O&M Cost Modelling, Technical Losses and Associated Uncertainties

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Summary:
Deutsche WindGuard has developed a simple approach to estimate the rise of repair and maintenance cost (here called O&M cost) and wind turbine downtimes with turbine age. The model has been tested successfully against true O&M cost of onshore and offshore wind farms. Data from various wind farms with different types of wind turbines, also in the higher age, have been considered for the analysis.
Furthermore, an approach has been developed, how uncertainties of the wind resource can be cumulated with uncertainties of estimated technical production losses in order to more accurately calculate risks involved in wind farm investments. It has been experienced that O&M cost are often underestimated in the high age. In addition, assumptions about turbine availability are often too optimistic for old wind turbines. This is mainly due to the fact that in the high age larger repairs are likely linked to a shortage of spare components, what then leads to single events with long standstills.

1 Introduction

The risk involved in wind farm investments is, among others, dependent on the O&M cost, its development over the wind turbine lifetime and associated production losses due to turbine downtimes. Accurate public data on O&M cost is rare, especially for old wind farms. As O&M cost and turbine downtimes can be expected to increase with turbine age, the question arises how long a wind farm can be financed.
A simple approach for the rise of O&M cost and turbine downtime with the turbine age has been developed.
The estimates of production losses due to turbine downtimes and the estimated O&M cost are often subject to significant uncertainties. For wind farm financing, normally only uncertainties of the wind resource are considered. Uncertainties of estimated technical production losses and O&M cost are mostly not considered. Thus, an approach has been developed, how these uncertainties can be cumulated with uncertainties of the wind resource in order to provide an improved risk assessment for earnings expected from a wind farm project.

2 Public O&M Cost Studies

A number of public available cost studies have been analysed. The three most important once are believed to be:

- O&M cost study of German Wind Energy Association from 1999 [1] and 2002 [2]: This study is mainly based on questionnaires of wind turbine manufacturers, service companies and insurances. According to these studies, on average 54 % of the investment cost must be expected as cost for repair and maintenance during 20 years project lifetime, while these cost are expected to be twice as high in the second decade than in the first decade.
- Annual report of the German Scientific Measurement and Evaluation Program of the year 2006 [3]: O&M cost of a few hundred wind turbines have been analysed here, also in dependence of age.
- Presentation about wind turbine failure rates of Durham University and Technical University of Delft from EWEC 2008 [4]: Different public available statistics have been analysed in respect to failure rates of certain wind turbine concepts.

The content of these studies in general suffers from the following shortcomings:

- The input data of these studies about O&M cost is mostly not very detailed.
- There is only little data from wind farms with high age of about 15-20 years included in the studies.
- There was a rapid development of technology and size of wind turbines ongoing during the last decade. It is not clear in how far experience about O&M cost gained with old generation wind turbines will hold true for today's state of the art technology.

Despite of these shortcomings, the above mentioned cost studies come to quite similar ranges of total O&M cost, and all of them let assume a rise of O&M cost with turbine age (Figure 1, Figure 2).

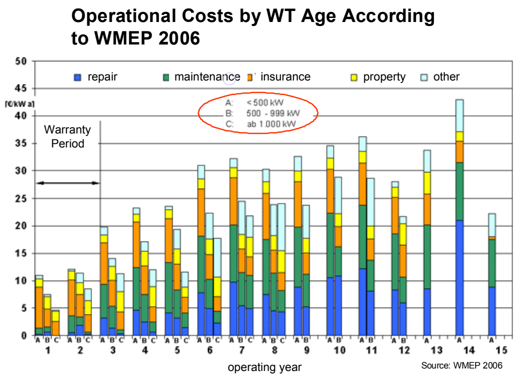

Figure 1: observed rise of O&M cost of wind turbines according to reference [3]

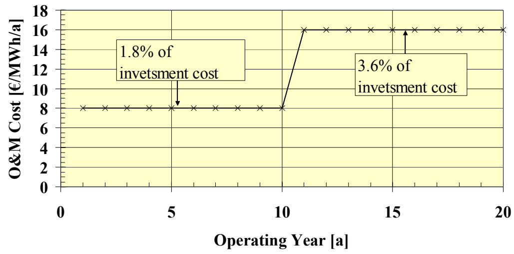

Figure 2: Repair and maintenance cost of wind turbines according to reference [1], [2].

