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Will 10 MW wind turbines bring down the operation and maintenance cost of offshore wind farms?

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Abstract

Larger wind turbines are believed to be advantageous from an investment and installation perspective, since costs for installation and inner cabling are dependent mainly on the number of wind turbines and not their size. Analogously, scaling up the turbines may also be argued to be advantageous from an operation and maintenance (O&M) perspective. For a given total power production of the wind farm, larger wind turbines give a smaller number of individual machines that needs to be maintained and could therefore give smaller O&M costs. However, the O&M costs are directly dependent on how failure rates, spare part costs, and time needed by technicians to perform each maintenance task and will develop for larger wind turbines. A simulation study is carried out with a discrete-event simulation model for the operational phase of an offshore wind farm, comparing the O&M costs of a wind farm consisting of 5 MW turbines with a wind farm consisting of 10 MW turbines. Simulation results confirm that O&M costs decrease when replacing two 5 MW turbines by one 10 MW turbine, if the total production capacity and all other parameters are kept equal. However, whether larger wind turbines can contribute to a reduction of cost of energy from an O&M perspective is first and foremost dependent on how the failure rates and maintenance durations for such wind turbines will develop compared to 5 MW wind turbines. Based on the results of this analysis, it is concluded that higher failure rates and maintenance durations rapidly are counterbalancing the benefits of larger wind turbines.

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1. Introduction

In the deployment of offshore wind power, a clear trend towards larger wind turbines can be observed. Prototypes of 7 - 8 MW offshore wind turbines are currently being installed [1] and developed [2, 3], and plans and designs for 10 MW turbines are being developed, such as the reference turbine of the NOWITECH research program [4, 5] or the DTU 10 MW reference wind turbine [6, 7]. It is believed that larger wind turbines can help to reduce the cost of energy for offshore wind farms. However, the use of wind turbines with higher power rating has different effects on the individual cost components of an offshore wind farm categorized into wind turbine, sub-structure, installation, decommissioning, electrical infrastructure, project management, and operation and maintenance (O&M).

The Upwind project [8] came to the conclusion that the levelized *wind turbine cost* for upscaled wind turbines will increase. This is due to the fact that the weight of the turbine increases faster than the power for pure geometrical upscaling, and,

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somewhat simplified, weight can be seen as being proportional to costs. However, the cost increase is only valid for pure upscaling without a change of the technology applied. It is possible that the cost will increase less or even stay stable when new technologies are applied. Therefore, it can be expected that wind turbine costs will in the best case be stable, but will not contribute directly to a reduction in the cost of energy. The cost of the *sub-structure* increases linearly with the rated power of the wind turbine according to [9]. No positive effect on the cost of energy can therefore be seen when using higher-rated wind turbines. The *installation cost*, the *decommissioning cost* and the *electrical infrastructure cost* are mainly dependent on the number of wind turbines. A lower number of wind turbines is needed with higher-rated wind turbines to reach a given total capacity. As a consequence, it can be assumed that these cost categories will help to reduce the cost of energy. I addition, minor savings in the cost for site assessment and *project management cost* will occur.

O&M costs are in this paper defined as the sum of the costs for vessels, personnel and spare parts needed for performing the required maintenance of the wind farm. Maintenance is understood to also include all inspections, repairs, replacement of components, etc. In addition, the O&M cost also includes the income lost due to downtime of the wind turbines. For a given total power production of the wind farm, larger wind turbines give a smaller number of individual machines that needs to be maintained and could therefore give smaller O&M costs. However, this reduction in O&M cost is directly dependent on how failure rates, time needed for each maintenance task and spare part costs will develop for larger wind turbines. In addition, each shutdown of a 10 MW turbine would cause a loss of production equivalent to two 5 MW turbines, and so a wind farm could experience reduced overall availability. It is therefore uncertain how the O&M cost will develop when using higher-rated wind turbines.

