Estimating the cost of offshore maintenance and the benefit from condition monitoring

Feuchtwang JB & Infield DG
mailto:julian.feuchtwang@eee.strath.ac.uk 'phone +44 (0) 141 548 5866
Institute for Energy and Environment, Dept. of Electronic and Electrical Engineering
University of Strathclyde, Royal College Building, 204 George Street, Glasgow G1 1XW

1 Abstract

The EU generally, and the UK, Belgium, Netherlands and Germany specifically, have ambitious plans for the large scale installation of offshore wind-power capacity. However, the cost of energy from offshore wind is much higher than that from land-based generation and anything between 15% and 30% may be due to the cost of Operation and Maintenance (O&M) [### Ref], largely driven by delays in access and repair caused by adverse weather and sea-state, high vessel costs, higher wage costs, and lost revenue from extended down-time.

A simple spreadsheet-based tool was developed at University of Strathclyde as part of a condition monitoring project funded by the Energy Technologies Institute (ETI). Its purpose is to estimate the cost of O&M and associated lost revenue, and also to estimate the potential benefit from condition monitoring.

The tool uses a closed form probabilistic method (explained in an earlier paper [1]) to estimate weather delays, based on an event tree, but without time-domain or Monte Carlo simulation. As it updates instantly when any parameter is changed, it is quick and easy to explore the impact of changing access thresholds, reliabilities, site parameters or the influence of condition monitoring without having to run a long series of simulations for each new situation. It currently uses wind and wave data, reliability data and component cost data mainly available in the public domain, but augmented with data from selected (and anonymised) proprietary sources. It could be updated with data specific to any potential windfarm development.

2 O&M Cost Estimators

A number of tools are available for estimating costs of Wind Turbine O&M, some only for land-based windfarms, others being suitable for offshore windfarms. In particular, the ECN O & M Tool, developed by the ECN Wind Energy Industrial Support (EWIS) Group [2 & 3], is available commercially and estimates offshore O & M costs.

3 The University of Strathclyde Differential O&M Cost Model

The University of Strathclyde (UoS) Differential O&M Cost Model was developed as part of an Energy Technologies Institute (ETI) funded condition monitoring project. The model was developed in order to explore the potential cost savings to be made by utilising condition monitoring and their sensitivities to various parameters in different scenarios. Much of the calculation of O&M cost has been carried out on a differential basis (i.e. looking for the difference in costs and revenue attributable to the condition monitoring system), so that not every contributor to the cost of a wind farm needs to be included, only those that would be influenced by maintenance strategies and methods. In addition, revenue from generation has been estimated and the impact of maintenance on this has been calculated.

The principal components of cost of maintenance operations in wind farms, whether based on land or at sea, are as follows:

- Component cost
- Personnel cost
- Vessel/vehicle/plant cost
- Loss of generating revenue

However, their relative magnitudes are radically different between land and sea. Component costs are largely the same, apart from the scaling effects associated with the larger mean size and rating of offshore wind-turbines compared to their cousins on land. There are other differences but they are relatively minor.

Personnel rates are higher at sea owing to the harsher, more hazardous conditions, and the greater levels of training required.

Vehicles for small maintenance on land are almost insignificant in the cost total, though heavy lifting gear for the larger jobs can be quite expensive. However, they pale into insignificance compared to the cost of sea-going vessels capable of heavy lifting, which is further exacerbated by the limited supply of such vessels. Furthermore, whilst there are wind restrictions on craning operations on land in order to ensure safety, there is nothing equivalent to the restrictions imposed on sea-going vessels of all types with regard to both wind speeds and wave heights. These restrictions have the potential to delay maintenance operations severely and consequently can incur very large costs in lost revenue due to a wind turbine being shut down, waiting for a critical repair, as well as the cost of personnel unable to do their job and possibly costs associated with the retention of the vessel. Consequently, estimation of such weather delays is at the core of calculating O&M costs for offshore wind farms, and in this model is based on the closed-form statistical-probabilistic methodology set out in [1].

An approximate schema of the model is shown below in Figure 1.

