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The Impact of Maintenance Contract Arrangements on the Yield of Offshore Wind Power Plants

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Abstract
In the optimisation of maintenance and vessel strategies for the operation of offshore wind plant, it is normally assumed that the offtaker of the power produced may directly control the dispatch of maintenance resources. However, in practice services such as maintenance technicians and vessels are usually contracted from companies with larger arenas of operation, and so the organisational interfaces between these parties, and the different objective functions involved, need to be considered. This paper looks at different current and future models for contracted maintenance, identifies interfaces and conflicts of interest, and constructs a quantified model demonstrating the potential impact on headline energy yields for a set of wind farms with a common contracted maintenance resource. The modelling illustrates that the performance of a site with contracted maintenance operations is not only dependent on the contracts held by that site, but also on the effective competition in place with other sites for a centralised resource, and the performance of a site may be highly sensitive to the alignment of contractual incentives, relative travel distances, and the relative size of the site in terms of energy yield.

Keywords
Offshore wind, Asset management, Maintenance modelling, Maritime maintenance, Decision support

1. Introduction

The recent commercialisation of offshore wind has lead to a rapid growth in installations worldwide, with the North Sea being a particular area of focus. In 2013, the generating capacity of offshore wind plant in Europe increased by 34% to 6.6GW across 69 sites [1]. This rate of installation has brought pressure on both the supply chain and operation and maintenance resources, particularly given the significant lead times involved in marine vessel procurement, and the economic pressure to reduce total energy costs towards that of other competing technologies [2].

This resource constraint means that there exists an effective competition between site owners for maintenance resources, which will in turn create a risk in terms of achieved turbine availability levels and, by extension, energy yield and financial revenue. If projected levels of turbine performance are not achieved due to the unavailability of maintenance resource, then the financial viability of a project may be undermined. Previous work has discussed optimal procurement and dispatch methods for offshore wind sites [3 4], or how risk-based Bayesian decision theory can be applied to offshore operations [5], but these ignore the potential for a different performance objective between a site and owner and a contracted maintenance organisation. Clearly a site owner will seek to contract maintenance resources with sufficient incentives for performance to reduce the risk to a given project, but where that resource is shared the allocation of risk may be unequally assigned between multiple projects according to any difference in contract terms between them. The weather-based nature of both the generation profile and vessel access adds a particular set of stochastic risk to offshore wind[6], which must similarly be divided contractually between the site owner and maintenance providers.

As offshore wind grows in installed capacity, clusters of sites can be seen which are grouped around zones favourable for development, either due to geographical constraints (such as water depth), political allocation of development zones, or from shared infrastructure such as high-voltage cabling to shore. Such clusters of sites may benefit, then, from the use of a shared maintenance resource through an economy of scale, but with the risk of that resource being utilised in an unequal manner by a central and independent operations dispatcher. Within the United Kingdom, for example, 3 potential clustering zones have been identified which may form the basis for a cost-reduction exercise through shared jack-up vessel mobilisation costs[7].

In this paper, the focus is on how the forms of maintenance contracts utilised by the site owner may create risk to the project in terms of lost yield and revenue. This is initially described in terms of the assumptions made in yield estimation, before analysing the potential contractual implications for maintenance behaviour from the point of view of the maintenance contractor. Finally, a quantitative simulation is developed for an illustrative case to determine the level of differential availability and yield which may be achieved for a set of independently-owned sites contracting a common maintenance resource.

2. Yield Estimation and Availability Losses

When modelling the projected annual energy production (AEP) of an onshore wind farm, a 3 stage process is typically used[8]. First a Measure-Correlate-Predict (MCP) model is derived and applied between reference and on-site anemometry in order to derive the long-term overall wind conditions of the wind farm location. Secondly, this wind resource is downscaled to the specific topology and layout of the site using flow, turbulence and wake modelling along with the turbine power curves in order to derive the energy production expected at each turbine under assumptions of perfect operation. Finally, loss factors are applied which approximate the expected losses against these assumptions, such as those due to extremes of temperature, performance degradation of the turbine blades, external grid downtime and the actual operational availability of the turbines[9]. These losses are often assumed to be independent of other variables and applied on a pro-rata basis to the gross calculated yield of the site.

Assumptions about operational availability often rely on two sources: historical performance of wind turbines across large publicly available datasets, and typical availability warranties from the turbine Operation and Maintenance Company (hereafter referred to as the O&M Contractor), utilising the assumption that any under-performance against this warranty will be recouped by the site owner in liquidated damages. The former source relies on the assumptions that future turbine reliability is adequately represented by past performance, despite improvements in technology and maintenance regimes, and that the reliability profile of turbines of a similar scale is constant across different models. The latter source assumes that the O&M Contractor will meet or exceed its warranty, and that the definition of warranted availability may be directly applied as one of technical availability. The weakness of these assumptions is investigated in Section 3.2.

