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The Financial Benefits of Various Catastrophic Failure Prevention Strategies in a Wind Farm: Two market studies (UK-Spain)

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Abstract. Operation of wind farms is driven by the overall aim of minimising costs while maximising energy sales. However, in certain circumstances investments are required to guarantee safe operation and survival of an asset. In this paper, we discuss the merits of various catastrophic failure prevention strategies in a Spanish wind farm. The wind farm operator was required to replace blades in two phases: temporary and final repair. We analyse the power performance of the turbine in the different states and investigate four scenarios with different timing of temporary and final repair during one year. The financial consequences of the scenarios are compared with a baseline by using a discounted cash flow analysis that considers the wholesale electricity market selling prices and interest rates. A comparison with the UK electricity market is conducted to highlight differences in the rate of return in the two countries.

1. Introduction

The costs of wind energy generation are given by the initial investment (capital expenditure – CAPEX) and the continuous costs for operations and maintenance on the wind farm (operational expenses – OPEX) [1]. Throughout the project lifetime, all Operation and Maintenance (O&M) decisions have a significant impact on the OPEX.

Part of the job of wind farm O&M engineers is to track the reliability of wind turbines and prevent catastrophic failures. Preventive replacements may result in two different outcomes under optimistic scenarios: improving the production efficiency of the wind turbines or stabilizing the functionality of the wind turbine without any change in production performance. In a case of predicted catastrophic blade failures in the investigated farm, the latter was true – costs were anticipated without any performance improvements. Current industry practice does not always consider in detail the value of timely OPEX in the overall costs of energy for wind farms. In this paper, the authors present a discounted cash flow analysis of blade OPEX in avoiding downtime and the balance between repair costs against the value of lost energy production.

The performance of a wind turbine is assessed before and after a blade replacement by comparing power output with a power curve, bearing in mind that underperformance may be affected by other possible causes such as wakes [2], icing [3], pitch [4] and yaw [5] misalignments, etc.

Potential generation revenue losses are projected in hypothetical scenarios investigating different levels of perfect and imperfect repair. Prevention of a catastrophic failure and maintenance efficiency

dependent four-year cash flow analyses are performed where the value of the same maintenance decision is compared for UK and Spanish electricity markets. This comparison gives insight in the complexity of optimizing O&M if an operator manages farms in different countries in an era of regional electricity markets in Europe [6].

2. Approach

This study analyses blade replacements in a Spanish wind farm with stall regulated turbines with rated power below 1MW. Two turbines are selected: Turbine E subject to blade replacement and Turbine C as a reference without replacement. The replacement was conducted to prevent catastrophic failure and consisted of two phases: Replacement in May 2015 and final repair in September 2015. Based on service logbooks and signals from the Supervisory Control And Data Acquisition (SCADA) system, the power production performance is evaluated.

In a second step, the financial consequences of several scenarios with different timing of the repair are investigated as detailed in Table 1. UK and Spanish electricity market data analyses are performed using the half hourly ELEXON [7] imbalance price data (assuming such data to be a reasonable proxy for daily wholesale market prices[1]) and the hourly OMIE prices [9], respectively, to conduct a discounted cash flow analysis with the projected production sales. A discounted cash flow analysis is used to estimate the net present value (NPV) of the maintenance decisions projecting forward to May 2017.

The process flowchart is given in Figure 1, which illustrates the required data and filtering operations as well as financial calculations. The analysis is conducted in MATLAB and R [10].

Table 1 Investigated maintenance timings

	Scenario	Failure	Temporary repair	Final repair
Baseline	Real case	-	5/2015	9/2015
1	Delayed final repair	-	5/2015	5/2016
2	Perfect repair	-	-	5/2015
3	Repair after downtime	5/2015	6/2015	10/2015
4	Repair after excessive downtime	5/2015	-	11/2015