3 Modelling of Rise of O&M Cost with Age of Turbine

3.1 Current State-of the Art

The expected increase of repair and maintenance cost with age of the wind turbine should ideally be evaluated on a type specific component by component basis and in dependence of site conditions. Unfortunately, the required information for this is available in the best case only for wind turbine manufacturers. In practice, case dependent O&M cost modelling on the basis of failure mode analysis of specifically applied components, like it is standard in the aircraft industry, is hardly possible to date for the wind energy industry. Consequently, the application of more generalised approaches for the increase of O&M cost with turbine age are normally applied. According to experience form a large number of due diligence cases in recent years, the following assumptions are often applied by wind farm developers or financers for the increase of repair and maintenance cost with time:

- no increase of O&M cost after the warranty period (except of rise of cost due to inflation),
- twice as high O&M cost in second decade than in first decade after warranty period (additionally corrected for inflation),
- increase of O&M cost in more steps, e.g. every 5th year (additionally corrected for inflation).

3.2 Improved Approach for Rise of O&M Cost with Age of Turbine

There is evidence that at current stage repair and maintenance cost is higher in the high age of wind turbines. Thus, the often seen assumption of constant O&M cost after the warranty period makes not much sense. An improvement over the assumption of a step function would be the assumption of an exponential increase of repair and maintenance cost, like it is often applied in other industries:

$$C = A \cdot e^{\beta \cdot t}$$

where

C: repair and maintenance cost
A: constant
β: constant
t: age of wind turbine

This function contains two constants, which must be determined for the modelling of O&M cost. There is often no proper information available to choose the constant β project specific. An approach for determining the constant β is to assume twice as high O&M cost in the second decade than in the first decade according to reference [1], [2]. The condition

$$\int_{t=0}^{t=10a} C(t)dt = \frac{1}{2} \int_{t=10a}^{t=20a} C(t)dt$$

then leads to

$$\beta = \frac{\ln(2)}{10a}.$$

The proportionality constant A can be adjusted to experience with the type of turbine under consideration of the wind farm site conditions, cost of repair and maintenance contracts for the first project years, or generalised cost assumptions. Figure 3 compares the approach of exponential increase of repair and maintenance cost with other cost rise assumptions for the example of average cost of 12€/MWh/a in 20 years.

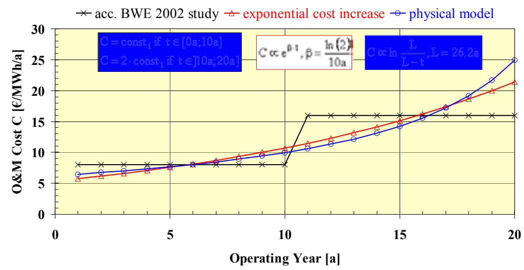

Figure 3: comparison of different approaches for rise of repair and maintenance cost with turbine age for the example of average cost of 12€/MWh/a in 20 years

3.3 New Approach for Rise of Q&M Cost with Age of Turbine

A better reasoned approach for the rise of repair and maintenance cost with wind turbine age has been developed on the basis of the following two assumptions:

- The increase of component damage per time is inversely proportional to the remaining lifetime.
- The increase of component damage is proportional to the increase of repair and maintenance cost.

These 2 assumptions lead to the differential equation:

$$\frac{dC}{dt} \propto \frac{1}{L - t}$$

where

C: repair and maintenance cost
L: lifetime
t: age of wind turbine

This differential equation has the solution:

$$C = const_1 \cdot \ln(L - t) + const_2$$

With the condition

$$C(t = 0) = 0$$

then follows:

$$C = const \cdot \ln\left(\frac{L}{L - t}\right).$$

This is an approach for repair and maintenance cost with 2 parameters (the proportionality constant and L).

The assumption of twice as high repair and maintenance cost in the second decade than in the first decade leads to:

$$L=26.2a.$$

As for the exponential law approach, the proportionality constant can again be adjusted to experience with the type of turbine, site conditions, cost of repair and maintenance contracts for the first project years, or generalised cost assumptions.