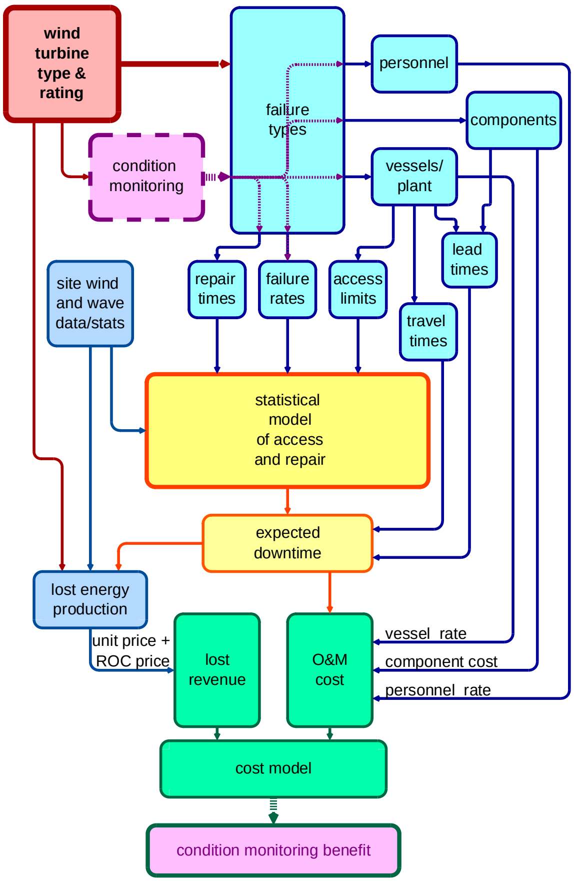

Figure 1: Schematic Diagram of the Cost Model

3.1 Data Input

A wide range of data is required in order to estimate the relevant costs and benefits some of which data are not always readily available.

The most crucial data are those that estimate the reliability (failure rates) for all possible faults on a turbine and the associated components required, the supply times, the number and qualification of personnel required, tools, equipment and plant required, the vessels required and the time required for the repair or replacement.

These inputs have been estimated with varying degrees of confidence from other sources with some adjustments when required.

3.1.1 Turbine Characteristics

Assumptions made about the turbines in the study are shown in Table 1 below.

Table 1: Baseline Turbine Characteristics

rated power	Prate	5	MW
rated wind speed	Urate	12	m/s
cut-in wind speed	Uci	4	m/s
cut-out wind speed	Uco	25	m/s
drive train efficiency	eff	96.5%	

3.1.2 Reliability and repair time

Some good data sets exist for the reliability of wind turbines but there are a few problems with them: they are mostly available only for relatively old, relatively small turbines sited in large numbers on land, whereas the data are needed for newer larger turbines sited at sea. However, even were data available, most of the turbines at sea are small in number and have not been operating long enough for useful statistics to be derived with confidence. Thus statistics for the turbines on land have been used to estimate figures for the larger turbines at sea. There are, no doubt, problems with the validity of such extrapolations but they are arguably the best estimates available for the time being.

Another problem is that the data give a general failure rate (and sometimes down-time per failure) for each subsystem of the turbine. However, the definitions are not made explicit of what is and what is not included in some of these subsystem categories. Furthermore, the failure rates given are the means of values ranging from minor to major faults. Since offshore weather delays vary as a non-linear function that increases very sharply in gradient, in order to estimate delay times, it is necessary to obtain data covering failure rates and the associated lead times and repair times for each likely fault type or at least for a range of classes of fault type.

For this study, only an overall whole-turbine failure rate has been derived from [4] & [5], where a trend can be observed of failure rate increasing with turbine size as shown in Figure 2 **Error! Reference source not found.**.