In summary, it can be seen that larger wind turbines are believed to be advantageous from an investment and installation perspective, since installation, decommissioning and electrical infrastructure cost are mainly dependent on the number of wind turbines and not their size. The development of the O&M cost is more uncertain when scaling up wind turbines. In addition, O&M costs are responsible for a large part of the total life cycle cost. Depending on the source and the definitions used in the cost assessments, the O&M costs are around 22–40 % of the total cost of an offshore wind farm [10, 11, 12, 13].

The objective of this work is therefore to answer the question of how O&M costs are likely to be affected when going from 5 MW turbines to 10 MW turbines in an offshore wind farm. Our starting point is the assumption is that the total production capacity of the wind farm is kept equal when analyzing the change in the O&M cost. This is necessary to allow for direct comparison of O&M cost for a given expected electricity production. Furthermore, the analysis will take into consideration the uncertainty related to future failure rates, maintenance durations and spare part costs.

2. Method

2.1. Analysis approach

Three maintenance parameters are identified as important for the change in O&M costs when scaling up wind turbines from 5 MW to 10 MW: failure rates, maintenance durations, and spare part costs. Since these maintenance parameters are unknown for future 10 MW turbines, a systematic scenario analysis approach is performed. Starting from an optimistic base case assuming that the maintenance parameters are equal for 5 MW and 10 MW wind turbines, these parameters are sequentially increased to find the limit where the O&M cost of the 10 MW turbine wind farm would exceed the O&M cost of the 5 MW turbine wind farm under the assumption that both wind farms have equal total installed capacity.

The change in the O&M cost is analysed by using a simulation tool, namely the NOWIcob model. NOWIcob is a discrete-event simulation model for the operational phase of an offshore wind farm, focusing on maintenance tasks and related logistics [14, 15]. It is developed by SINTEF Energy Research and has been evaluated in cooperation with an international expert group [16]. The model considers different O&M strategies and logistic setups for the maintenance operations. Since offshore operations are highly weather dependent, weather uncertainty and the uncertainty about the points in time when failures occur are considered in NOWIcob by using a Monte Carlo simulation approach. The results delivered by the model include performance parameters such as the O&M cost split and the availability of the wind farm. In this analysis the focus will be on the O&M cost including lost income due to downtime.

2.2. Base cases for 5 MW and 10 MW turbine wind farm

Two reference wind farms are defined to compare how the O&M cost are affected when one replaces 5 MW turbines with 10 MW turbines. Both wind farms have a total rated production capacity of 400 MW: One farm consisting of 80 x 5 MW turbines and the other wind farm consisting of 40 x 10 MW turbines. The two wind farm cases are identical except from the differences in the rated power of the wind turbines. The wind farm is located 50 kilometers from the maintenance harbour. Weather conditions are based on the weather and wave conditions in the British part of the North Sea. To be more specific, the weather time series for wave height and wind speed are obtained from ERA-interim hindcast data from the ECMWF archive for the coordinates 53.265°N 1.38°E [17]. Furthermore, the following base case values, presented in Table 1, were used for the analysis.

Table 1. Base case values for the wind farms.

Parameter	Base case value
Electricity prices	0.09 £/kWh
Fuel price	0.60 £/l
Personnel cost	80 000 £/technician and year

The logistic setup is based on a relatively conventional strategy. Three conventional crew transfer vessels (CTV) are operated from the onshore base. The number of technicians available at the harbour at each working shift is 25, and each shift lasts for 12 hours. For major maintenance tasks, a field support vessel (FSV) or a jack-up vessel is chartered when needed. More detailed vessel data can be found in Table 2. This base case is in many respects similar to the one described in more detail in [16].

Table 2. Vessel parameters.