This new approach for the increase of repair and maintenance cost with time is compared to the exponential law approach and the step function approach in Figure 3 for the example of average cost of 12€/MWh/a in 20 years. The new approach leads to quite similar results than the exponential law approach in the first 18 years. In the higher turbine age, the new approach leads to significantly higher assumptions for the cost increase than the exponential law approach. This is more in line with the typical bathtub curve of failure rates as explained in reference [4].

4 Comparison of Observed O&M Cost with Modelled Cost

Repair and maintenance cost of several wind farms with different types of wind turbines in the age of up to 15 years have been analysed and compared to the modelled cost. Exemplary and typical results are shown in Figure 4. Only operating periods out of the warranty period have been considered for the comparison, as the true repair and maintenance cost during the warranty period were not available. The approach of exponential cost increase with age has been applied for the comparison. Twice as high cost in the second decade than in the first decade has been assumed in order to determine the constant β. The proportionality constant of the exponential law has been fitted to the observed data after the warranty period.

Figure 4 shows a clear tendency of increasing O&M cost with turbine age in case of the wind farm data. Outliers to high cost values are observed in single years, which are due to gearbox damage in the shown cases. The increase of cost with turbine age, at least when cumulated over a few years, is fitted reasonably well by the exponential law.

The exponential law has been extrapolated to 20 years as illustrated in Figure 5. The resulting O&M cost averaged over 20 years is shown in Figure 4 and Figure 5 for different types of wind turbines. For onshore wind farms average O&M cost between 7 €/MWh/a for the analysed direct drive wind turbines and between 12 €/MWh/a and 17 €/MWh/a for the analysed wind turbines with gearboxes follows. This cost range and also the difference in O&M cost between direct drive and gearbox machines is well confirmed by a recent analysis of operating cost of 66 wind farms in the years 2006 and 2007 as reported in reference [5] and [6]. It is also well in line with typical cost of full service contracts as offered by some wind turbine manufacturers for onshore wind farms of a bit more than 10 €/MWh/a (typically for the first 10-12 years of operation).

Figure 4 and Figure 5 contain also repair and maintenance cost of the nearshore wind farm Middelgrunden as reported in reference [7]. The exponential extrapolation would here lead to average O&M cost of 24 €/MWh/a, i.e. much higher values than for the analysed onshore wind farms.

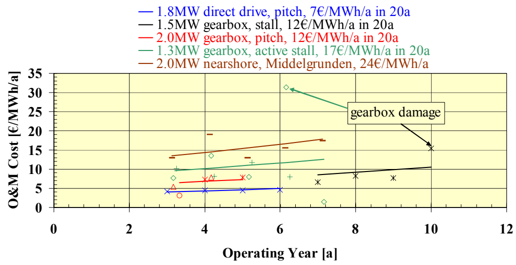

Figure 4: Comparison of observed and modelled repair and maintenance cost. The legend explains the type of wind turbine technology analysed as well as the average cost that result for a 20 years operating period if an exponential cost increase is fitted to the observed data.

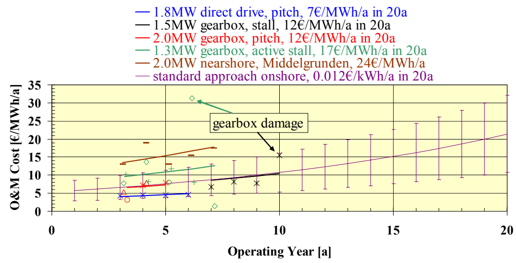

Figure 5: illustration of extrapolation of observed O&M cost to a period of 20 years