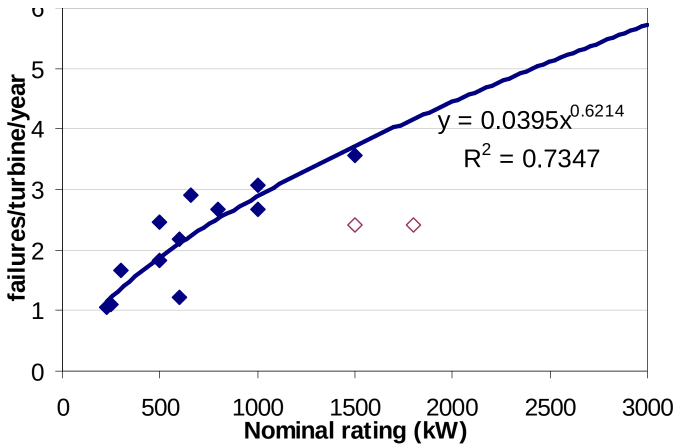

Figure 2: Trend in turbine failure rate with rated power

These studies are based on data collected by the Land Wirtschafts Kammer Schleswig-Holstein (LWK).

It is possible to fit a power law trend through these figures with reasonable correlation:

$$\text{failure rate} = 0.0395 \text{ failures/yr} \times (\text{Power/kW})^{0.621} \ (R^2 = 0.735)$$

Extrapolation gives overall wind turbine failure rates of 5.4 and 7.9 failures per year for turbines of 2.75 MW and 5.0 MW respectively.

Although the LWK data does break reliability down by subsystem, a more recent study, conducted by Garrad-Hassan as part of the Reliawind project [6], breaks it down much further into a larger number of subdivisions and utilises data from more recent turbines, albeit a smaller number of them. This study, in order to preserve anonymity of data, gives subsystem reliability and downtime per failure not as absolute figures but as percentages of the overall figure.

These percentages, as measured from the graph, have been used to allocate failure rates to subsystems in this study.

Data are scant concerning splitting each of these failure rates between repair categories, but recently [7] was published, based on the WMEP programme, in which repair data have been split into minor and major faults, depending on whether the turbine was stopped for less than or more than a day. This is important in terms of overall economic impact and reflects the nature of the repair required.

3.1.3 Repair Categories

In order to calculate estimates of delay times, repairs have been assumed to follow a schema loosely based on one devised in the DOWEC project and as part of the ECN O&M cost estimator [8]. See Table 2 below.

Table 2: Repair categories & times (loosely based on [8])

REPAIR CATEGORIES			**Heavy comp**				
REPAIR CATEGORIES		**repair type**	**Heavy comp^t^s, external crane** Au	**Bulky comp^t^s external crane, severe wind limit** Bu	**Small parts, internal crane** Cu	**Small /no parts** Du	**Inspect and repair** Duii
weight limit	t		500	150	1	0.015	0
repair time	hrs	trep	168	168	72	24	4
lead time	hrs	tlead	168	336	48	24	4
people req^d^		p	7	7	4	2	2
vessel		Tu	Crane Vessel	Crane Vessel	Supply Vessel	Supply Vessel	Supply Vessel
wave limit	m	Hmax	2	2	1.4	1.4	1.4
wind limit	m/s	Umax	11	9	12	12	12
travel speed	kn	Vmax	10	8	25	25	25
positioning time	hrs	tpos	3	2	1	1	1

3.1.4 Failure Rate Allocation

The required failure rates for each repair category are derived from an overall turbine failure rate (allowing for scaling), a percentage split between subsystems, and for each subsystem, a percentage split between repair categories.

Table 3: Failure rate allocation to fault classes

FAULT TYPES subsystem	%of all faults e	failure rate /yr ef	heavy Ext Au	Bulky Ext Bu	Light Int Cu	Small Quick Du	ext inspect Duii
Total reliability	100%	3.000	0.165	0.024	0.270	0.317	2.224
Frequency Converter	12.0%	0.359	10%	0%	11%	0%	79%
Generator Assembly	5.6%	0.168	22%	0%	11%	0%	67%
Pitch System	15.9%	0.478	5%	0%	10%	18%	67%
Blades	1.4%	0.041	0%	8%	10%	0%	82%
Yaw System	12.0%	0.359	6%	0%	10%	12%	72%
Gearbox Assembly	5.3%	0.159	22%	0%	11%	0%	67%
Tower	3.2%	0.097	0%	10%	5%	5%	80%

This cell is the overall failure rate of the turbine
It is based on the trend with turbine size in data from:[5]

This column is the percentage split of the overall rate between different subsystems.
It is based on [6]

Each row in this block is the percentage split between repair categories for each subsystem.
A partial check on comes from data on a 'major/minor' repair split in [7]

3.1.5 Siting

Siting has a significant effect on generation and accessibility but obviously these are project dependent. A standard fictitious site was used as a baseline, as set out in the assumptions of ETI's cost model **[confidential communication]**. Based on these assumptions, 3 Weibull distribution parameters were derived, as set out in Table 4 below.