The averaged impact of time-based availability[10] assumed in such analysis will also be convoluted in actual operation with the wind speed probability distribution to give a resulting loss of energy. The contracted availability may exclude considerations of wind speed, exposing the site owner to this convoluted risk, which may be considered systemic due to the dependent nature of wind speed and technical turbine availability[11].

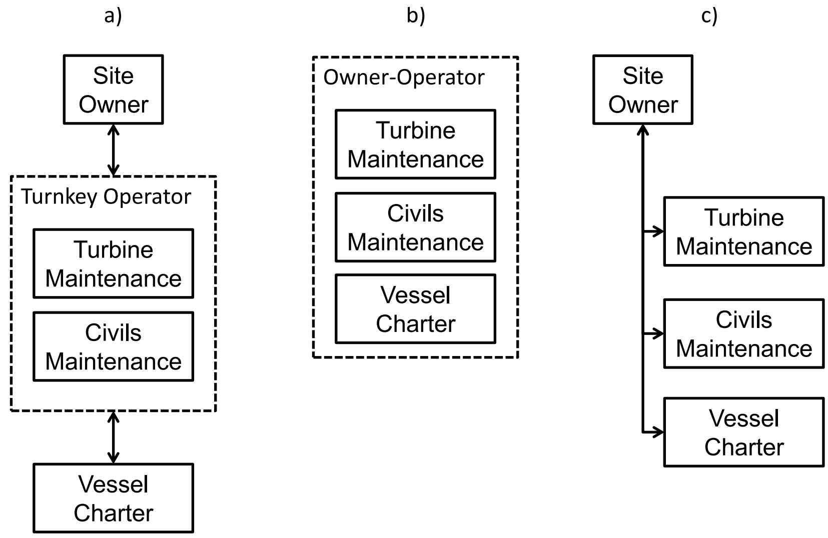

Fig. 1. Contractual interfaces for offshore wind farm operation under a) a turnkey operations contract; b) a full owner-operator and c) multiple contractor arrangements

Small discrepancies in achieved availability against projected may have large financial implications for offshore wind plant; an averaged 1% loss in availability unrecouped on a 50 x 5MW turbine site achieving a 30% capacity factor with an energy value of 100 euro/MWh would result in an annual loss of revenue of 657,000 euro.

3. Contracting Structures

In the operation of an offshore wind plant, the owner will require three sets of services: a maintenance resource of technicians and equipment to effect repairs and servicing; a vessel resource to provide transportation to the maintenance resource to and from the wind turbines; and an onshore maintenance hub with provision of vessel harbouring, spare parts warehousing, and personnel accommodation.

The three main models for contracting operations is shown in Figure 1. Each of these services may be procured through owner-operation, where the site owner owns and operates all infrastructure, equipment and personnel. Due to the magnitude of investment and associated services required, this would generally be restricted to larger utilities. Alternatively, the use of such resources could be done through leasing, whereby the site owner retains control of how the resource is despatched, but does not carry the capital cost of the resource. Finally, the owner may contract for the services of an operations and maintenance company, where all resource dispatch is controlled by the contracted party, and the owner is provided with performance guarantees. The choice between these different forms will be determined by the size of the site, the predicted availability and cost of different forms of vessel charter (discussed below) and the volume of other offshore wind projects in the vicinity with whom shared resources might reduce operational costs.

As turbine manufacturing companies generally sell turbines under an initial operations and maintenance contract and warranty (typically covering the first 5 to 10 years of operation), and the majority of offshore sites are still under this early life guarantee, the use of contracted maintenance services under performance guarantees is the predominant contract form, as discussed further in section 3.2 below.

3.1. Vessel Procurement

A site owner may either own and operate their own vessels in their entirety, or may charter vessels as required. [12] presents three contractual arrangements for chartering vessels:

1. Bareboat charter, whereby the charterer takes on daily running costs, voyage costs and cargo expenses, with the vessel owner only responsible for the capital cost of the vessel;
2. Time charter, whereby the charterer takes on the voyage costs and cargo expenses, normally on a per-day basis, and the vessel owner covers daily running costs;
3. Voyage charter, where the charterer pays only on a cargo basis and the owner covers all other costs. This may be conducted via a spot market.

Different forms of chartering will be most cost-efficient for differing forms of maintenance activity - long-term charters will require advanced scheduling, whereas short-term charters are most suited to unplanned maintenance activities and circumstances requiring instant access for limited periods, such as catastrophic failures.