	Crew transfer Vessel	Field support vessel	Jack-up vessel
Number of vessels	3	1	1
Governing weather criteria	Wave	Wave	Wave / wind
Weather criteria	1.5 m	1.5 m	2.0 m / 10.0 m/s
Mobilisation time	0 weeks	3 weeks	2 months
Mobilisation cost	£ 0	£ 0	£ 500 000
Speed of vessel	20 knots	12 knots	11 knots

2.3. Maintenance parameters analysed

The focus of the analysis is on three important maintenance parameters: failure rates, maintenance duration, and cost of spare parts. These parameters are defined in the following way: Failure rates are understood as the average number of failures in a year. In principle, the failure rates can be influenced through the choice of turbine technology in the investment phase and by the choice of preventive maintenance strategy in the operational phase. Maintenance duration is understood as the time needed at the wind turbine by the technicians to finish a maintenance task. Even if the frequency of preventive maintenance is fixed, there is still variability in the actual time spent for performing the maintenance. The variability is even greater for the time needed for corrective maintenance tasks, and estimates for maintenance durations for larger wind turbines are uncertain. The costs of spare parts and consumables needed in preventive and corrective maintenance are uncertain for 5 MW turbines and even more so for 10 MW turbines.

As a base case, we start with the assumption that one is able to achieve the same failure rates and the same durations of corrective and scheduled maintenance tasks for 10 MW turbines as for 5 MW turbines. Furthermore, it is also assumed that the spare part costs are equal. All these assumptions should be regarded as overly optimistic, but a major modelling challenge here lies in the absence of reliable predictions of how these parameters will develop with increasing turbine size. Particularly the spare part costs are expected to increase. This will at least be the case for replacement of major components as gear boxes etc. The reason is that the weight of these components typically increases rapidly with increasing rated power, leading to an increase in costs, as also discussed in Section 1 in relation to investment costs. Again, the assumption is that similar technologies are used for 5 MW and 10 MW turbines. In principle, one could use scaling models to estimate the component costs for higher-rated wind turbines [8, 9, 18], but this would introduce new uncertainties in our analysis that would have to be taken into account in the interpretation. For the clarity of the comparison, we have chosen to keep the base case values the same as for 5 MW turbines for all the maintenance parameters, treating them on the same footing.

Table 3 summarises the base case values for the maintenance parameters and for related parameters. The spare part costs are taken from [19], and we refer to [16] for other details.

Table 3. Failure categories input data.

	Manual reset	Minor repair	Medium repair	Major repair	Major replacement	Annual Service
Maintenance duration (h)	3.0	7.5	22	26	52	60
Technicians	2	2	3	4	5	3
Vessel type	CTV	CTV	CTV	FSV	Jack-up	CTV
Failure rate (per year)	7.5	3.0	0.275	0.04	0.08	1
Spare part cost (£)	0	1000	18 500	73 500	334 500	18 500

A systematic scenario analysis approach is performed. The changes in O&M costs (inclusive lost income due to downtime) are studied when the failure rates, maintenance durations and spare part costs are increased. All parameters are increased with 25 %, 50 %, 75 % and 100 % individually, and combinations of increased values are also considered. For spare part costs, we will also consider larger increases since the expected increases in this parameter are greater than for the other maintenance parameters.

The analysis approach assumes the same logistic setup for all cases as described in the previous section. This logistic setup can be unrealistic for some of the cases and lead to biased values of the O&M cost compared to a logistic setup that is adapted to the expected number of failures and the maintenance durations. Therefore, a careful analysis of this assumption is undertaken by the means of a sensitivity analysis to understand if the results are biased or valid. In the sensitivity analysis, the logistic setup is specified by two parameters: the number of CTVs and the number of technicians.

3. Results

All cases were simulated with NOWIcob with 20 iterations over 5 years of the operational phase of the wind farm. The O&M cost results showed relatively small variability (standard error of the average of the order of 1–2 % of the result average) and therefore the number of iterations has to be regarded as sufficient for our purposes. Figure 1 summarises some main results with focus on how sensitive the O&M costs of the 10 MW case are to changes in each of the maintenance parameters, holding the other parameters at the base case value. In addition, the O&M costs are presented for the cases where all maintenance parameters are increased with the same relative value simultaneously to show interaction effects between the different input parameters.