Table 4: Baseline site metocean characteristics

Wave Weibull Parameters	Site Name	ETI	
distance to shore	ds	100	km
wave location parameter	Ho	0.325	m
wave shape parameter	kh	1.777	
wave scale parameter	Hc	1.569	m
mean wave height	Hm	1.72	m
Wind Weibull Parameters	Windsite	ETI	
wind location parameter	U0	0.000	m/s
wind shape parameter	kU	2.000	
wind scale parameter	Uc	10.155	m/s
mean wind speed	Um	9.00	m/s

3.1.6 Vessels

The relevant characteristics of the maintenance vessels have been derived from [8] with some adjustments.

Table 5: Assumed vessel characteristics

Vessel_Description	max wave height m Hv	max wind speed m/s Uv	speed knots Vv	position-ing time hrs tv	nominal day rate £k vessel rate	Wave Access-ibility 1-Ph	Wind Access-ibility 1-Pu
supplier with MOB	1.4	12	25	1	£12k	40%	75%
crane vessel	2	9	8	2	£160k	67%	54%
self-propelled jack-up	2	11	10	3	£160k	67%	69%

Vessel costs per day have been assumed to scale with turbine size with a power law of index 0.5.

3.1.7 Financial Assumptions

A number of reasonable other assumptions have been made regarding costs and revenues as shown in the table below.

Table 6: Financial assumptions

personnel hourly rate	rh	25	£/hr
electricity sale price per unit	pe	40	£/MWh
ROC price per unit (2 ROC / MWh offshore)	pr	90	£/MWh
shift length	tshift	12	hr
proportion of delay charged for unscheduled vessel	pves	25%	
proportion of delay charged for scheduled vessel	pves	0%	

3.2 Calculation

3.2.1 Weather Delay Calculation

As explained in [1], calculation of weather delays is carried out according to an event tree and by the appropriate integral moments of the relevant frequency distributions of the durations of periods above and below wave and wind thresholds. The threshold used is selected on the basis of the vessel required and the type of operation. Thus lifting a large bulky part such as a blade requires a stricter wind threshold than lifting a heavy but dense part such as a gearbox. The length of the delay is a function of the wind or wave parameters, the applicable threshold and the operational period required. It has been assumed that the duration of the latter consists of twice travelling time, positioning time and the repair time itself.

3.2.2 Maintenance Strategy

A distinction is made throughout between unscheduled operations and scheduled operations. The baseline case is assumed to be based on unscheduled repairs. The turbine is shut down when a component fails and remains shut down until it is fixed. There is frequently a weather delay. It has been assumed that any vessels required for the repair may need to be retained, and thus paid for, whilst waiting out the delay though it has not been assumed that this would be for the full delay every time.

When maintenance is able to be scheduled, the turbine is only stopped when the vessel approaches and is restarted as soon as the repair is completed. Also there is no need to pay a retainer on the vessel whilst waiting out weather delays

3.2.3 Lost Revenue Calculation

It has been assumed that when an unscheduled repair is required, the turbine is shut-down from the moment of occurrence of the fault and that it remains shut down throughout any delay and the operational period until the end of the repair but is restarted before any return journey.

It would be inaccurate to apply a single figure for the rate of generation thought the shut-down period. Rather, it should be assumed that wind speed and wave height correlate well and thus to a large extent, when there is a weather delay, the generation being lost is at a high level. During the journey out and during the actual repair, the winds must be assumed to be relatively low.

In order to estimate these effects, a simplified power curve has been assumed. Above cut-in wind speed and below rated power, the power output follows a cubic characteristic in relation to wind speed and suffers a fixed power loss. Above rated and below cut-out, the power is constant at its rated value, and is zero below cut-in and above cut-out. The wind speed is assumed to follow a Weibull distribution. Over any range of wind speeds, multiplying the power curve by the probability density function and integrating over the appropriate wind speed range gives a notional mean power over that range or a notional capacity factor if the power is divided by the rated power of the turbine.

