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"Economic Viability Study for Offshore Wind Turbines Maintenance Management"

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Chapter 1
Economic Viability Study for Offshore Wind Turbines Maintenance Management

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Abstract Nowadays, there is a growing interest in the development of offshore wind farms due to the increasing size and capacity of wind turbines, improvement of wind resources, social acceptance, noise reduction, depletion of onshore locations with great wind resources, etc. However, the operation and maintenance (O&M) costs are too high to make offshore wind turbines economically viable. The use of condition monitoring systems (CMS) appears as a solution to minimize O&M costs and increase the reliability of offshore wind farms. The quantification of the economic benefits of CMS is a non-trivial problem. In this work is presented a novel maintenance management research based of an economic study of the Life Cycle Cost (LCC) of CMS for offshore wind turbines. The model includes the costs of investment and O&M of the CMS and costs for reduction of O&M and energy losses of the wind turbine generates by the implementation of CMS. These costs are related with a reliability analysis of a real case study. The application of the economic model on a real case study assuming different scenarios enables the analysis of the economic benefits to use CMS in offshore wind turbines.

Keywords Life cycle costs · Condition monitoring systems · Wind energy · Offshore wind turbines

1.1 Introduction

Owing to climate change is a reality, the European Union target for 2020 is to reach that the 20% of the total energy consumption will be generated by renewable ener-

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gies [4]. Wind energy represents an essential technology of the electricity production sector and has enjoyed a growing interest in recent years [5]. Offshore wind projects have been part of this expansion due to the increase in size and capacity of wind turbines, better wind resources than onshore, depletion of ground locations with great wind resources, higher social acceptance and noise reduction. However, the operational and maintenance costs are too high to make offshore wind turbines economically viable [17]. The energy research Centre of the Netherlands (ECN) revealed an estimation of these costs for offshore wind farms is in the order of 30-35% of the cost of electricity (distributed in 25-30% in preventive maintenance and 65-75% in corrective maintenance) [15].

The use of CMS is needed to improve the availability, reliability, safety and maintenance costs of offshore wind farms. The main reasons for the implementation of CMS are the following [6, 9]:

- Higher power installed and, therefore, higher wind turbine investments. Higher wind turbines fail more frequently.
- Reduction of corrective maintenance costs.
- Increasing reliability, decreasing downtime.
- Offshore installations with difficult access to carry out maintenance tasks.
- Requirements from insurance companies in the EU countries to regularly realize replacement and repair operations in offshore wind farms.
- High interest of specialized companies which supply advanced CMS.

In the scientific literature can be found different techniques used in wind turbines such as acoustic emission [16], ultrasonic systems [7], oil analysis [18] or strain measurements [13], among others. However, the quantification of the economic benefits of CMS is a problem non-trivial. In [14] is studied the cost benefits on a CMS for onshore wind turbines and a relationship between gearbox maintenance costs and CMS efficiency is found. In [10] is provided an economic justification of CMS regarding to operational parameters for a wind farm showing that the accurate diagnosis of CMS in the interval 60% - 80% makes them cost-effective. In [1] is demonstrated the effectiveness of the online monitoring system for wind turbines using an economic model. In [11] is developed and analysis with different strategies where the use of CMS improves maintenance planning in offshore and onshore wind farms.

In this research is presented a novel maintenance management research based of an economic study of the Life Cycle Cost (LCC) of CMS for offshore wind turbines. The model includes, on the one hand, the costs of investment and O&M of the CMS and on the other hand, costs for reduction of O&M and energy losses of the wind turbine generates by the implementation of CMS. These last costs are related with the failure rate and downtime, respectively, from a reliability analysis of a real case study. The net present value (NPV) is used in the economic model including different NPV factors in the interval between 1% and 10%. The application of the economic model on a real offshore wind farm is developed, assuming different scenarios including different percentages of energy losses and different percentages of preventive and corrective maintenance tasks. In addition, the problem is raised in two different approaches: initial investment provided by the company and initial investment supported by a bank loan with an interest rate of 6%. This study will give us a map of the different solutions varying the variables considered.

The work is structured as follows: Sect. 1.2 explains the theoretical foundations of the maintenance management research based of the LCC of CMS for offshore wind turbines presented in this work. In Sect. 1.3 is presented the application of the maintenance management model on the real data reported from Egmon aan Zee wind farm in the Netherlands. Finally, Sect. 1.4 illustrates conclusions of the work.