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[1] For negative net imbalance volume (NIV) the system buy price and for positive NIV the system sell price value is taken as the market index price according to [8].
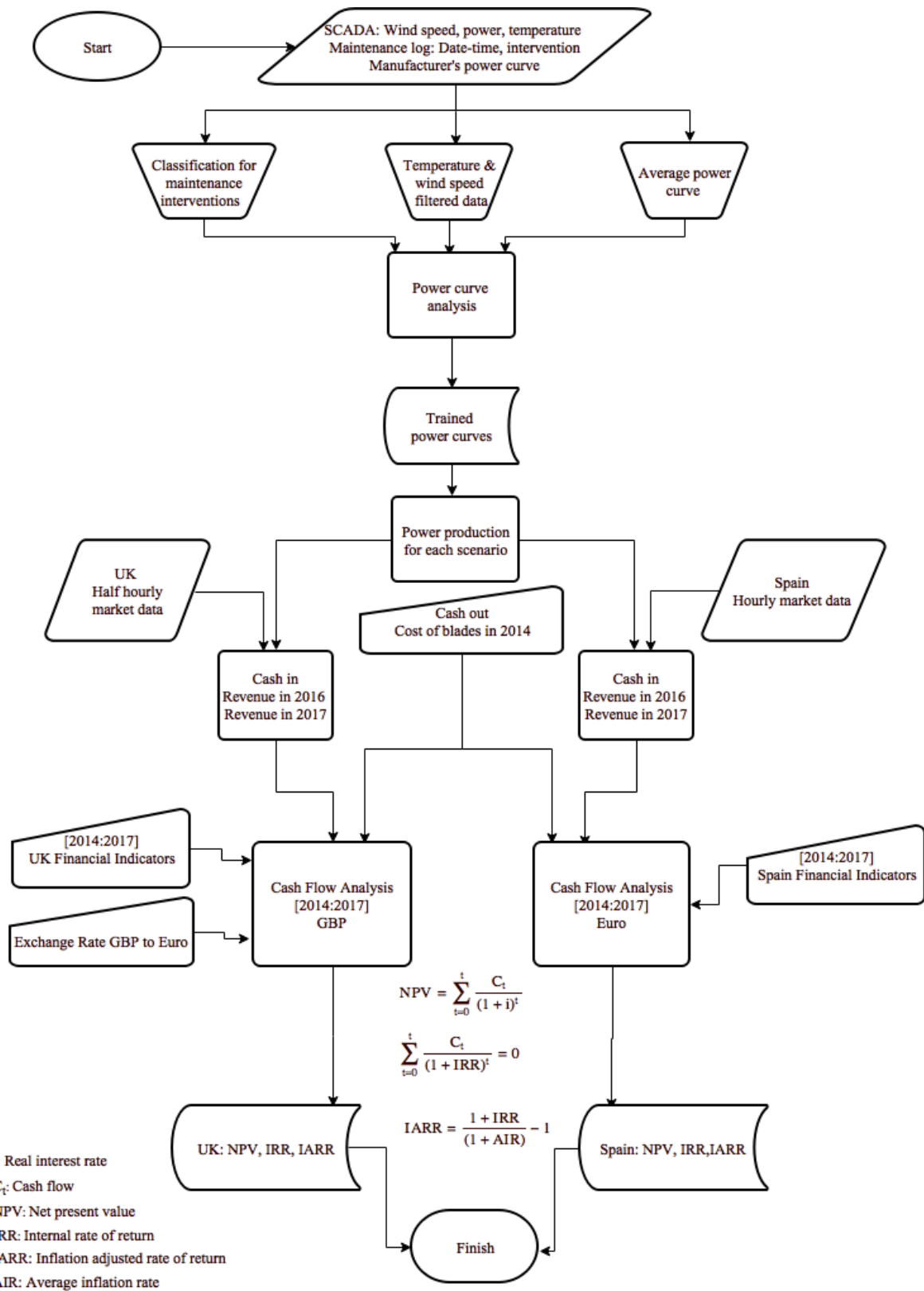
Figure 1. Flowchart of the process.

3. Power performance analysis

In an initial step, means of active power production for each wind speed bin are used to compare the two turbines. In a second step, a detailed power-curve analysis is conducted to reduce the impact of wind speed variations.