Aside from economic considerations, the different forms of procurement will also affect the risk exposure of the contracting organisation, which can be significant in the event of, for example, large jack-up vessels requiring unexpected maintenance [13]. The optimum contractual arrangements are, then, a combination of both expected expenditure and risk exposure, alongside an understanding of turbine failure rates and access restrictions. Use of voyage charter allows the risk of under-utilisation of assets to be placed on the contractor, whereas owner-operation and bareboat charter carries exposure to the risk of incorrectly assessing utilisation rates.

3.2. Contracted Turbine Availability

A paper review of multiple operation and maintenance contracts in place in the UK was conducted. An example can be found in the Vestas Wind Systems' (a Danish turbine manufacturer) AOM service contracts [14], which provide a variety of service arrangements, ranging from pay-per-repair services through to full risk-sharing. Many offered packages include 'availability' guarantees, such as either providing a guarantee to the site owner around the proportion of time that a set of turbines will, on average, be capable of operation, or energy-based guarantees, where the owner is guaranteed a certain level of energy yield given a known wind profile, with a proportion of the risk and revenue being shared between the owner and maintenance contractor. Other turbine manufacturers have similar bases for contracts, but these are generally confidential documents. The review found that historically time-based availability was used as the basis for calculating contracted availability levels, taking the generalised form shown in Eq. 1:

$$A_t = \frac{T_{operation} + T_{exclusion}}{T_{total}} \tag{1}$$

where A_t is the availability of a turbine, $T_{operation}$ is the total time that the turbine was technically capable of operation within the warranty period of length T_{total}, and $T_{exclusion}$ is the total time that the turbine was incapable of operation within the warranty period for reasons for which the contractor does not hold contractual liability. The availability of the site, which carries the contracted target, is taken as the arithmetic mean of the availability of the individual turbines.

More recently, energy-based availability contracts have become used, where the aim is to guarantee a level of energy yield, which may incentivise the contractor to conduct scheduled activity around periods of lower wind [15]. This takes the generalised form shown in Eq. 2.

$$A_t = \frac{E_{metered} + E_{exclusion}}{E_{total}} \tag{2}$$

where A_t is the availability of a turbine, $E_{metered}$ is the total energy that the turbine was measured to have exported within the warranty period, $E_{exclusion}$ is the total energy lost by the turbine while incapable of operation within the warranty period for reasons for which the contractor does not hold contractual liability, and E_{total} is the modelled energy output of the turbine had it been capable of full operation throughout the warranty period.

The following are examples of causes of non-availability for which the contractor did not hold contractual liability:

1. A fixed number of hours per year per turbine allocated for scheduled maintenance activity (usually around 40 to 60 hours per turbine per year);
2. A fixed number of hours per year per turbine allocated for retrofit activity (again usually around 40 to 60 hours per turbine per year, in addition to the period allocated for scheduled maintenance);
3. Periods during which either the site HV infrastructure or the external site grid connection was not available or within specified limits;
4. Periods of extreme weather, such as wind speeds sufficient to cause automatic shut-down of the turbines, icing conditions, lows and highs of temperature and lightning strikes;
5. Periods where turbines had failures requiring manual restoration but sea conditions (e.g. wave height) did not permit maintenance access to facilitate repairs;
6. General force majeure exclusions, such as vandalism, criminal acts, extreme weather events and environmental catastrophes.

Contracts differed in their handling of cases where multiple causes of non-availability might apply, such as where a turbine failure coincides with an external grid outage.

Exclusion 3 can be modelled through the use of electrical modelling of the proposed cable layouts and published grid availability data. Exclusion 4 can be modelled through analysis of historical weather and climate data. The effect of exclusions 1 and 2, however, as well as the proportion of time- and energy-based availability lost to non-excluded outages, will be highly dependent on the maintenance strategy adopted by the Operation and Maintenance Company.

The payment of liquidated damages under a time-based availability calculation is normally calculated as a pro-rata volume of energy against either the metered energy of the site for the warranty period, or an average expected yield for the warranty period based on an assumed wind distribution stated within the contract. This volume of energy is multiplied by either the average value of the energy sold during that period (which may be subject to a cap), or a pre-determined fixed energy price.

The payment of liquidated damages under an energy-based availability calculation is calculated as the volume of lost energy attributable to causes for which the contractor is liable, again multiplied by an energy price as above.

