Modelling the effect of maintenance strategies and reliability for long-term wind yield assessment

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Abstract

Where a number of onshore wind farm locations are being maintained by a single central Operation and Maintenance Contractor, an effective competition exists between those sites for the use of that maintenance resource. Any differentials between those sites in terms of the costs of repair to the contractor, or the potential return to the contractor for improving the site availability under the Operations and Maintenance Contract, may mean a variance in the level of operational availability achieved by each site. A review of UK contract terms illustrates the potential differentials that may occur. A maintenance optimisation model is created which is used to simulate the potential availabilities of a set of wind farms maintained from a central resource in response to typical published failure rates and restoration times.

Keywords: Wind Energy, Maintenance, Yield Assessment, Reliability

1. Introduction

When modelling the projected annual energy production (AEP) of an onshore wind farm, a 3 stage process is typically used. 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. 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.

Maintenance planning approaches such as that presented in [1] usually assume that the site owner is also directly responsible for operation and maintenance. While offshore wind farms are usually of a scale that they are serviced by a single maintenance centre with no other responsibilities, onshore a single contractor will usually be servicing multiple sites from a single centralised location, which may even be based at a site of sufficient size as to incentivise minimisation of travel times. This introduces an inherent bias to failure response times

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 underperformance 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.

However, where the O&M Contractor is responsible for the maintenance of multiple sites from a finite central dispatchable maintenance resource, there may be a conflict between those sites in terms of the priority with which repairs are enacted, either due to an inequality in contract terms between those sites leading to a differential in values of repairs to the O&M Contractor, or by an inherent differential in the cost of repairs due to the distance of sites from the central maintenance location.

Secondly, the expected wind farm output should take into account the failure and repair rates of individual turbines within the context of a stochastic wind resource [2], with the wind farm model comprising both wind resource and turbine models. This has an impact on how availability measures may differ according to whether they take a time- or energy-based approach, as assessed in [3].

This paper firstly provides an overview of typical O&M Contract terms found from a survey of UK maintenance contracts in order to indicate the likely nature of the dispatch problem from the point of view of the O&M Contractor. Secondly a simulation is created with a combined wind resource and turbine model to quantify the impact of this dispatch problem on the availabilities of a number of separately contracted wind farms utilising a single central maintenance resource. Finally, this simulation is conducted for a range of scenarios to provide a sensitivity analysis which may be used to inform energy yield assumptions for a specific site location.

2. Contracted Availability

A paper review of multiple operation and maintenance contracts in place in the UK was conducted. This found that historically time-based availability [4] was used as the basis for calculating contracted availability levels, taking the approximate form shown in Eq. 4.

$$A_t = \frac{T_{operation} + T_{exclusion}}{T_{total}} \quad (1)$$

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. This takes the general form shown in Eq. 2.

$$A_t = \frac{E_{metered}}{E_{total} - E_{exclusion}} \quad (2)$$

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. General *force majeure* exclusions.

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).

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

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

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.

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. In the next section of this paper, this is simulated for an example scenario to illustrate the potential variance in technical availability.

3. 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 [5]:

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

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 wind speed for the wind resource location, U_{res}^{mean} .

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 [2]), 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. 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 [7], 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 ranking.

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;
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 the depot;
6. Any maintenance teams arriving at the depot become available for re-assignment within working hours.

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 1. 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.