1.2 Model Definition

The research presented in this work studies the feasibility of CMS for offshore wind turbines through a Life Cycle Cost (LCC) using different annual rates of return. The main objective of the study is to illustrate that the use of CMS are highly profitable in offshore wind turbines. The LCC model proposed for the CMS of offshore wind turbines presents a similar structure than the model used in [8], applied to railway industry. The definition of the LCC takes into consideration the following assumptions: (a) Property tax, value added tax, etc., and general inflation are constant and included within the annual discount rate (defined as k); and (b) Cash required for investment is provided by the company (rather than being borrowed) so the equity rate is 1. Then, the LCC is based on the following expression:

$$\mathbf{Y} = \sum_{i=1}^{n} \mathbf{y}_i = \lambda \sum_{i=1}^{n} \mathbf{a}_i \cdot \mathbf{c}_i^T ,$$

where $\mathbf{Y}$ is the total cost, $\mathbf{Y}$=$[Y_1, \cdots, Y_t, \cdots, Y_T]$, Y_t denotes the cumulative cost in year t, the subscript T is the total number of years, Y_t indicates the cost of breakdown in category i, and λ expresses the net present value factor vector defined by the following expression:

$$\lambda = \sum_{t=1}^{T} \frac{1}{(1+k)^{t-1}} = 1 + \frac{1}{k}[1-(1+k)^{1-T}],$$

being T the total number of years of the study (10 years) and k the factor of the NPV. In the case study considered in this work, it is selected $n = 5$ (CMS investment: $i = 1$; CMS operation: $i = 2$; CMS maintenance: $i = 3$ and; maintenance reductions by CMS: $i = 4$ and; energy production and energy losses by CMS $i = 5$). Now, if the term a_{ij} indicates the number of times that the unit cost c_{ij} is incurred, the matrix A and C can be described as $A = [a_1, \cdots, a_5]$, and $C = [c_1, \cdots, c_5]$, where a_i and c_i are one dimensional arrays of length 4, i.e., $a_i = [a_{i1}, \cdots, a_{i4}]$ and $c_i = [c_{i1}, , c_{i4}]$. The base year has been set 0. Therefore, the values that compose the matrices A and C are the following:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \\ a_{51} & a_{52} & a_{53} & a_{54} \end{bmatrix}, C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \\ c_{51} & c_{52} & c_{53} & c_{54} \end{bmatrix}$$

The detailed description of the different costs that compose the matrixes A and C are developed next.

1.2.1 CMS Investment Costs

The CMS investment cost c_1 is related to the costs of capital. These costs are represented by the general investment costs of CMS, and the costs of the different parts of the CMS installed in the wind turbine (tower, nacelle and blades). The elements of c_1 are therefore described as follows (Table 1.1):

Table 1.1 CMS investment costs

	Definition	This term includes the cost of:
c_{11}	General CMS investment costs	capital, installation (operator, technical and diver salaries), regulatory approval, initial testing, software, power, communications and the transport costs (boat).
c_{12}	Tower CMS investment costs	data acquisition system (hardware, data transmission and software), installation costs (operator, technical and diver salaries), the acquisition of the different sensors necessary to monitor the tower of the wind turbine, the initial testing and the transport costs (boat).
c_{13}	Nacelle CMS investment costs	data acquisition system (hardware, data transmission and software), installation costs (operator, technical and diver salaries), the acquisition of the different sensors necessary to monitor the nacelle of the wind turbine, the initial testing and the transport costs (boat).
c_{14}	Blades CMS investment costs	data acquisition system (hardware, data transmission and software), installation costs (operator, technical and diver salaries), the acquisition of the different sensors necessary to monitor the blades of the wind turbine, the initial testing and the transport costs (boat).

On the other hand, the number of times incurred in these costs are: $a_{11} = a_{12} = a_{13} = a_{14} = 1$.

1.2.2 CMS Operation Costs

The CMS operation cost c_2 is the cost incurred by the technical operation process in a period of time. The most significant costs incurred in this term are (Table 1.2):

Table 1.2 CMS operation costs

	Definition	This term includes the cost of:
c_{21}	General CMS operation costs.	data acquisition and transmission, software, testing, power consume and human resources (operator and technical salaries).

Operation costs are performed monthly, therefore, $a_{21} = a_{22} = a_{23} = a_{24} = 12$. Finally, $c_{22} = c_{23} = c_{24} = 0$.

1.2.3 CMS Maintenance Costs

The CMS maintenance costs c_3 are the cost for CMS maintenance management processes. The most significant costs incurred in this term are (Table 1.3):

Table 1.3 CMS maintenance costs

	Definition	This term includes:
c_{31}	General CMS maintenance costs.	Corrective and preventive CMS maintenance costs.

