine's substructure. According to Hexicon AB tow-to-port operations would require roughly 2 months of planning, more research is required into alternative options. Another constraint is that not all UK ports have the required draft and space for tow-to-port operations and may not always be available for the major turbine maintenance operation. The UK floating wind farms Hywind and Kincardine send their turbines for major maintenance to Norwegian fjords and Rotterdam port in the Netherlands respectively [7,8].

4 Conclusion

This study compared O&M of a floating wind farm with 50 single 14 MW turbines and a floating wind farm with 35 twin 10 MW turbines, with the help of input from the major twin turbine developer Hexicon AB. Based on the publicly available data trends, the study assumed that failure rates (excluding major failures requiring replacement) scale linearly with the turbine rating. Other parameters were also scaled for the sensitivity analysis purposes. Results of O&M simulations performed using COMPASS show that O&M costs for the scenario with single turbines are at least 4.5% higher than for the farm with twin turbines, with the assumptions used in this study. This difference increases to 5.3% if compared to a scenario where spare part lead time and maintenance duration of activities are 20% higher for 14 MW turbines. This study found that OPEX for the cases with single turbines is at least 6.0% higher in scenarios with single turbines than in the twin turbine scenario. Despite more frequent tow-to-port operations in the scenario with twin turbines, scenarios with single turbines were more expensive mostly because of the higher number of cables in the farm. Due to the lack of data, quayside costs were not included in these comparisons, however this study found that even with the most conservative estimations for quayside costs, O&M of twin turbines will remain to be cheaper than that of single turbines. Future work should include failure rate sensitivity analysis and other major replacement methods, e.g., using a heavy lift vessel instead of towing to port.

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Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent was obtained for all individuals. Documentation provided upon request. This article does not include any research in which animal participants were involved.

Data Availability Statement

No data, models, or code were generated or used for this paper.

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