Increasingly found in modern contracts is a similar clause which rewards the contractor for over-performance against the warranty, whereby a proportion of the "additional" revenue (typically ranging from 20% to 50%) is returned to the contractor, calculated against the warranted level. This means that from the point of view of the O&M Contractor, each potential turbine repair carries a potential value, which may be defined as the marginal value of repair, given as the return gained by incrementing the availability of the site as a whole at the time of failure. This is given for time-based availability in Eq. 3 and energy-based availability in Eq. 4.

$$MVR_f = \begin{cases} \frac{AEP}{N*8760} * EP, & \text{if } A_{warranted} > A(t)_{actual} \\ \frac{AEP}{N*8760} * EP * IR, & \text{if } A_{warranted} \leq A(t)_{actual} \end{cases} \tag{3}$$

$$MVR_f = \begin{cases} P_n(t) * EP, & \text{if } A_{warranted} > A(t)_{actual} \\ P_n(t) * EP * IR, & \text{if } A_{warranted} \leq A(t)_{actual} \end{cases} \tag{4}$$

where AEP is the Annual Energy Production of the site, EP is the Energy Price used in the calculation of liquidated damages, N is the number of turbines, IR is the Incentive Ratio giving the proportion of increased revenue paid to the contractor for over-performance, $P_n(t)$ is the power output of turbine n at time t, $A_{warranted}$ is the target level of availability specified in the contract, and $A(t)_{actual}$ is the availability of the site from the beginning of the warranty period up to the time t of the failure, with 8760 being the number of hours in a non-leap year.

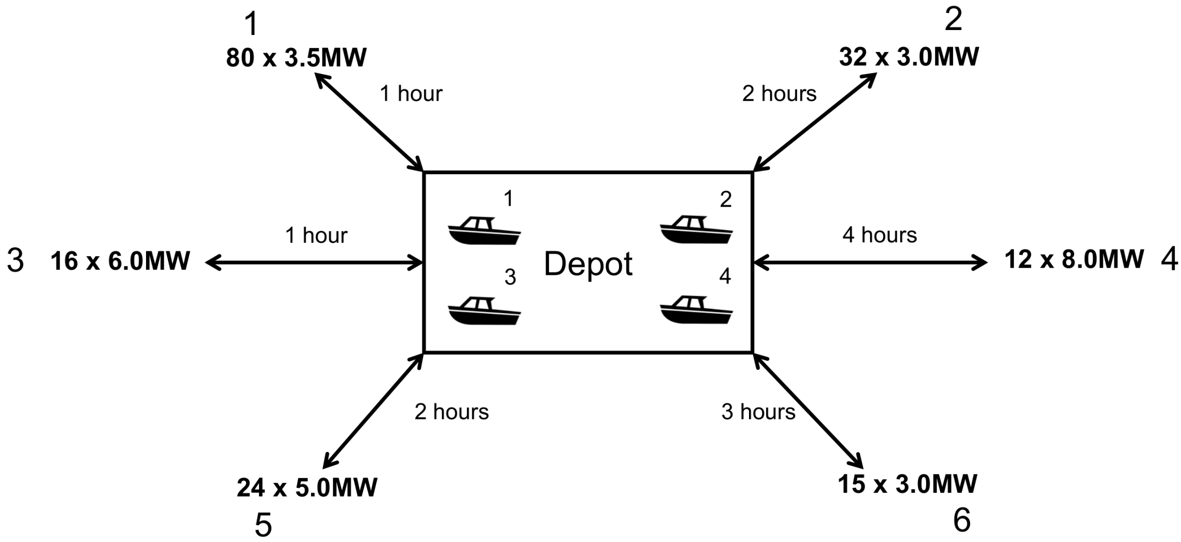

Fig. 2. Example central dispatch simulation, showing 6 offshore wind farms of varying installed capacity and model type, dependent on one onshore maintenance depot with 4 dispatchable maintenance teams.

This shows the differential between the marginal value of a repair on a site performing below warranty, and the lower value of a repair on a site performing above warranty - potentially zero if no over-performance incentive exists. In addition, once the exclusions of liability are applied, this means that the optimum technical availability achieved from the point of view of the contractor may be below the contracted availability level, dependent on availability of maintenance resources.

When conducting an energy yield assessment for a potential wind farm, then, the developer needs to assess not only the specific contract which may be in place, but also the context of that potential site in terms of the likely competition with other sites for use of the central maintenance resource. The impact on any given site of this competition is difficult to solve analytically, as it depends on the specific group of sites in question, as well as behavioural assumptions behind how a maintenance contractor might operate. For this reason, an agent-based simulation, which represents the activity of a human dispatcher in making decisions based on perceived external parameters, is considered to be a useful method of exploring and quantifying this impact. In the next section of this paper, this is simulated for an example scenario to illustrate the potential variance in technical availability and energy yields.