3.1. Power and wind speed bins

In Figure 2, the power production for two months (before and after the replacement) are given. The power bins of Turbine C, which was not subjected to blade replacement, tend to have a distribution with a positive skew. The power bins of Turbine E, which was subjected to blade replacement, tend to show a 'u-shaped' distribution where the turbine is spending more time at rated power. However, the reason for these differences may be found in differences in the wind speed distributions as shown in Figure 3.
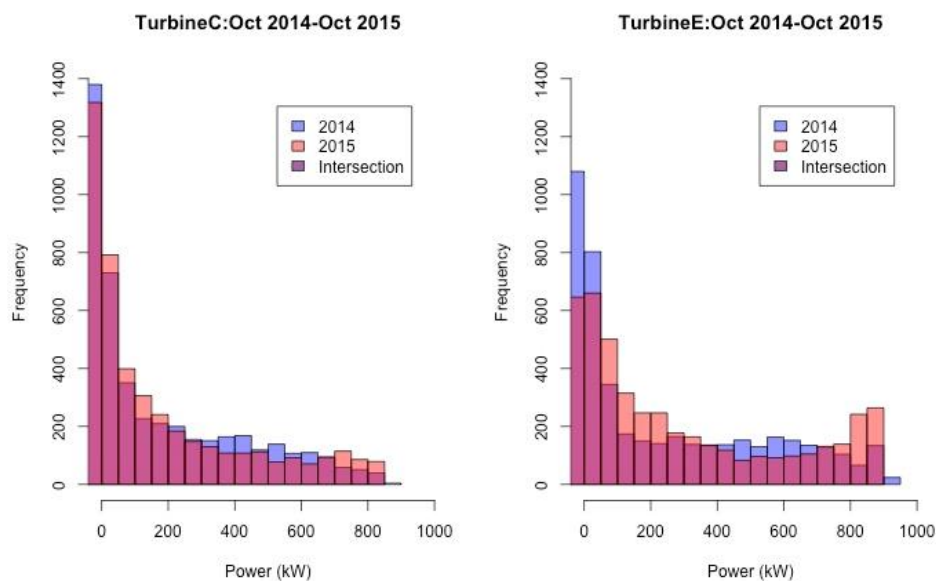

Figure 2. Power histograms for October of 2014 and 2015.
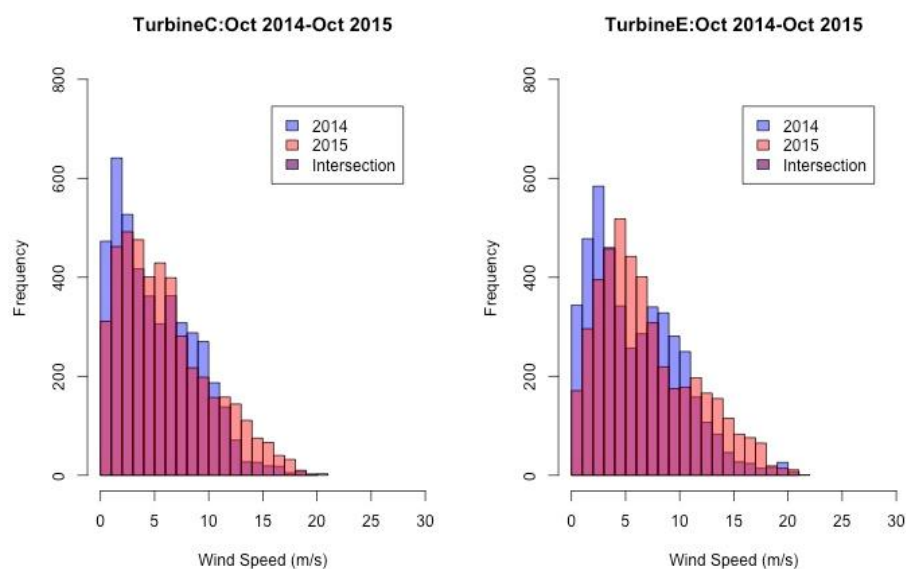
Figure 3. Wind speed distributions for October 2014 and 2015.
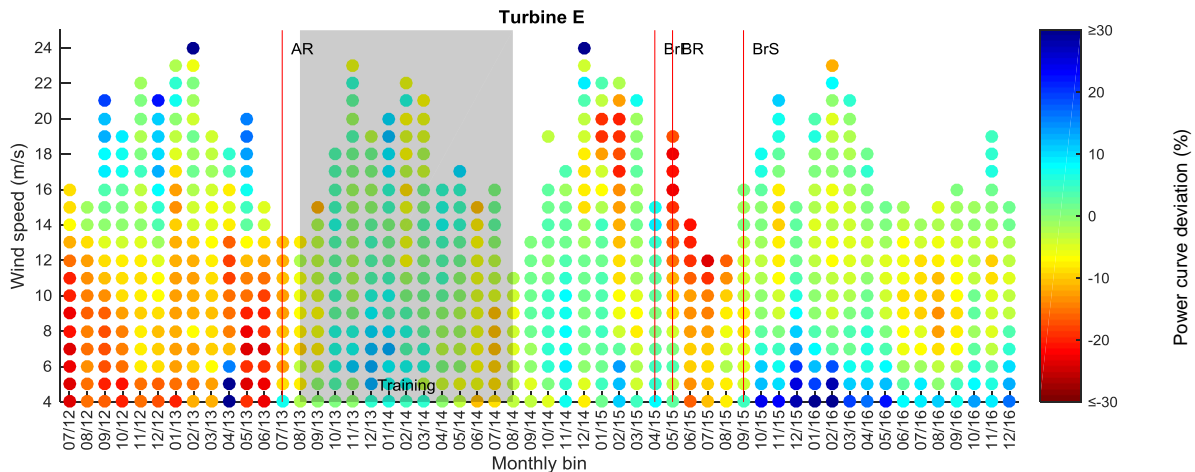
3.2. Power curve deviation