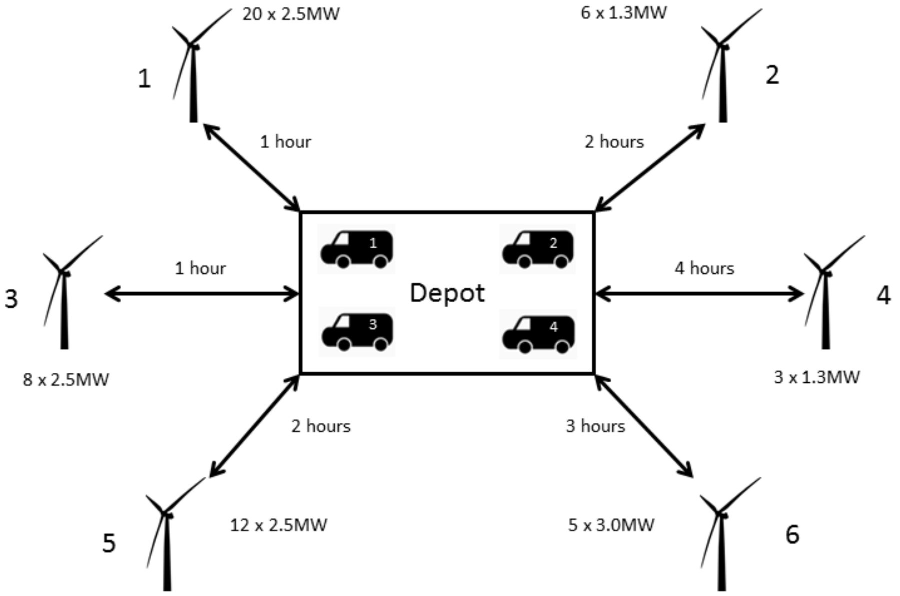

Figure 1 - Illustrative scenario for a centralised maintenance depot servicing 6 wind farms

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 2. 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 noise. 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.

However, under an energy-based availability guarantee, the energy-based availability can be expected to differ from the time-based availability, and these values are shown in Figure 3.

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.

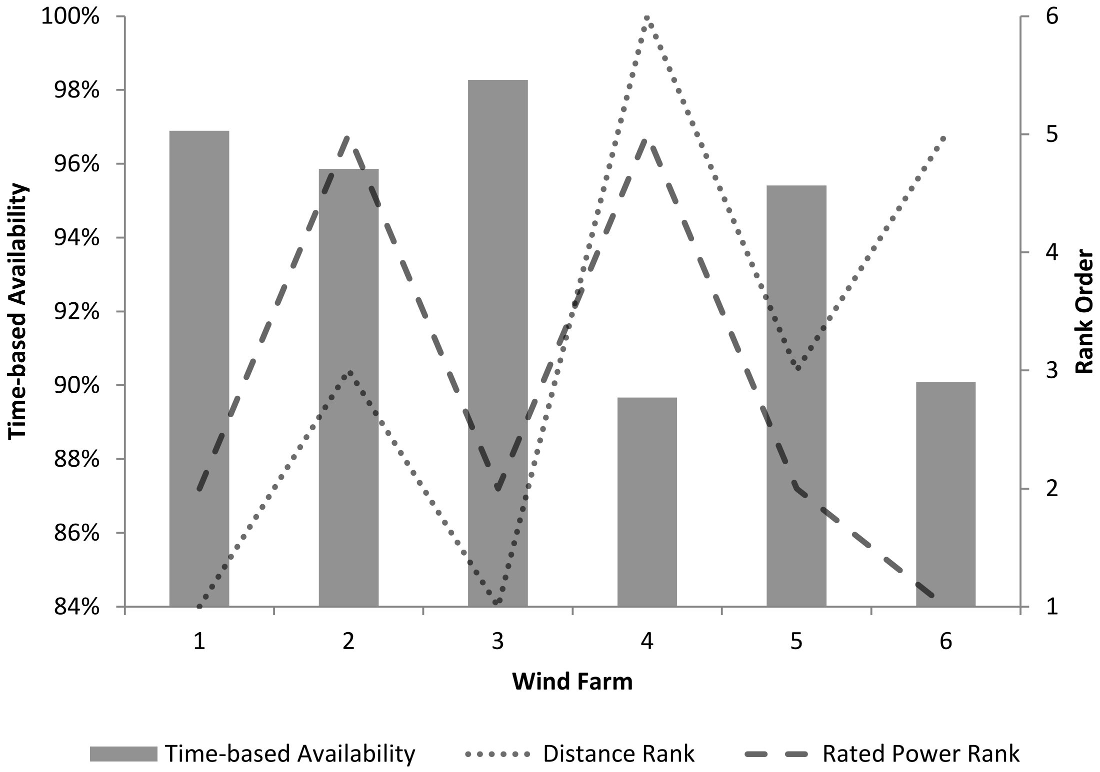

Figure 2 - Time-based availability under time-based contract for illustrative scenario