Maintenance costs are carried out once a year, therefore, $a_{31} = 1$. Finally, $c_{32} = c_{33} = c_{34} = 0$ and $a_{32} = a_{33} = a_{34} = 1$.

1.2.4 Maintenance Reduction Costs by CMS

This costs represents the difference between total maintenance costs with and without CMS. The computation of these costs includes the assumption that preventive and inspection costs are reduced in 75% with CMS and corrective maintenance costs are reduced in 40% using CMS. The failure rates of the different components of the wind turbine from the case study have been used to calculate these costs. The elements of c_4 are therefore described as follows (Table 1.4):

The number of times that these cost are incurred are: $a_{41} = a_{42} = a_{43} = a_{44} = 1$.

1.2.5 Energy Production and Energy Losses by CMS

The cost due to energy production losses is represented by the cost difference of production losses with and without CMS. The downtime of the different components

Table 1.4 Maintenance reduction costs by CMS

	Definition	This term includes:
c_{41}	General maintenance reduction costs	preventive costs (helicopter rand barge costs, operator, technical and diver salaries, cleaning costs, etc.) and corrective costs (other failures, see failures rates in Fig. 1.1).
c_{42}	Tower maintenance reduction costs	preventive costs (base inspection, tower inspection and alignment of the turbine costs, technical and operator salaries and cleaning costs, etc.) and corrective costs (base repair without dismantling, base replacement, base transport (boat), base repair, technical installer and technical operator salaries, etc).
c_{43}	Nacelle maintenance reduction costs	this term is included the preventive and corrective maintenance costs of the elements that compose the nacelle of the wind turbine.
c_{44}	Blades maintenance reduction costs	preventive and corrective maintenance reduction costs of the blades.

of the wind turbine from the case study have been used to calculate these costs. The main assumptions used in the computation of the energy production and energy losses employing CMS are resumed in Table 1.5.

Table 1.5 Assumptions for the LCC calculation

	Assumptions
Assumptions Hours by year	8760
Wind turbine Eficiency (%)	0.6
Electricity price (€/kWh)	0.083
Failures reduction by CMS (%)	0.4

The values of c_5 are defined as the electricity price (0.083 €/kWh) [2] and the elements of a_5 are defined as the difference of power loss (kWh) between the different elements with and without CMS.

1.3 Case Study

The data used for the evaluation of the proposed maintenance management approach are the annual operations reports from Egmond aan Zee wind farm in Netherlands [12]. It was the first large offshore wind farm installed in the Dutch coast (in the North Sea). It comprises 36 Vestas V90-3 MW turbines producing 108 MW and is located 10 to 18 km from the coast covering around 27 km^2. The data is available for 2007 to 2009 and illustrates the failures and the hours lost related with the different components of the wind turbines installed. This data information is depicted in Fig. 1.1.

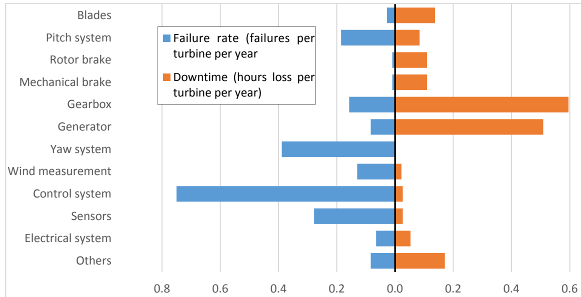

Fig. 1.1 Failure rates and downtime associated for 2007 to 2009 in Egmond aan Zee wind farm

In the application of the LCC described in the previous section to the case study the values that compose the matrices are the following:

$$A = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 12 & 12 & 12 & 12 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 132.2 & 0 & 1048 & 160 \end{bmatrix}, C = \begin{bmatrix} -19133.3 & -100970.6 & -74434.2 & -83285.3 \\ -4877.8 & 0 & 0 & 0 \\ -8333.3 & 0 & 0 & 0 \\ 37250 & 19500 & 83140.7 & 4672.2 \\ 0.083 & 0.083 & 0.083 & 0.083 \end{bmatrix}$$