The simulation results show a decrease of ca. 24 % in the total O&M cost for the whole wind farm when replacing two 5 MW turbines by one 10 MW turbine, all other parameters being equal in the base cases. This is not surprising, since the total number of failures is divided in half when two 5 MW turbines are replaced by one 10 MW turbine. Furthermore, as illustrated in the Figure 1, the O&M costs are highly dependent on the assumptions for the development of the maintenance parameters, when scaling up from 5 MW to 10 MW. An increase in failure rates of 50 % already leads to higher O&M cost than for 5 MW turbines even though the total number of failures is still lower than for the 5 MW turbine wind farm.

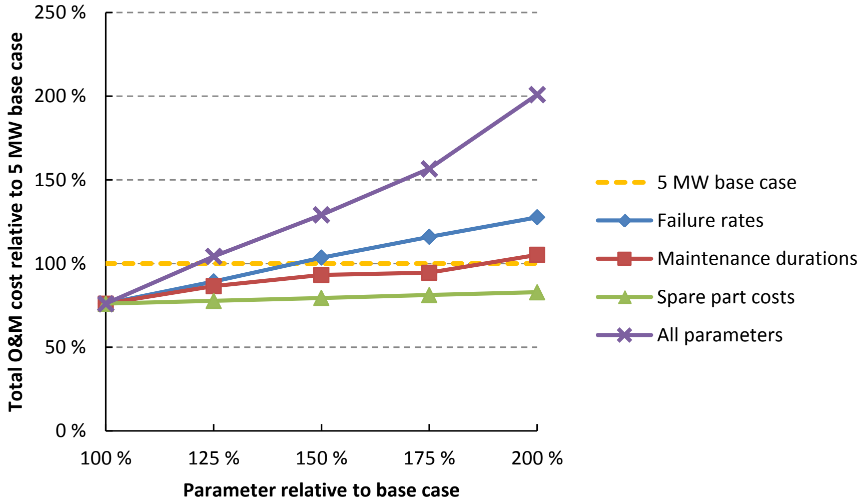

Figure 1. Sensitivity of O&M costs to changes to the maintenance parameters for the 10 MW case .

The relationship between failure rate, power rating and O&M cost can be readily explained in the following, simplified manner. The average lost income of the wind farm relative to the theoretical income can be estimated by the average unavailability of each turbine, which can be approximated as $\text{Unavailability} \approx \text{Downtime}/\text{Lifetime} = (\text{Maintenance duration} + \text{Logistics time})/\text{Lifetime}$. The logistics time typically dominates the downtime for offshore wind farms. Going from two 5 MW turbines to one 10 MW turbine with the same maintenance parameters, the average logistics time for each turbine decreases because of the reduced maintenance amount for the wind farm and thus reduced stress on the logistic setup. This explains why the O&M cost for the 10 MW base case is below that of the 5 MW base case in Figure 1. If we now double the failure rate for the 10 MW turbine, the wind turbine unavailability becomes approximately $\text{Unavailability} \approx 2 \times (\text{Maintenance duration} + \text{Logistics time})/\text{Lifetime}$. Since the total stress on the logistic setup is now comparable to the case of two 5 MW turbines, the average logistics time for a 10 MW turbine is comparable to that of each 5 MW turbine. Comparing with the above unavailability of 5 MW turbines, the unavailability of a 10 MW turbine with twice the failure rate will be substantially higher even though the expected number of failures now is the same as for the two 5 MW turbines together.

The O&M costs are not so sensitive to increases in maintenance durations, but an increase between 75 % and 100 % also leads to higher O&M cost than for the 5 MW turbine case. Doubling the maintenance duration corresponds to a downtime of $2 \times \text{Maintenance duration} + \text{Logistics time}$, where the logistics time will be increased indirectly due to increased stress on the logistic setup. Doubling the failure rate, on the other hand, corresponds to $2 \times \text{Maintenance duration} + 2 \times \text{Logistics time}$, with the logistics time being increased indirectly here as well. This explains why increasing the maintenance duration has a smaller effect on the O&M cost than increasing the failure rate.