Although the manufacturer defines the expected performance of the turbine, the manufacturer's power curve does not account for site effects and is based on free stream wind speeds and not measurements on the nacelle. A reference power curve is derived by using the binning method described in the IEC 61400-12-1 standard [11]. In our case, 1 m/s width bins are used in order to get a reliable power curve. A representative power curve is constructed with one year of data starting after an anemometer replacement, which ensures the quality of the wind speed data. Figure 4 shows the established power curve.
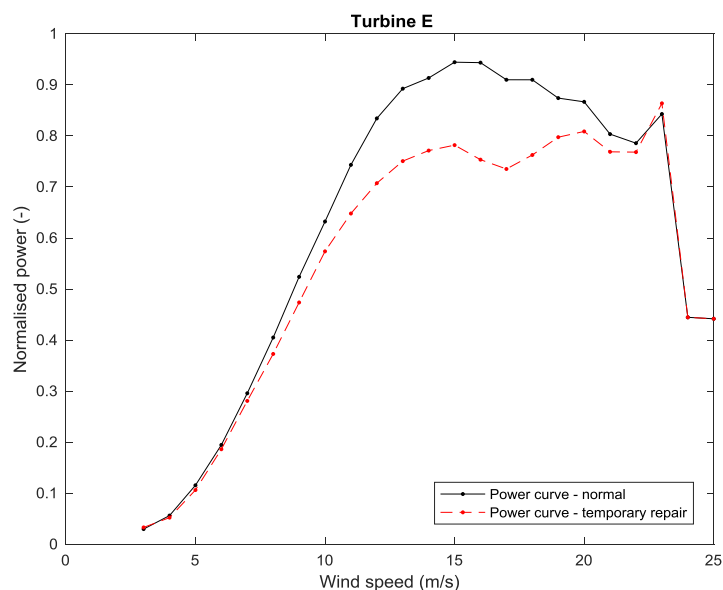

Figure 4. Wind turbine power curves based on a binning method.

In the next step, the deviation from the established power curve is analysed. Therefore, the monthly averaged power production of each wind speed bin is compared with the power curve. In Figure 5 the relative deviation is illustrated by colouring: red indicates underperformance, green implies performance according to the normal power curve and blue stands for a performance better than the power curve. If there is no significant occurrence of the particular wind speed, the bin is left blank (white). Various maintenance interventions are marked with vertical lines. It can be seen, that the performance varies significantly during the four years. The period from July 2012 to June 2013 is affected by mostly underperformance for wind speeds up to 13 m/s and performance similar to or even higher than the reference for wind speeds above 13 m/s. This might be explained by a faulty anemometer as the maintenance records indicate that the anemometer was replaced in July 2013. The period from August 2013 to July 2014 had been selected for deriving the power curve and accordingly the performance is mainly normal. The subsequent period shows similarly little deviation from the power curve except for strong underperformances in January and February 2015 at high wind speeds. It is likely that this is due to icing of the blades. Filtering of the observations to ensure an ambient temperature no less than 2°C [12], as shown in Figure 6, excludes the possible icing effects. Further underperformance is seen from May to August 2015 – the period of temporary repair. After September 2015, the power output is mostly according to the power curve except for some performance higher than expected for wind speeds of 4 to 6 m/s. This cannot be explained based on the records, but it should be noted that although the relative deviation is ≥30 %, the absolute deviation is not significant due to the operation at less than 20 % of rated power.

To further quantify the underperformance of the temporarily repaired blades, a second power curve is established for May to September 2015 and added in Figure 4 (red dashed line). It can be seen that the underperformance is strongest for wind speeds from 12 to 20 m/s. There is a slight increase of power for the 23 m/s bin, but this might be affected by the small sample size in this bin. Wind speeds of 24 or 25 m/s did not occur in this period and the power is set to the values of the normal power curve here.