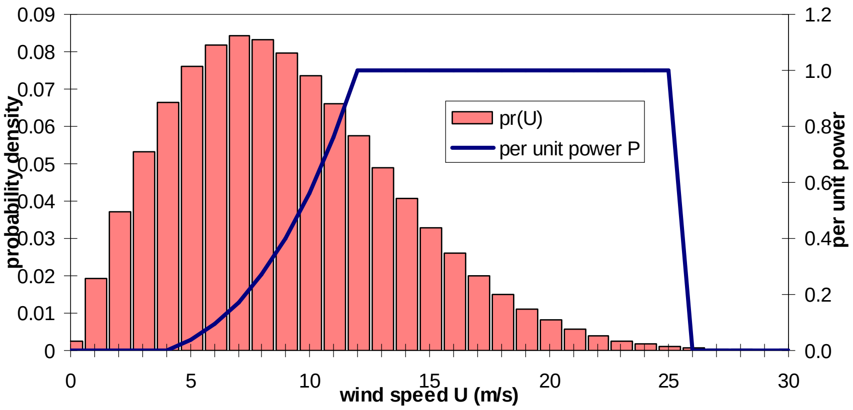

Figure 3: Idealised Wind Turbine Power Curve with Weibull Probability Density Function

Thus if there were no downtime at all, given the power curve parameters stated (Uci = 4 m/s, Urated = 12 m/s, Uco = 25 m/s) and the wind distribution parameters stated (Umean = 9 m/s, Weibull shape parameter k =2), the turbine would operate at a capacity factor of 44.5% and a mean power of 2.22 MW.

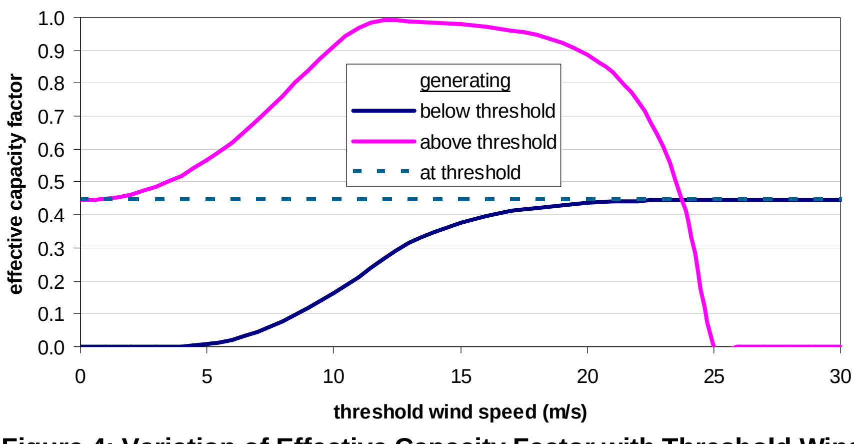

Figure 4: Variation of Effective Capacity Factor with Threshold Wind Speed for Above Threshold and Below Threshold Generation

3.2.4 Vessel Cost Calculation

Vessel costs are calculated on a per day basis. As explained earlier, the vessel is assumed to be charged for during a proportion of any delays in unscheduled operations but not in scheduled operations. It is also charged for whilst travelling, positioning and whilst carrying out repair operations.

3.2.5 Personnel Cost Calculation

Personnel are assumed to be paid throughout operations including delay and travelling time.

3.2.6 Component Costs

Two main sources were used as the basis for estimating component costs. The first, in the public domain is [9]. This study gives a broad breakdown by subsystem and includes a scaling study, representing the scaling of component cost with turbine size as following a power law. A finer breakdown into individual components is from a confidential source. As this latter source is more recent than [9], its costs are used whenever possible but power law indices and scale factors are derived from [9] for all subsystems. In the absence of an applicable power law from [9], an index of 0.7 with rated power has been assumed.

3.3 Effect of Condition Monitoring

The effect of condition monitoring has been taken into account in three ways in this study.