Spare part costs are seen to have only a weak influence on the O&M cost, and even with an increase of 100 %, the 10 MW turbine wind farm is still beneficial with respect to changes in this parameter. As mentioned, it is reasonable that spare part costs for 10 MW wind turbines may increase substantially more than 100 %. Still it will not be disadvantageous to move to 10 MW turbines due to spare part costs alone until the increase in spare part costs reaches 450 % of the base case value. This means that if the base case values of spare part costs were increased to, e.g., twice the values of 5 MW turbines, the sensitivity would still be clearly weaker for spare part costs than for maintenance durations.

These result only show the sensitivity when one maintenance parameter is changed separately while holding the other parameters constant. If all parameters are changed simultaneously, an increase of the parameters by only 25 % is enough to make the O&M cost of the 10 MW turbine wind farm higher than the O&M cost of the 5 MW turbine wind farm.

Figure 2 presents more detailed results on how long the O&M cost remains lower for the 10 MW turbine wind farm when two maintenance parameters are increased simultaneously and the third parameter is kept constant at the base case value. These figures show the border in the parameter space beyond which 10 MW turbines are not advantageous from an O&M perspective compared with 5 MW turbines. Due to the weak sensitivity to changes seen in spare part costs and the expectation of much larger values of this maintenance parameter for 10 MW wind turbines, we here consider increases up to 400 % instead of 200 % for the spare parts cost.