4. Central Dispatch Simulation

The simulation model is an hourly time-stepped combination of the following:

1. A set of wind farms located at varying distances from a central maintenance depot, each comprising a number of identically rated wind turbines;
2. A central maintenance depot with a fixed number of dispatchable maintenance teams;
3. A wind resource model which is used to determine the potential production of each turbine at each time-step;
4. A randomly-seeded reliability model which generates failures with corresponding repair times;
5. An operations agent which deploys the maintenance teams according to a prioritisation algorithm.

The wind resource model involves the use of an exponentially decaying autocorrelation function based on a Markov random walk[16]:

$$\{r\}^n = [P]^{n-1}[G]\{p\}^{n-1} \tag{5}$$

where $\{p\}$ is the initial probability distribution function (pdf), $\{r\}$ is the probability vector equivalent to the limiting pdf, $[P]$ is the initial probability distribution function matrix, and $[G]$ is the decay matrix.

The limiting probability distribution function is set as a Rayleigh distribution (a Weibull distribution with shape parameter equal to 2) with the average value set as the mean monthly wind speed for the wind resource location, U_{res}^{mean} . The use of monthly means introduces a seasonal scaling to the wind resource. This wind resource is then linearly scaled to each wind WPP according to their own scaling parameter, assuming that the geographical separation between WPPs is not significant enough to create a time lag between sites on an hourly timescale:

$$U(t) = U_{res}(t) * U_{conv} \tag{6}$$

This wind speed is converted to the power output of the site by conversion through a generic wind farm power curve and scaling to the rated power of the site.

The reliability model is based on data from the WMEP reliability survey as published in [6]. This gives an average turbine availability of 98.1% (comparable to the earlier figure of 98.0% given in), with 2.45 failures per year and a Mean Time To Repair (MTTR) of 2.82 days. In the simulation, this is approximated by a failure rate of 0.00027968 failures per turbine per hour, with the required working time for each failure randomly sampled from a Weibull distribution with a mean of 67.68 hours.

The failure rate is modelled as being constant and simulated as a fixed probability of failure per hour of operation. While failure rates of some components would be expected to increase over time, the maintenance contractor could also be expected to provide additional resource over time to compensate for the increased maintenance requirement. Hence the question addressed in the simulation is over the deviation in availability from the mean at different sites, rather than how that mean availability may change over time, which we would expect to be managed by the contractor at a relatively constant level in order to maintain their revenue.

The Rayleigh distribution is used to model the distribution of repair times (i.e. how many man-hours are required to fix a particular fault) and is chosen because it represents, in a complex electro-mechanical system like a wind turbine, the relatively higher frequency of faults with a short repair time, while including the long tail of significant mechanical failures that require significant man-hours to address.

As the MTTR statistics include maintenance response times as well as working time, this is likely to be an overestimate, but provides a base case which is held constant over all simulated sites. It would also be expected that the underlying failure distributions would vary between sites according to turbine model and age[17], but this is excluded from the simulation for the purpose of limiting the number of extraneous variables.

The operations agent will generate a rank score between 0 and 1 for each active non-assigned failure, with 1 being highest priority, according to the algorithm in Eq. 7:

$$R_f = a.min\left[\left(\frac{T_f}{T_f^{max}}\right), T_f^{max}\right] + b\left(\frac{MVR_f}{MVR_f^{max}}\right) + c\left(\frac{d_{max} - d_n}{d_{max}}\right) \tag{7}$$

Where R_f is the rank score of failure f, T_f is the time elapsed since failure f first occurred, T_f^{max} is the maximum response time of the contractor to a failure, MVR_f is the marginal value of repair calculated according to Eq. (3) or (4), MVR_f^{max} is the maximum possible marginal value of repair across all sites, d_n is the distance to site n, and d_{max} is the distance to the furthest site. Coefficients a, b, c sum to 1 and provide the weightings for each of the three terms to the