Detection is when a fault is detected before it runs to complete failure. The repair category is the same as with reactive maintenance but the repair can be scheduled. There is thus a percentage transfer of failure rate from all the unscheduled categories to the equivalent scheduled categories.

Pre-Empt is when a fault is detected before it escalates in severity and so the repair category can be downgraded as well as being scheduled. Thus there is a percentage transfer of failure rate from the unscheduled heavy repair categories to the scheduled light repair categories.

False-Positive is when a fault is detected when there isn't one and it results in a scheduled repair visit. Thus there is an increase in all the scheduled category failure rates as a percentage of the equivalent unscheduled values.

Table 7: Baseline assumptions about effect of condition monitoring

subsystem	detectability	pre-empt	false-pos
Generator Assembly	40%	20%	10%
Gearbox Assembly	50%	25%	10%
Blades	20%	10%	5%
Pitch System	35%	10%	5%
Yaw System	35%	10%	5%

4 Results

The results of the baseline FLOW cost calculations can be seen below in Figure 5 as the relative contributions to the overall O&M cost per unit.

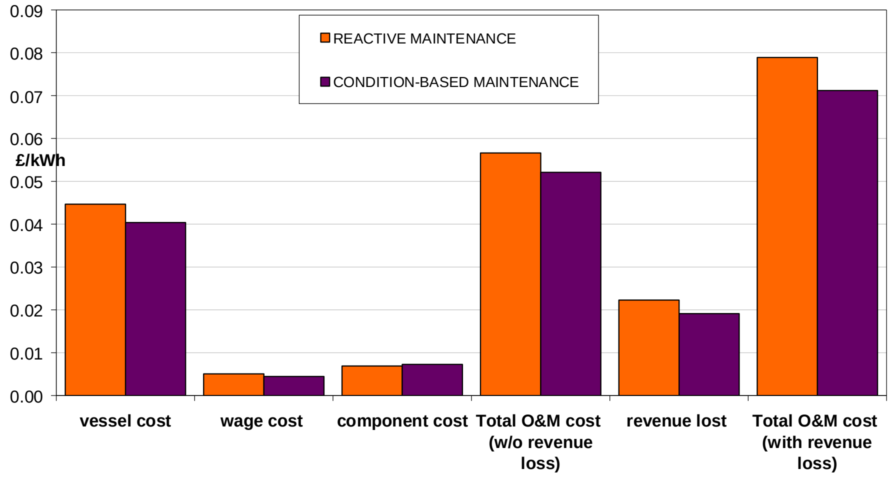

Figure 5: Expected annual contributions to O&M cost in reactive and condition-based maintenance

Condition-based maintenance case has a significant effect on the O&M contribution to the cost of energy relative to the case of purely reactive maintenance. With the detection etc. rates given above, O&M cost per unit falls 8%. Once revenue is taken into account, falls nearly 10%.

The significant saving of lost revenue occurs despite only a small increase in availability. This can be attributed to the importance of saving periods of high productivity by scheduling repairs and by avoiding stopping the turbine during weather delays.

5 Sensitivity Analysis

To illustrate the possibilities for sensitivity analysis, the baseline assumptions regarding condition monitoring of the gearbox assembly have been varied as this is an item of particular importance. In particular, sensitivity of lost revenue (per unit) and maintenance cost (per unit) to detectability, pre-emptive detection and false positives (as defined earlier) are presented below.

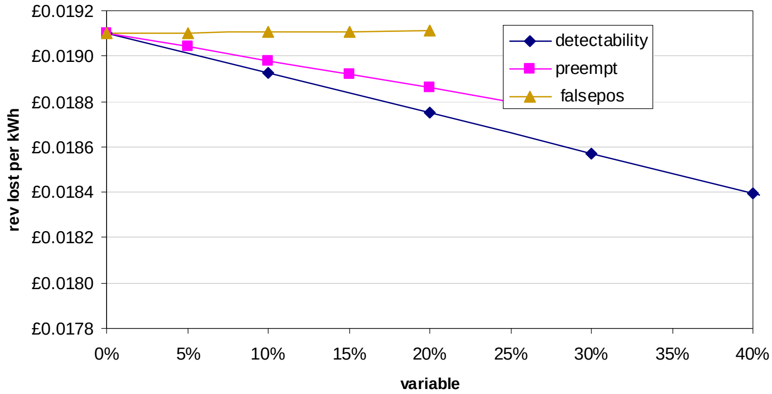

Figure 6: Sensitivity of lost revenue to 'detectability', 'pre-empt' and 'false-positives'.