Figure 5. Monthly power curve deviation per wind speed bin (AR: anemometer replacement, Br: minor blade repair, BR: blade replacement, BrS: final blade repair on site).
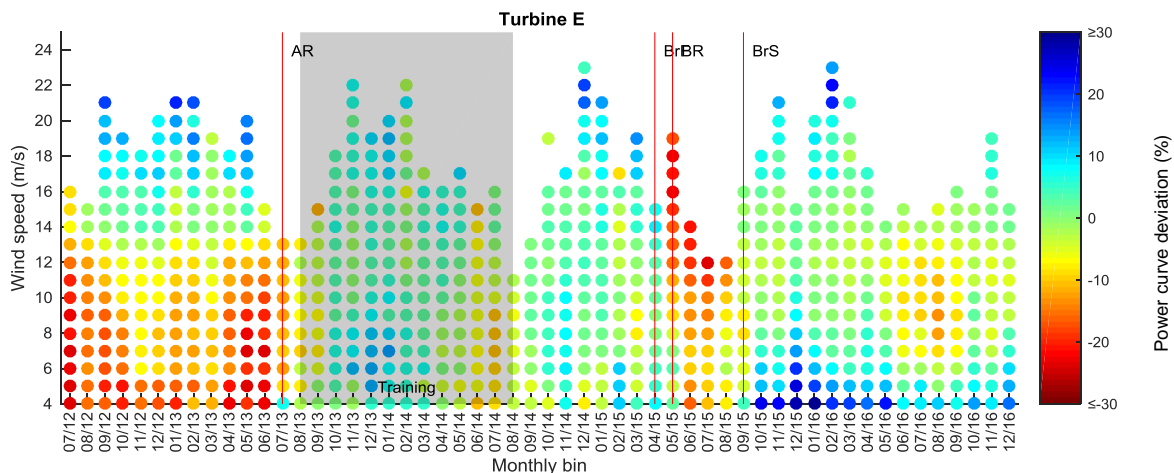
Figure 6. Monthly power curve deviation per wind speed bin – icing free (AR: anemometer replacement, Br: minor blade repair, BR: blade replacement, BrS: final blade repair on site).

4. Financial assessment
In this section, a 'what if?' analysis is performed to compare the financial implications of the different scenarios with varying maintenance dates.

4.1. Revenue evaluation
The power curves for normal operation and temporary repair are used to generate the power production in the artificial scenarios. In case of corrections to better or worse performance, only the difference of the two power curves is applied. By this, efficiency changes due to other effects and random variations remain. Table 2 shows the overall differences of the power production in the five scenarios for the first year. The power production from May 2016 to May 2017 is not varied in the scenarios (2011 MWh produced energy). In the last step the revenue is calculated by a multiplication of the market price and

the energy production. The power production at 10-minute resolution is reorganised as hourly summations for the OMIE and as half hourly summations for the ELEXON data.

Table 2 Summary of power production for May 2015 to May 2016

	Scenario	Produced energy (MWh)	Change
Baseline	Real case	2360	± 0 %
1	Delayed final repair	2137	− 9.5 %
2	Perfect repair	2535	+ 7.4 %
3	Repair after downtime	2155	− 8.7 %
4	Repair after excessive downtime	1506	− 36.2 %

4.2. Cash flow analysis

Operating a wind farm is a business which requires various investments at separate times. In this manner, the profitability evaluation of possible investment is important and can be addressed by taking the project lifetime of each option into account. The discounted cash flow considers the time value of money and provides financial indicators such as net present value (NPV), internal rate of return (IRR) and inflation-adjusted rate of return (IARR). Country dynamics are here considered by using a real interest rate, which is the difference between the nominal interest rate (long term interest rate (IR)) and the inflation rate (consumer price index change (CPI) in %), as given in Table 3 [13–17]. Table 3 introduces two types of indicators as actual and forecast values. For 2017 forecasted IR and CPI values are relevant, whereas for the past years actual published IR and CPI values are appropriate. The forecasting accuracy of OECD's estimation methodology [15,17] can be tracked via 2014-2016 forecast and actual data columns.