5 Observed Availability Losses in Old Wind Farms

Detailed public data on availability figures of wind farms is rare. A recent study about availability of wind turbines reported in reference [8] covers mainly wind farms up to 10 years old. While average availability of utility scale wind turbines is reported as about 97% in reference [8], it is suggested to assume lower availabilities for wind farms older than 10 years. Production losses due to non-availability of a large number of wind farms with wind turbines mostly between 500kW and 3MW rated power have been analysed by WindGuard in the frame of wind farm performance analysis and optimisation during the last years. The average availability resulting from this analysis turned out to be very dependent on the type of wind turbine and was on average lower than 97% (Figure 6). Remarkably, the analysed wind farms with direct drive wind turbines have in tendency higher average availabilities than the analysed wind farms where gearboxes are applied, what is well in line with the observed tendency to lower repair and maintenance cost of direct drive wind turbines as shown in Figure 4. The reason for the lower average availability analysed by WindGuard compared to the value reported in reference [8] is believed to be due to the fact that the availability has been defined in terms of the energy production by WindGuard rather than in terms of the availability in percentage of time. As reported in reference [9], the energetic availability has in tendency found to be significantly lower than the availability in percentage of time in cases with low availability numbers. This is likely due to the fact that low availability numbers are often due to unscheduled downtimes caused by wind turbine failures, which occur more frequently during high wind speeds than at low wind speeds. Furthermore, all wind turbine downtimes have been accounted as non-availability periods by WindGuard, even if it was caused by external conditions, like e.g. grid downtimes.

Significant experience with the technical availability of old wind farms in the age of 15-20 years exists from the region Eastern-Frisia in the Northwest of Germany where many wind turbines have been installed in the early 1990's. The general observation made there is that old wind turbines normally have a high technical availability in the order of 97% to 98%. However, it is also observed that many of these wind turbines have single longer lasting downtimes due to component failure or wear-out with a typical duration of 2 to 6 months. Often the right spare parts are not available in time or not available for reasonable cost, so that repair takes long. A single wind turbine downtime of 3 months duration means at the most 75% technical availability in the year of occurrence and 2.5% availability loss when calculated for a decade. Even if the turbine availability is 98% in the remaining time of the decade, the total availability will only be 95.5% averaged over the decade in case of a single event with 3 months downtime. Thus, the average wind turbine availability in tendency decreases in the high age.

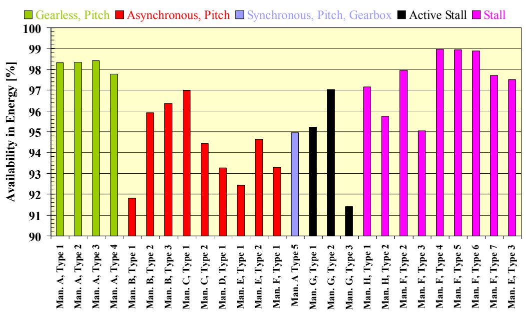

Figure 6: True technical availability in terms of energy production for different types of wind turbines.

6 Approach for Increase of Availability Losses with Age of Turbine

It is likely that the increase of repair and maintenance cost with the age of wind turbines is linked to increasing production losses with the turbine age. A simple approach is to assume that the non-availability losses increase proportionally with repair and maintenance cost. Then, the models explained above for the increase of repair and maintenance cost hold true also for the non-availability losses.

Figure 7 illustrates the approach of exponential increase of non-availability losses for the case that it is initialised with 3% average non-availability in the first decade. Then, 6% non-availability losses follow for the second decade, what reflects well the above explained case of a single longer lasting downtime of an old wind turbine. For a 20 year operating period, then average non-availability losses of 4.5% result, what is believed to be more realistic than the often seen assumption of 3% non-availability losses over the whole lifetime of the wind farm.

In practice, the exponential law (or the law explained in section 3.3) can be adjusted to warranties of the wind turbine manufacturer or independent maintenance providers, to experience with the considered type of wind turbine or to the observed non-availability losses in the past operating period. An example for the latter case is given in Figure 8. In that example, the wind farm had significant teething problems in the first 1.5 operating years. Afterwards, an availability of about 98% was reached with a tendency to decrease in operating year 6 to 8.5. The exponential law has been fitted to the operating period after the teething problems were solved. As a result, 4.3% average non-availability losses have been estimated for the remaining lifetime (operating year 8.5 to 20). In the shown case, it is already known that significant repair of the wind turbines will be required over the next years, so that the lower availability evaluated in the remaining period is by far more realistic than assuming 98% availability like observed on average in operating years 1.5 to 8.5.

The assumption of increasing non-availability losses influences cash flow models of the considered wind farms, as it leads to a decrease of expected revenues with time.