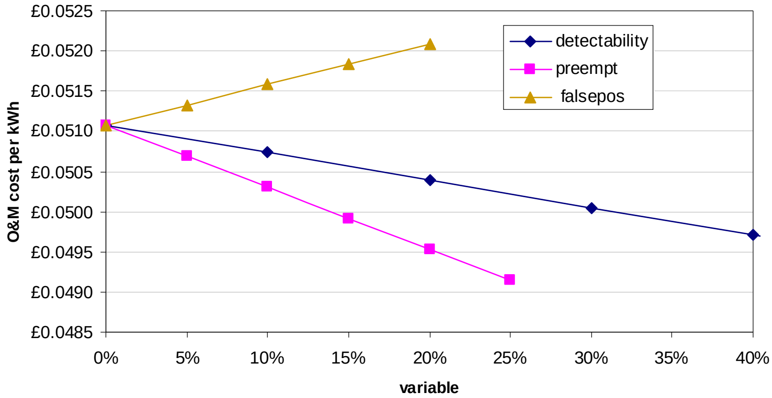

Figure 7: Sensitivity of O & M cost to 'detectability', 'pre-empt' and 'false-positives'.

6 Conclusions

The results presented show that a simple spreadsheet-based O & M cost estimator can be used effectively for estimating the effect of condition monitoring on O & M costs. In the absence of definitive data for many of the inputs it is difficult to give absolute values of O & M costs but their sensitivities to a range of parameters can be explored effectively.

Offshore O & M costs seem to be dominated by vessel costs, whilst revenue loss is also significant and these are both areas where significant cost savings can be made with condition monitoring.

Despite its shortcomings, in particular its requirement for relatively simple scenarios, the closed-form calculation of weather-delays has proved to be an effective tool. Given that few of the required input data are available in the public domain relating directly to offshore windfarms, any errors arising from the input data may well be larger than those associated with simple calculation approach. Whether more complex methods of calculation are justified is an open question.

7 References

1 Feuchtwang JB & Infield DG; 'The Offshore Access Problem and Turbine Availability - Probabilistic Modelling of Expected Delays to Repairs'; European Offshore Wind Conference 2009, Stockholm

2 Rademakers LWMM; 'ECN O&M Tool'; http://www.ewis.nl/fileadmin/ecn/units/wind/docs/EWIS/SP-310_OM_Tool_Brochure.pdf (accessed 09/12/2011)

3 Eecen PJ, Braam H, Rademakers LWMM & Obdam TS, 'Estimating costs of operations and maintenance of offshore wind farms'; ECN-M--07-045, EWEC 2007 Milan

4 Tavner PJ, Spinato F, Bussel GJW van & Koutoulakos E; 'Reliability of Different Wind Turbine Concepts with Relevance to Offshore Application'; EWEC 2008, Brussels

5 Spinato F, Tavner PJ, Bussel GJW van, Koutoulakos E; 'Reliability of wind turbine subassemblies'; IET Renew Power Gen,2009,Vol 3,Issue 4, pp387–401

6 Wilkinson M, Hendriks B, Spinato F, et al; 'Methodology and Results of the Reliawind Reliability Field Study'; EWEC2010 no58

7 Faulstich S, Hahn B, & Tavner PJ; 'Wind turbine downtime and its importance for offshore deployment', Wind Energy 2011; Vol. 14; pp327–337

8 Rademakers LWMM & Braam H; 'O&M ASPECTS OF THE 500 MW OFFSHORE WIND FARM AT NL7 - (80 × 6 MW Turbines) - Baseline Configuration'; DOWEC Report Nr. 10080 rev 2, 2002, ECN & TUDelft, NL

9 Malcolm DJ & Hansen AC; 'WindPACT Turbine Rotor Design Study'; NREL subcontract report NREL-SR-500-32495 rev April 2006