Table 3 UK and Spain financial indicators (with NA as not available and NI as not included)

Indicator (%)	2017		2016		2015		2014	
	Forecast	Actual	Forecast	Actual	Forecast	Actual	Forecast	Actual
UK CPI	2.77	NA	0.64	0.70	0.05	0.00	1.47	1.50
UK IR	1.03	NA	1.31	1.31	1.90	1.90	2.57	2.57
UK Real IR	-1.74	NA	NI	0.61	NI	1.90	NI	1.07
Spain CPI	2.34	NA	-0.34	-0.20	-0.63	-0.50	-0.19	-0.15
Spain IR	1.71	NA	1.39	1.39	1.74	1.73	2.72	2.72
Spain Real IR	-0.63	NA	NI	1.59	NI	1.79	NI	2.87

NPV, IRR and IARR are used as evaluation indicators and calculated according to equations $(1) - (3)$. Here, i is the minimum attractive rate of return (real interest rate in our analyses), C_n represents net cash flow at time n and N stands for the lifetime of the project. The variable i^* is the breakeven interest rate and AIR is the average inflation rate [13].

$$\text{NPV}(i) = \sum_{n=0}^{N} \frac{C_n}{(1+i)^n} = \frac{C_0}{(1+i)^0} + \frac{C_1}{(1+i)^1} + \frac{C_2}{(1+i)^2} \ldots + \frac{C_N}{(1+i)^N} \tag{1}$$

$$\text{If NPV}(i^*) = \sum_{n=0}^{N} \frac{C_n}{(1+i^*)^n} := 0, \text{then } i^* \to \text{IRR} \tag{2}$$

$$\text{IARR} = \frac{1+\text{IRR}}{1+\text{AIR}} - 1 \tag{3}$$

Due to the complexity of real cash flow for a wind farm, only a simplified analysis is conducted here which provides a comparison of the maintenance scenarios, but does not represent the real cash flow. We consider the blade repair costs of 70,000 Euro as investment taking place in 2014 as spare blades need to be acquired before repair. In the real cash flow, the income is generated by the continuous energy sales. The income is budgeted for the initial acquisition of the turbine and all costs in operation. As we only consider one maintenance action here, we only look at a limited number of years of revenue to pay for this repair. Accordingly, we do not consider any income until May 2015. All projected energy sales from May 2015 to May 2016 of the different scenarios are utilised and registered as cash in 2016. Additionally, the real energy sales from May 2016 to May 2017 are also used to finance this repair action and registered in 2017. Any tax rates and subsidies are neglected. For the analysis of the UK setup, the initial investment is converted to GBP with an exchange rate of 1 Euro = 0.7763 GBP from May 2014 to May 2015. The cash flow analysis is subsequently conducted in GBP and finally converted back to Euro with an exchange rate of 1 GBP = 1.1828 Euro from May 2016 to May 2017 [18].

The selection of two years' energy sales as income to balance the repair costs provided a setup with at least a positive NPV as the baseline. However, the hypothesis that the full income of the two years can be used for paying the repair costs is not valid in reality. As this analysis looks only at a relative comparison, this should not matter.

Figures 7 and 8 are generated based on equation (2) and the graphical internal rate of return estimation procedure [13]. It can be seen, that scenario 2 results in an IRR of 51 % for Spain and 69 % for UK. On the contrary, scenario 4 has an IRR of 31 and 48 %, respectively for Spain and UK. An IRR ranking could be employed for the profitability evaluation of the projects [19], however, the investment evaluation must at the same time consider the NPV values for the mutually exclusive projects [20].