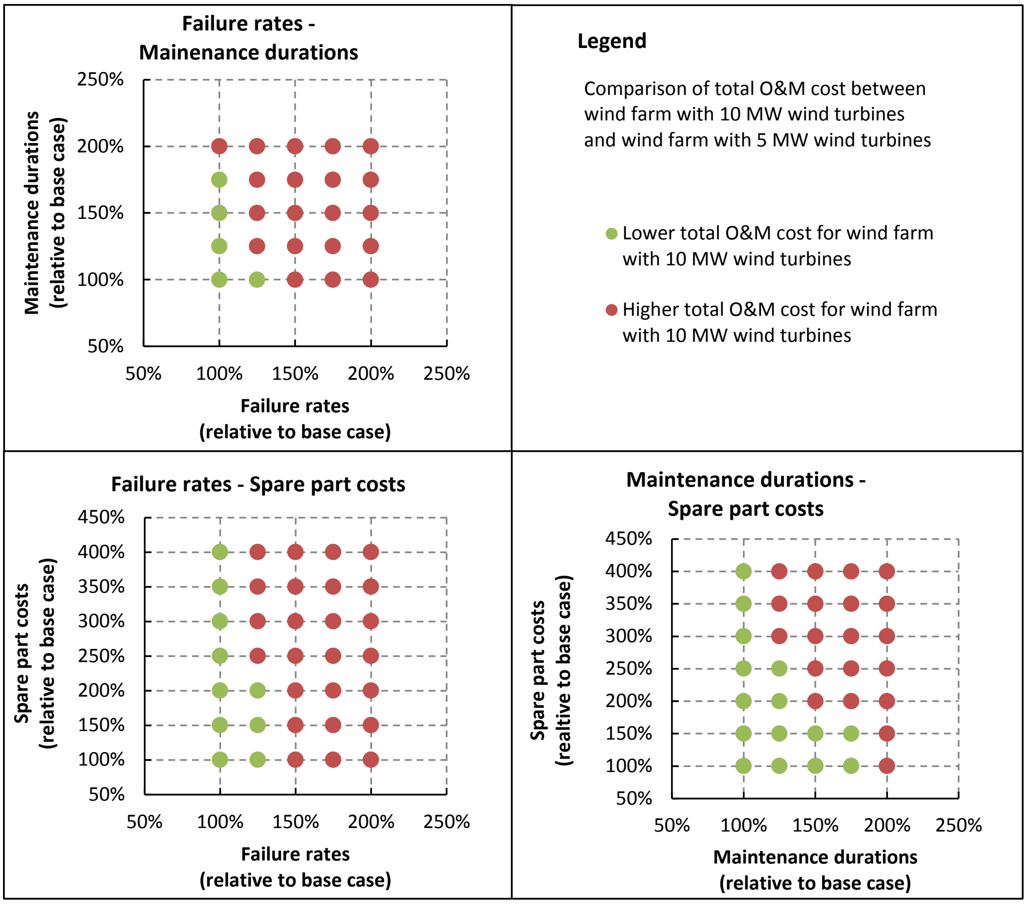

Figure 2. Comparison of O&M cost when changing two maintenance parameters simultaneously.

These results show a similar picture as the sensitivities of the maintenance parameters presented earlier. Failure rates are most important for the development of the O&M cost, followed by maintenance durations. Already a combined simultaneous increase of 25 % of these parameters lead to higher O&M cost for 10 MW turbines compared with the 5 MW wind turbines. Spare part costs have weaker influence on the border outside which 10 MW wind turbines are less beneficial. When changing spare part costs and failure rates simultaneously, this relative insensitivity to spare parts costs is evident.

All cases are simulated with the same logistic setup. This assumption can have an effect on the results, since the logistic setup is not necessarily equally appropriate for all the cases and would not be chosen in reality. For example, it could be more realistic to use more vessels when the number of failures is increased. To find out if this assumption biases the results, a sensitivity analysis is performed for two special cases: 1) the 10 MW turbine base case and 2) a worst case scenario for the 10 MW turbines with a simultaneous increase of both failure rates and maintenance durations to 200 % compared to the base case. These two cases represent two extreme limits regarding the amount of maintenance operations to perform. Figure 3 summarises the results of the sensitivity analysis for the number of technicians and the number of CTVs.

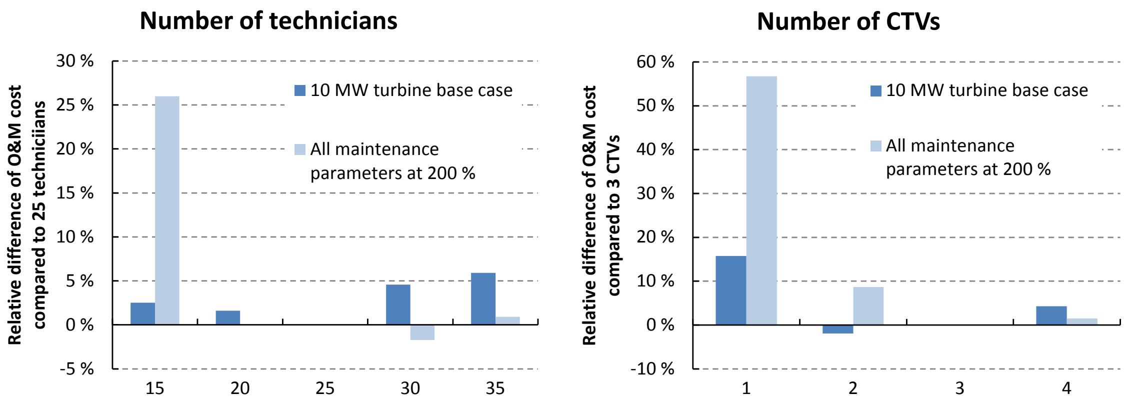

Figure 3. Sensitivity of O&M cost related to logistic setup specified by number of technicians and CTVs.

The sensitivity analysis of the logistic setup shows that the setup chosen, 25 technicians and 3 CTVs, is adequate for all cases, even though it may not be the optimum. Total O&M cost for better setups are only up to a few percentages lower and have therefore no major influence on the results. One could of course apply an even more thorough and sophisticated analysis to find the optimal combination of vessel number and technician number, but as long as the improvements for better setups is so small, this is of limited value. The assumption of equal logistic setup should therefore not bias the results and can be expected as adequate for this analysis.