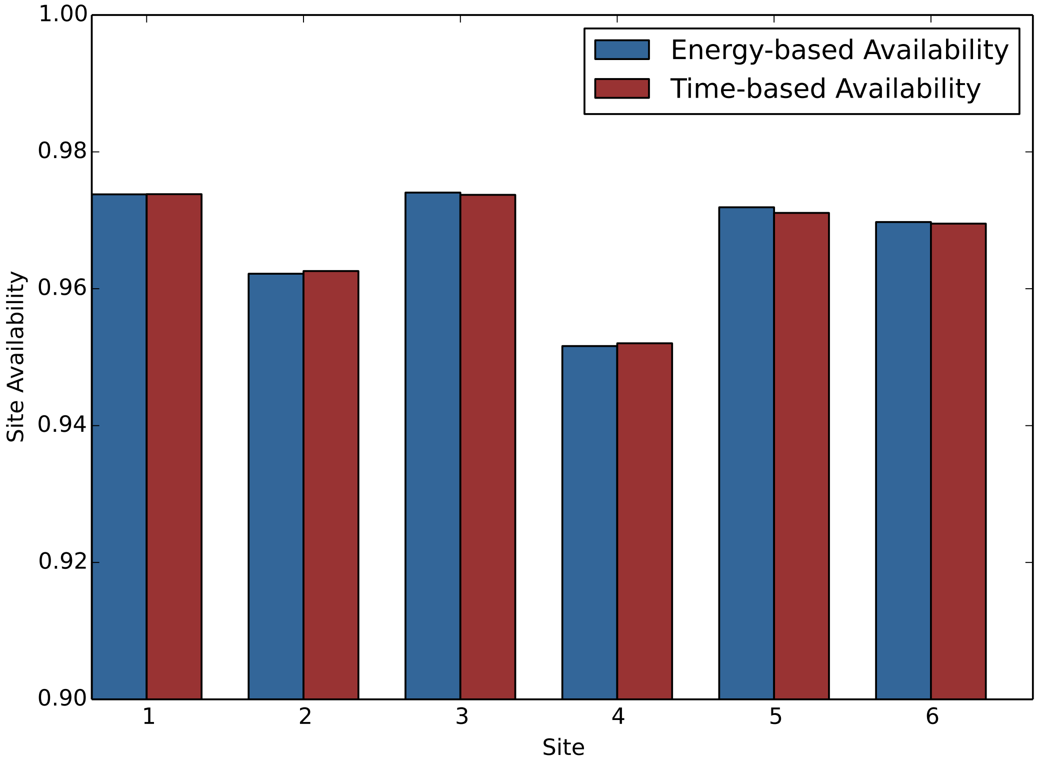

Fig. 3. Achieved availability under time- and energy-based contracts for illustrative scenario

ranking. These coefficients represent the agent balancing the value of repair against the potential punitive contractual terms of repair-specific delays and costs generated by vessel transit times.

If a maintenance contractor had perfect knowledge and fault visibility (i.e. knowing exactly how much resource is required to repair a given fault, and the expected lost energy), then a Marginal Cost of Repair could be calculated. However, a short-term maintenance dispatch decision is more likely to be based on heuristics, and for this reason the three terms are chosen to represent the three key influences upon a maintenance manager's decision-making process. The first term, a function increasing with the time elapsed since failure, is used since the contractor is likely to be subject to increasing pressure from the site owner to fix a fault the longer it is left unaddressed, with a backstop of the guaranteed response time. The second term, the Marginal Value of Repair, provides a weighting towards sites with a better Incentive Ratio, and also a weighting towards sites with larger rated turbines if the guarantees are energy-based. This represents a heuristic representation of how contract terms might be interpreted in real-time operations. Lastly, the final term represents the distance to site, which will affect the effective repair time for a given fault. This might provide a final means by which the dispatcher might prioritise sites where other terms are broadly equal. At the extremes, a=1 would mean the dispatch would be entirely on the basis of fixing the faults in the order in which they occur. Alternatively b=1 would mean the dispatch would be solely on the basis of which site has the most favourable contract (also weighted by turbine size if under energy-based guarantees). Setting c=1 would mean the dispatch would always be in ranked order of travel time to site, shortest travel time first.

For each hour time step of the simulation, the following occurs:

1. The wind resource is updated and the theoretical output of each turbine is calculated;

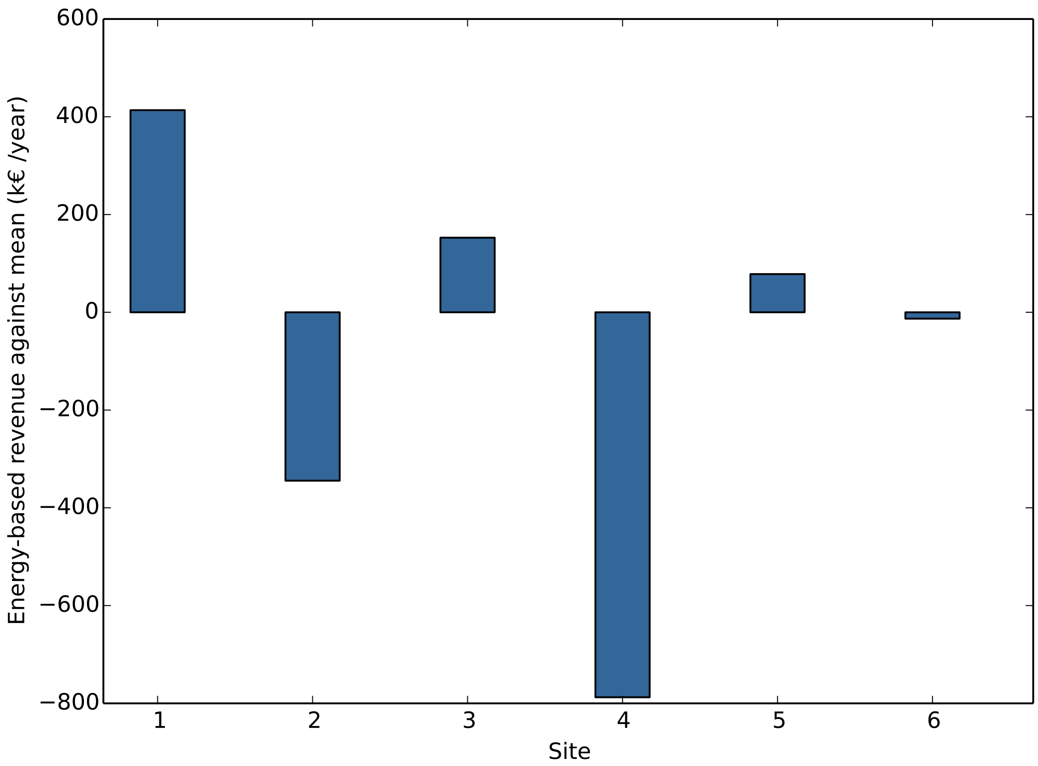

Fig. 4. Effect on annual revenue of each site against average energy-based availability, assuming 30% capacity factor and an energy value of 150 euro/MWh

2. Each operational turbine randomly checks for failures and updates its time- and energy- based availability statistics respectively;
3. The operations agent allocates non-assigned maintenance teams to any non-assigned failures (filtered against distance from depot and available working hours) according to the prioritisation algorithm;
4. Any maintenance teams en-route to their destination advance by one step, and any maintenance teams en-route to the depot advance by one step;
5. Any maintenance teams at their assigned location conduct one period of work on the failure, unless there is insufficient working hours remaining, where they begin to return to shore;
6. Any maintenance teams arriving at the depot become available for re-assignment within working hours.

A wave height access model is not included within the simulation as all the wind farms are within the same meteorological zone, and are hence assumed to be affected equally by maintenance access restrictions. This is in keeping with the contractual handling of vessel access with regards to turbine availability discussed in Section 3.2, and wave access restrictions are considered a separate risk to energy yield which should be modelled in isolation.

Working hours are assumed to be 6am to 9pm, reflecting normal extended coverage without 24/7 response. As an illustrative scenario, four maintenance teams are dispatchable to six wind farms, each with travel times and turbine ratings as shown in Figure 2. While in practice offshore wind turbines will tend to be larger than this in both terms of turbine rating and turbine numbers, the example is intended to demonstrate the impact of variation in both parameters. The coefficients a, b, c are set to 0.4, 0.5 and 0.1 respectively to reflect the importance of contracted response and returns. This weighting is chosen as it prioritises the value of repair, ensuring that the contractor is primarily motivated by financial returns, but

Table 1. Energy-based availability sensitivities to wind farm parameters

Parameter	Energy-based availability sensitivity
Travel time	-0.62% per hour
Incentive Ratio (IR)	0.0018% per percent
Rated Power	0.05% per MW

balanced against the penalties that may result from overly long response times. The distance to site is given a smaller weighting as this is intended only to provide a determination between sites where they are otherwise at a near-equal priority, and might reflect the decision-making of an operations manager where two faults are seen as carrying a near-equal contract value.

Running the above simulation over a period of 10 years under a time-based availability guarantee gives the resulting time-based availability values shown in Figure 3. Because there is no prioritisation of failures according to wind speed, the energy-based availability values can be expected to be approximately the same, with any difference due to random variations in wind speed This shows that despite the low weighting given to distance in the prioritisation algorithm, this appears to be a key factor in determining the overall availability achieved by the site. This is further emphasised in the sensitivity analysis.