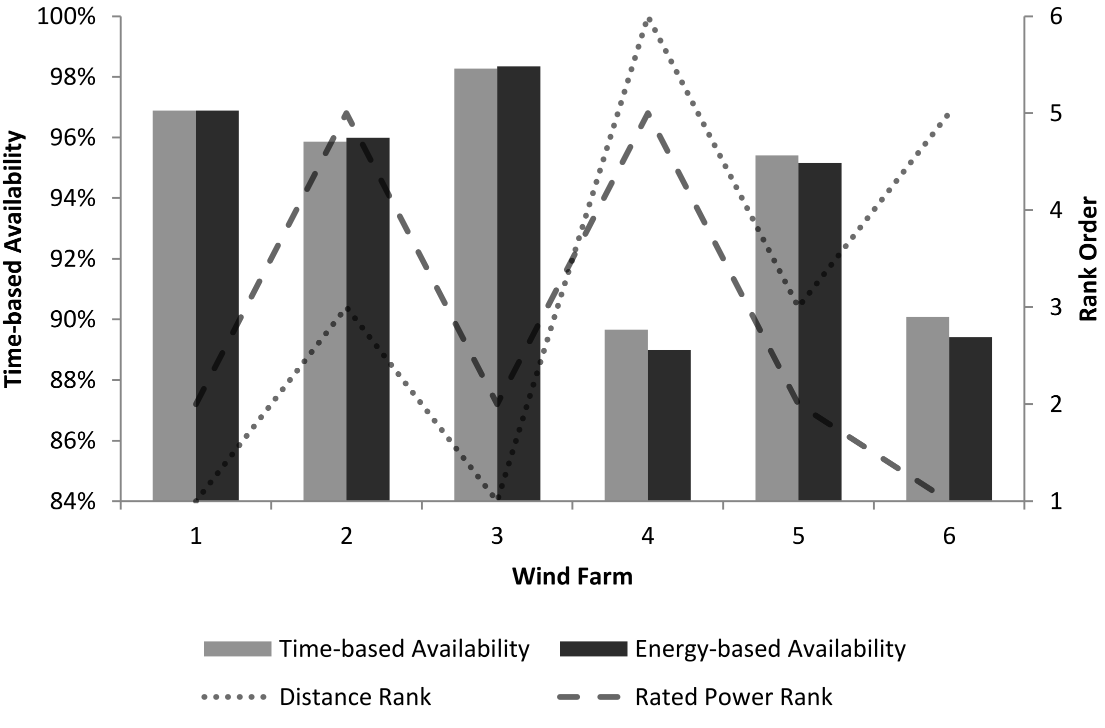

Figure 3 - Time-based and energy-based availability under energy-based contract for illustrative scenario

4. 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 [8].

5. References

[1] F. Besnard and L. Bertling, “An approach for condition-based maintenance optimization applied to wind turbine blades,”*, IEEE Transactions on Energy*, vol. 1, no. 2, pp. 77–83, 2010.

[2] F. C. Sayas and R. N. Allan, “Generation availability assessment of wind farms,” *IEE Proceedings on Generation, Transmission and Distribution*, vol. 143, no. 5, p. 507, 1996.

[3] N. Conroy, J. P. Deane, and B. P. Ó Gallachóir, “Wind turbine availability: Should it be time or energy based? – A case study in Ireland,” *Renewable Energy*, vol. 36, no. 11, pp. 2967–2971, Nov. 2011.

[4] International Electrotechnical Commission, “Standard 61400-26: Time based availability for wind turbines,” 2010.

[5] G. M. McNerney and P. S. Veers, *Markov method for simulating non-Gaussian wind speed time series*. Sandia National Laboratories, 1985.

[6] Reliawind Project, “Report on Wind Turbine Reliability Profiles,” 2008.

[7] F. Spinato, P. J. Tavner, G. J. W. van Bussel, and E. Koutoulakos, “Reliability of wind turbine subassemblies,” *IET Renewable Power Generation*, vol. 3, no. 4, p. 387, 2009.

[8] R. Sarker and A. Haque, “Optimization of maintenance and spare provisioning policy using simulation,” *Applied Mathematical Modelling*, vol. 24, no. 10, pp. 751–760, Aug. 2000.