4. Discussion and conclusion

The results presented in this paper are based on several assumptions. The values for the maintenance parameters failure rates, maintenance durations and spare part costs in the 5 MW base case are based on best knowledge, but have appreciable uncertainty also for current turbines. However, it is expected that all the base case values and the value range covered in the scenario analysis are at least of the right order of magnitude, so such biases should be only moderate. For the 10 MW turbines, the base case values, chosen to be equal to the 5 MW values, should be understood merely as a starting point for the scenario analysis rather than as realistic estimates. As discussed, the spare part costs have a weak influence on the results of the analysis, and this could partly be due to unrealistically low values assumed in the base cases. This is taken into consideration by covering a wider range of values in the scenario analysis for the spare part costs than for the other maintenance parameters, and the influence of the spare part costs is relatively modest also up to 400 % of the base case value. The values for failure rates and maintenance durations in the 10 MW base case are probably also lower than what will be the case for an actual 10 MW wind turbine, but to a smaller degree than for the spare part costs. Such considerations should be taken into account when interpreting the results, but as long as the values are of the right order of magnitude, they can be used meaningfully as the starting point for a scenario analysis. Given the large difference in the influence of the maintenance parameters on the O&M cost, our main result is that increases in spare part costs are likely to be less critical than increases in maintenance durations and that increases in maintenance durations are likely to be less critical than increases in failure rates.

Another assumption in the analysis is that both base case wind farms have an equal total rated production capacity. A wind farm of 10 MW turbines could probably use a limited space more efficiently and reach a higher total rated production capacity than a comparable 5 MW turbine wind farm in the same area. This effect was not considered in this analysis, and it is expected that this effect is more important from a cost of energy perspective than from the O&M cost perspective. More work would be needed to throw light on these effects. The assumption of equal logistic setup for all cases is not essential to obtain the results we report in this paper, since the sensitivity analysis of the logistic setup showed only small changes in the O&M costs.

As discussed above, this first step in investigating the O&M costs of future wind farms with high-rating wind turbines opens up for some possibilities for future work. Comparing a 10 MW turbine wind farm with a 5 MW turbine wind farm where the total area, and not the total rated power, is assumed to be equal, may lead to a more realistic analysis of the effects on cost of energy due to changes in O&M cost. This would, however, require more careful consideration of wake effects to allow for accurate modelling of the power production lost due to downtime. Neither changes in wake effects, inter-turbine distance nor power curves when going from 5 MW to 10 MW turbines are considered in this work.

Another extension of this analysis is to investigate more in detail how the optimal O&M strategy would evolve when going from turbines of 5 MW to turbines of 10 MW. One hypothesis is that a more unconventional logistics setup, e.g. based on vessels with technicians staying offshore for extended periods of time or based more on helicopters, would be more optimal than the harbour-based strategy considered here. Due to the increased loss of income for each single failure, it could be economically beneficial to invest direct O&M costs in a maintenance and logistics strategy that allows one to respond more rapidly to failures.

Simulation results confirm that larger wind turbines can lead to lower O&M costs. However, such a reduction in the O&M cost is heavily dependent on the assumptions done for the development of the maintenance parameters when scaling up to 10 MW. Based on the results of this paper, it can be concluded that higher failure rates and maintenance durations quite fast will counterbalance the benefits of larger wind turbines. Already a simultaneous increase of failure rates and maintenance durations by 25 % will lead to higher O&M cost for a wind farm with 10 MW wind turbines compared to a 5 MW turbine wind farm. Therefore, to reduce O&M costs of higher-rated wind turbines, one has to focus on reliability, and further work should look more into the uncertainty around estimates for reliability of future 10 MW wind turbines. To the extent that the conclusions from this simulation study are applicable to future real-world wind farms, the results challenge the offshore wind industry to uphold and improve reliability and maintainability of future wind turbine concepts.

Acknowledgements

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