However, under an energy-based availability guarantee, the energy-based availability can be expected to differ from the time-based availability. To provide further context, the impact of these availability figures on the annual energy revenue of each site (ignoring resulting damages paid by the maintenance contractor) are given in Figure 4 against the mean energy-based availability achieved on a per-site basis. Under an energy-based guarantee, the differential in achieved availability on each site is increased, as there will now exist periods during which high wind speeds additionally incentivise response towards sites at a shorter distance where repairs may be enacted more rapidly. The results shown indicate that the gains and losses are not evenly spread, with one site predominantly favoured and one site subject to disproportionate losses, reflecting the average frequency with which each site may find itself at the top or bottom of the ranking algorithm.

These results demonstrate that even where contractual terms (such as the Incentive Ratio) is set at a value which may appear to adequately incentivise a high lvel of availability for a given site, the actual achieved performance of that site may be subject to additional external factors, and that a site owner will need to consider the operational context of their site to determine the optimal contract arrangements. For example, a site located further from shore may need to increase the incentive ratio for payments to the contractor to compensate for the additional costs the contractor faces in dispatching maintenance resource to that site. Under and energy-based guarantee, the site owner may similarly wish to scale their incentives to that of the largest rated power turbines in the vicinity, to ensure that their turbines are treated on a equal per-failure basis to other sites, where the energy yield may be proportionally higher.

Table 1 shows the sensitivity factors for each of the site parameters in terms of the average impact upon the energy-based availability. The sensitivity for travel time to site, in particular, illustrates the significant impact of man-hours expended on travel (which will add to the cost of repair without increasing the value of that repair to the contractor) to the discrepancies in performance between sites. The quantified sensitivity for the Incentive Ratio (IR) allows the site owner to make a quantified decision about how increasing the proportion of revenue shared with the contractor might affect their financial returns - but this value will also vary according to the IR values of other sites, and so may need to be revised if, for example, additional sites are constructed within a zone of shared resources.

5. Conclusion

The analysis presented here illustrates the importance of considering the context of an onshore wind farm within the wider maintenance activity of the O&M Contractor, whose contractually motivated goals may not always be in line with the owner of each site, when considered individually. Hence where energy yield analyses are being conducted for prospective onshore sites, sites with smaller models of turbines located at a greater distance from the proposed maintenance centre should take into account the low priority that failure responses may take for their site as opposed to larger, more centralised wind farms or ones within which the maintenance depot is located. The modelling conducted shows that distance to sites is a key consideration, and the form of warranty taken (time- or energy-based) should also be taken into account. This work may be further expanded by considering the availability of spare parts, and where competition for such parts exists between multiple sites, especially within the context of serial defects and retrofitting. This could be achieved through the addition of an optimised spare provisioning policy following the approach described in [18].

Furthermore, the offshore wind sector is increasingly being seen as an economical use case for advanced condition monitoring technologies [19] and consideration could be given to how predictive maintenance strategies may be effectively incentivised across contractual boundaries, particularly with respect to warranty breakpoints which may cause the long-run outcome may affect each party differently, again increasing risk exposure for the project owner.

This work further demonstrates the onus on site developers to consider in detail the contractual frameworks necessary for financial performance of their wind projects, and that if key elements are to be outsourced, that the developer needs to ensure that the contractual interfaces they utilise can, firstly, allow them to respond to external factors such as new incoming sites competing for the same resource, and secondly, to redefine financial incentives to their contractors in order to allow them to exercise some degree of responsiveness should a constraint in maintenance resources arise. It would be of interest to evaluate how the contracts of multiple sites in a region might evolve over time as such competition for resources increases, or to look into the effects of component ageing increasing competition through additional maintenance requirements. This would also require more detailed modelling of the long-term behaviour of a contractor in forecasting, costing and providing the optimal level of resource, against a competitive background of multiple service providers.

One aspect that this work highlights is that the form of contract arrangements used by site owners may appear to provide security for future operations but in reality the achieved performance may depend on external factors outside of their control. This may be alleviated by further alignment of Key Performance Indicators (KPIs) with maintenance contractors, to the extent that if an underperformance of a site is linked to the unavailability of a maintenance resource, that the KPIs ensure that the contractor is incentivised to increase that resource rather than electing to take on the financial penalties of underperformance. It could also be seen that high-level availability contracts, such as those described, are a blunt instrument which provides the site owner with little ability to intervene. An alternative structure might see owners taking a day-to-day approach in balancing the costs and benefits of maintenance activity, with multiple sites bidding for maintenance provision dependent on the predicted wind resource and energy trading position of the energy off-taker. Similarly, a wind site could choose to receive short-term compensation from other sites to balance a delay in repair, funded by the differential in repair values between sites. Analysis of such a framework through game theoretic methods would inform how sites being developed in future offshore development zones might interact and socialise the costs incurred by the overall benefit of utilising communal operational resources, and could be of great value to the expanding industry.

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