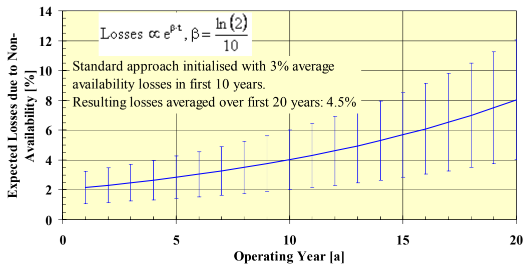

Figure 7: Standard approach for increase of non-availability losses with the turbine age. The bars denote the estimated standard uncertainty of the non-availability losses.

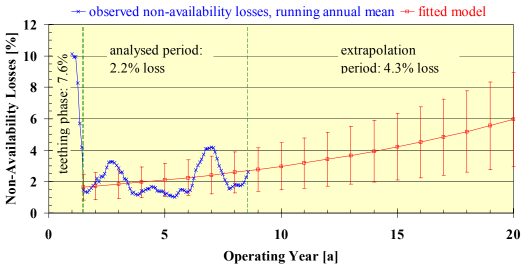

Figure 8: Fit of exponential law for increase of non-availability losses with age to observed data. The bars denote the estimated standard uncertainty of the non-availability losses.

7 Combination of Uncertainties of Wind Resource (Revenue) and O&M-Cost

Risk assessments of wind farms normally include uncertainty analysis of the wind resource, i.e. the probability of exceeding certain energy yields is calculated for economic considerations. According to current practice, these surveys of uncertainty account for technical losses, like non-availability losses and line and transformer losses, however the uncertainty of the technical losses is not included. This is considered as a shortcoming, because the non-availability losses of wind farms can have significant uncertainty. Normally, this uncertainty increases with increasing expected non-availability losses (see bars in Figure 7 and Figure 8 for illustration). Especially for offshore wind farms, the uncertainty of non-availability losses reaches easily the same magnitude than the uncertainty of the wind resource. By cumulating the uncertainty of the wind resource and the technical losses, a more realistic risk assessment for the project revenues is gained. Notice that the uncertainty of non-availability losses increases with the project age if an increase of these losses is assumed, i.e. the revenue of old wind farms is not even matter to decrease with age, it is also linked to increased uncertainties.

As O&M cost of wind farms make out a significant amount compared to revenues, the uncertainty of O&M cost should be taken into account for evaluating earnings from wind farm projects. Also this is not state-of-the-art today. The uncertainties of O&M cost must be cumulated with the uncertainties of the revenues, i.e. a solution is needed how to calculate the earnings exceeded with a pre-defined probability (P-value of earnings). An aspect to be considered here is that the repair and maintenance cost normally decrease with decreasing wind resource. This issue can be accounted for as follows (see also illustration in Figure 9):

- First, the expectation value and standard uncertainty of the repair and maintenance cost should be calculated on the basis of the wind resource which is exceeded with a certain probability. This means, the repair and maintenance cost and its standard uncertainty is assumed to be proportional to the energy production at a certain time (but it is assumed to decrease with age of the wind farm). However, the energy production used for this estimation is the energy yield exceeded by the required probability level instead of the expectation value of the energy production.
- As next step, the standard uncertainty of the repair and maintenance cost and the standard uncertainty of the wind resource in terms of earnings are considered as independent from each other, i.e. they are added as root of the square sum in order to calculate the standard uncertainty of the earnings. This is justified only because of the previous step of estimation of repair and maintenance cost.
- Finally, the earnings exceeded with a certain probability are calculated from a normal distribution with the expectation value as difference of the revenue for P50 and the repair and maintenance cost referring to the required exceeding probability and the combined standard uncertainty.

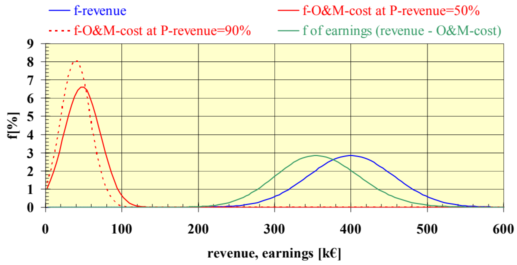

Figure 9: Illustration of combination of uncertainties of repair and maintenance cost and uncertainties of the wind resource (expressed as revenue) to a cumulated uncertainty of the earnings

Another aspect when cumulating uncertainties of the revue with the uncertainty of repair and maintenance cost is that the increase of non-availability losses with the age of the wind turbine is highly correlated to the increase of the repair and maintenance cost with turbine age. In good approximation, the uncertainty component of the revenue due to the uncertainty of the assumed non-availability losses can be combined with the uncertainty of the repair and maintenance cost linearly.