Table 4 gives the results of the what-if analysis showing the real NPV, which is calculated with the real interest rate, and the IARR of the four scenarios compared to the baseline. The highest NPV and IARR is found for scenario 2 in UK, the lowest for scenario 4 in Spain.
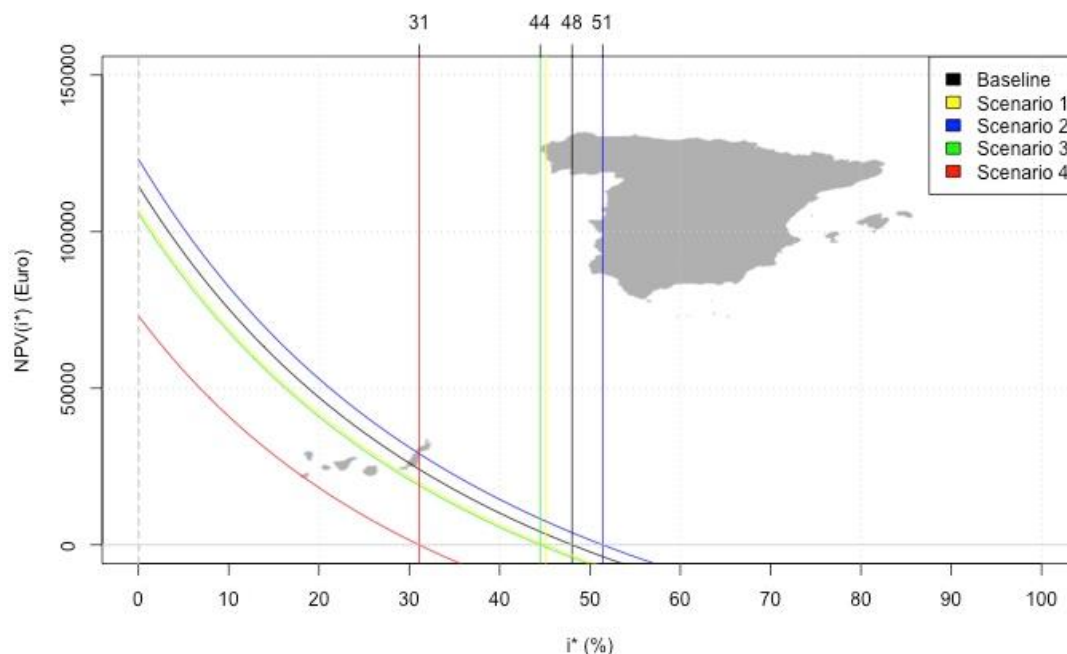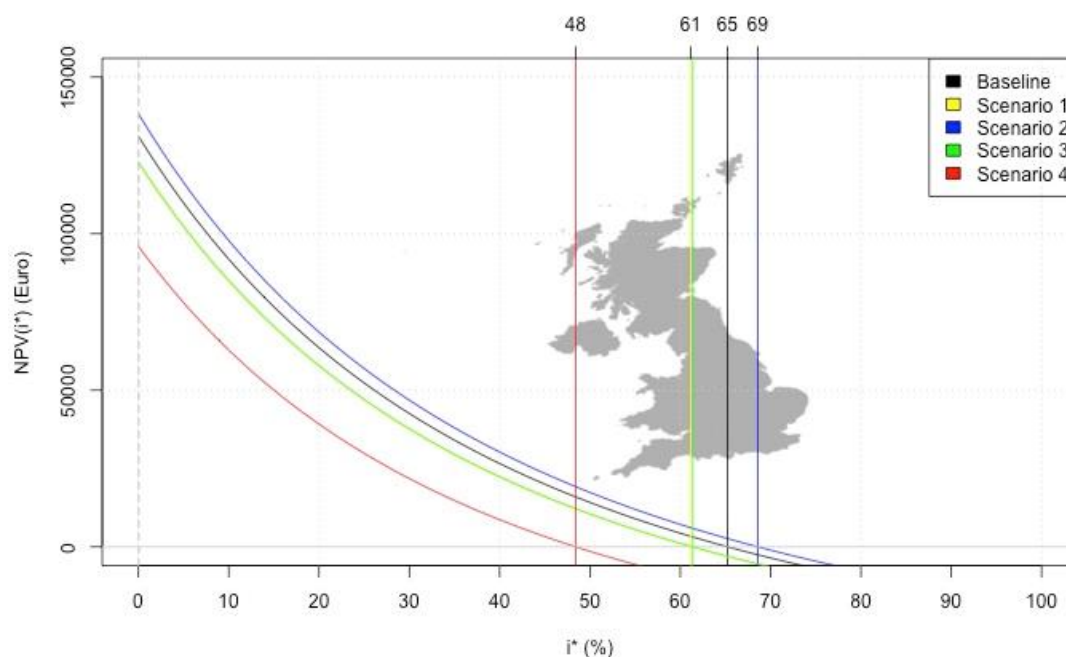

Figure 7. Graphical Internal Rate of Return Estimations for Spain (scenario 1 and 3 coincide in this figure)

Figure 8. Graphical Internal Rate of Return Estimations for UK (scenario 1 and 3 coincide in this figure)

Table 4 Cash-flow results for the O&M scenarios (Real NPV)