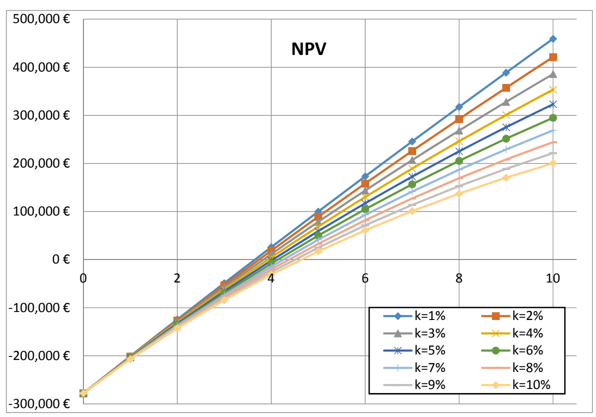

Fig. 1.2 NPV results for different values of rate of return and for different years of operation in Vestas V90

Fig. 1.2 displays the NPV values for ten years operation considering 40% of reduction of failures by using CMS. This figure illustrates different curves depending on the annual rate of return k. It is observed that the initial CMS costs are recovered for all the values of k in the 3rd year of operation. There are energy production benefits from the 4th year of operation making the use of CMS profitable. Additionally, it is shown that the lower is the rate of return k greater is the benefit obtained.

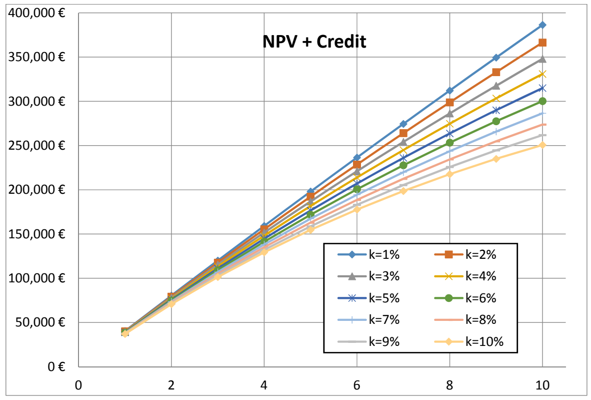

Fig. 1.3 Investment costs supported by a bank loan - NPV results for different values of rate of return and for different years of operation in Vestas V90

An extension of the LCC proposed above is the assumption that the investment costs for CMS are supported by a bank loan with an interest rate of 6% and 10 years. The study includes the NPV results for values of rate of return between 1% and 10%. Fig. 1.3 shows that the benefits caused by the use of CMS start appearing between the 3rd and the 4th year of operation for all the values of rate of return. Similarly than in the previous study, the lower is the rate of return k greater is the benefit obtained.

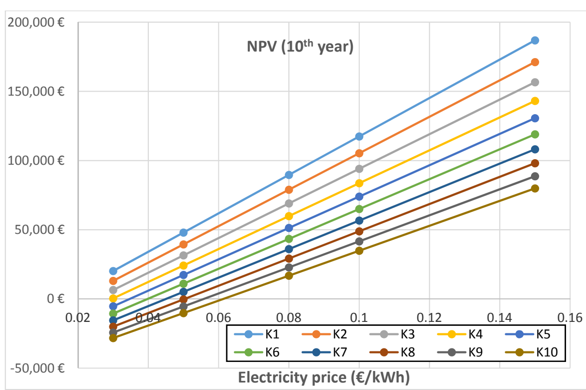

Fig. 1.4 NPV results for different values of rate of return and for different years of operation in Vestas V90 assuming changes in the electricity price

Finally, a study of the NPV results has been carried out under the assumption of variations on the electricity price. Fig. 1.4 shows the NPV results in the 10th year of operation for values of rate of return between 1% and 10%. The graph shows that CMS are profitable in most cases. Additionally, benefits are always obtained for values of rate of return between 1% and 4%. For high values of k and small values of electricity price gives the use of CMS not profitable.

1.4 Conclusions

A CMS for offshore wind turbines is proposed in this work to reduce operation and maintenance costs. The use of CMS has been demonstrated to be an effective solution to avoid large failures and/or downtimes. The economic study of the LCC of CMS for offshore wind turbines reveals the effectiveness of the CMS itself, economic benefits of CMS and the sensitivity to O&M costs under different scenarios: (a) initial investment provided by the company; (b) initial investment supported by a bank loan with an interest rate of 6%; and (c) variations in the electricity price. The following conclusions were achieved: 1) the results for case (a) shows that the return of the initial CMS investment cost is in the 3rd year and small values of rate of return caused higher CMS benefits; 2) similar results are obtained when the initial investment of CMS is supported by a bank loan (case (b)); and 3) The electricity price highly influences in the benefits obtained using CMS.

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