The outcome of such an analysis is the earning exceeded with a requested probability in dependence of the age of the wind farm. This can be used for the evaluation of the lengths of a feasible economic operation of a wind farm. Examples are shown in Figure 10 in case of a wind farm with relatively low capacity factor in combination with a high energy tariff (left diagram) and in case of a wind farm with high capacity factor in combination with a low energy tariff (right diagram). In the first example, the earnings remain relatively high even in operating year 20, however, in the second example, the earnings decrease rapidly in the high age of the wind farm, and an economic operation may be questionable in the high age.

In principle, the evaluations can be extended to operating periods longer than 20 years. However, a problem for a wind turbine operation longer than 20 years is that normally the building permit of the wind turbine is linked to the proof of construction of the wind turbine. The proof of construction is normally the type certificate, and the design calculations performed for type certificate assume normally 20 year lifetime. Thus, normally the building permit is indirectly valid only 20 years. In cases, where the annual average wind speeds at the wind turbine site or other site conditions are far below the design assumptions, a special type approval (S-class) for a longer wind turbine lifetime may be a solution for an extension of the operating period beyond 20 years. The following problems of this solution have been observed in practice:

- The special type approval must follow the current design standards. As there were large improvements of the design standards over the last 15 years, the design of old wind turbines in some cases would not fulfil the design requirements according to the current design standards for the required extended operating period (in some cases not even for 20 years).
- The special type approval is linked to significant cost. Wind turbine manufacturers normally have no interest to maintain type approvals of wind turbine types which are not sold anymore. Usually, the wind farm owner cannot order the special type approval by himself at the certification body, because he does not have the design documents or because the effort for the special type approval would be too high for single wind turbines in many cases.
- A solution could be a long-term monitoring of loads experienced by the individual wind turbine as proof that the design equivalent fatigue loads have not been reached in the past operating period. Economic and reliable solutions for such long-term load monitoring have not been realised yet.

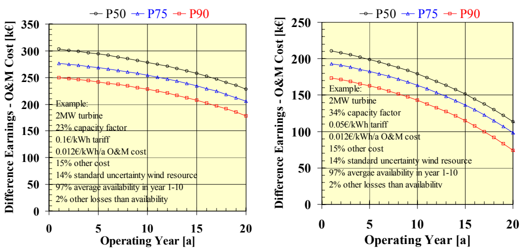

Figure 10: example of P50, P75 and P90 in dependance of age of wind farm for a relativly low capacity factor combined with high energy tariff (left) and for a high capacity factor combined with low energy tariff (right)

8 Conclusions

In a number of due diligence cases too optimistic assumptions for long-term O&M cost and non-availability losses have been observed, often leading to mostly unrealistic expected EBITDA margins in the order of 85%. According to a recent survey of O&M cost of 66 wind farms in the operating year 2008, average EBITDA margins of 76% have been reported [5].

The modelling of the increase of repair and maintenance cost and non-availability losses over the project lifetime individually for each wind farm helps to overcome such shortcomings when setting up economic considerations of wind farms. Simple approaches for this have been presented. The uncertainties of expected repair and maintenance cost and non-availability losses should be taken into account and should be cumulated with the uncertainties of the wind resource. The cumulating of uncertainties should consider the correlation between wind resource and repair and maintenance cost.

The outcome is a decrease of earnings and increase of uncertainties of earnings with increasing project age. The results can be used in order to evaluate the economic feasible lengths of operating period or financing period.

It turned out that in a combination of low to moderate wind resources and high energy tariffs, like it is present in many regions, wind farm projects could in principle be operated for more than 20 years. In practice, however, the project lifetime is often limited by the validity of the wind turbine type certificate.

9 References

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