	Scenario	Spain		UK		
		NPV (Euro)	IARR	NPV (GBP)	NPV (Euro)	IARR
Baseline	Real case	113,729	47.2 %	135,114	159,813	63.3 %
1	Delayed final repair	106,719	44.3 %	126,542	149,674	59.3 %
2	Perfect repair	122,021	50.6 %	142,219	168,216	66.7 %
3	Repair after downtime	105,197	43.7 %	127,017	150,235	59.6 %
4	Repair after excessive downtime	73,501	30.4 %	100,404	118,758	46.7 %

5. Discussion

The evaluation of the power production highlights that a simple comparison of energy production is not sufficient to identify underperformance due to the significant variation of the wind resource even in neighbouring turbines. Instead, a binning method has shown it is possible to generate a reasonably accurate power curve. If the deviation of the power production from the power curve is analysed, it can be seen that the performance is significantly changing during the four years. Although a filtering of events with low temperatures proves to eliminate underperformances that are related to icing, further anomalies are seen. Two main maintenance interventions, namely the anemometer replacement and the temporary blade repair, strongly influence the performance results. However, further variation is visible and might need more advanced power curve modelling to account for e.g. air density changes and directional variation. As the performance difference for the temporary repair period is in the order of up to 20 %, the limitations of the power curves will not strongly affect the evaluation of the scenarios.

The financial evaluation for the baseline case shows that a NPV of 113,729 Euro and an IARR of 47.2 % is gained under the assumption that two years of energy sales are budgeted for the repair costs

(in Spain). Although this neglects the initial acquisition of the turbine and other costs, it is visible that the investment in new blades is very attractive and reasonable. The same investment in the UK would result in a higher NPV and IARR (159,813 Euro / 63.3 %), which demonstrates the differences in the electricity markets of Spain and UK. Assuming an operator with two farms in both countries and similar maintenance decisions to be made, there might be the question in prioritising one farm. Here, the importance of the blade maintenance intervention in the UK is greater from a financial viewpoint. However, this assumes no correlation between the wind conditions at the wind farms and the market prices in the two countries.

If the scenarios are compared with the baseline, we see similar trends in NPV, IARR in both countries:
1. Perfect repair is better than the baseline
2. Longer temporary repair results in higher losses
3. Excessive downtime is harmful

In detail for both countries, the perfect repair prevents five months underperformance occurrence with temporarily repaired blades and improves the NPV by 8,292 Euro (~1,658 Euro/month) in Spain and 8,403 Euro (~1,681 Euro/month) in UK. For the delayed final repair, an extension of the temporary repair period by seven months, the NPV is reduced by 7,010 Euro (~1,001 Euro/month) in Spain and 10,139 Euro (~1,448 Euro/month) in UK. The difference in the NPV change per month of temporarily repaired blades indicates that there might be potential in optimising the timing of maintenance based on monthly market and wind potential fluctuations. Further scenarios and improved power curves are needed to discuss this effect in more detail.

Additionally, we see that delayed final repair (Scenario 1) and repair after downtime (Scenario 3) cases result in nearly the same energy losses and NPV values for both countries. This could mean that a short downtime of less than a month in summer might be a preferable to longer underperformance.

6. Conclusions

A catastrophic failure prevention in a Spanish wind farm is studied in terms of the effects to the power production and financial consequences of the undertaken maintenance for various scenarios.

The power curve analysis shows that the performance of the investigated wind turbine is clearly reduced during a phase of temporary repair and regains a normal level after the final repair. Further performance variations are successfully traced back to an anemometer fault and icing events. A second power curve is established to describe the underperformance during temporary repair.

The financial consequences of the maintenance intervention are implemented in a simplified cash flow analysis assessing the rate of return of blade replacement costs balanced with revenue from power production sales of two years. The results show that the investment in new blades is financially reasonable as an inflation adjusted rate of return of 47.2% is achieved in Spain baseline case. A variation of the timing of the temporary and final repair confirms the importance of maintenance efficiency and highlights the importance of scheduling maintenance and underperformance. The comparison of the scenarios indicates that there might be potential for further optimisation of the maintenance scheduling.

A comparison of the same maintenance scenarios implemented in the UK electricity market shows that a similar investment in a UK wind farm would be favourable due to the higher electricity prices. The higher revenue is reflected in higher net present values and rate of returns. All trends of the different scenarios are the same as for the Spanish electricity market.

This study does not consider the full complexity of power performance and the cash flow for a wind farm. Future work will address the simplifications and assumptions to get a more realistic picture of decision making in the O&M of wind turbines. Additionally, a study of further fine-tuned scenarios might be beneficial to evaluate practical options and optimisation potential in more detail.

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