Maintenance Management of Wind Power Systems Using Condition Monitoring Systems—Life Cycle Cost Analysis for Two Case Studies

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***Abstract*—The large growth in the wind power industry in the past years mainly focuses on a growing market and the development of large turbines and offshore farms. The high technical availability of wind turbines comes with a greater need for frequent maintenance. Current maintenance planning is not optimized, and it is possible to make maintenance more efficient. Condition monitoring systems (CMS) could resolve the growing wind power industry's need for better maintenance management and increased reliability. Such systems are commonly used in other industries. CMS could continuously monitor the performance of the wind turbine parts and could help determine specific maintenance timing. This paper presents a life cycle cost (LCC) analysis with strategies where CMS improved maintenance planning for a single wind turbine onshore and a wind farm offshore. Case studies are based on real data from *Olsvenne2* at Näsudden (Gotland, Sweden) and *Kentish Flats*, in the U.K. The main conclusion is that CMS benefits maintenance management of wind power systems. Improvements can be especially shown for offshore wind farm maintenance planning.**

***Index Terms*—Condition monitoring systems (CMS), life cycle cost (LCC), maintenance, reliability centered maintenance (RCM), wind power.**

I. Introduction

THE wind power industry has experienced large growth in the past years. The growth mainly focuses on a growing market, wind power's better economic conditions (because of political decisions), and the development of large wind turbines and offshore farms. One of the goals is to increase reliability for turbines. The issue is even more important for offshore farms, where service is difficult and expensive. The industry has incentive to make maintenance more efficient.

Condition monitoring systems (CMS) could be the answer for better wind power industry maintenance management and increased reliability. Such systems are commonly used in other industries. CMS continuously monitors the performance of wind turbine parts, e.g., generator, gearbox, and transformer, and helps determine the optimal time for specific maintenance. This paper investigates these systems' support for the wind power user.

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A further step could be to implement CMS as a part of reliability centered maintenance (RCM). RCM is a structured approach that focuses on reliability when planning maintenance, i.e., finds a balance between preventive and corrective maintenance. RCM determines maintenance requirements of any physical asset and its operating context [1].

Condition monitoring can consist of e.g., vibration analysis and oil analysis. Several methods can be used in these two different analyses. The components of interest for condition monitoring, due to the wind turbine design, are the gearbox, generator, and main shaft. The most interesting component, the demonstrated critical component, is the gearbox because of its impact on system availability [2].

This paper presents the current approach used for operation and maintenance at two companies, Swedish Vattenfall and Danish Elsam, and presents a life cycle cost (LCC) analysis with possible maintenance management benefits in strategies where CMS is used [3], [4].

II. Theory

A. Availability

Availability is a fundamental measure of reliability. It combines both the outage time when an interruption has occurred and the frequency of interruptions. The concept of availability has several different definitions. According to Holen *et al.* [5], the definition is: the probability that the component or system is capable of functioning at a time t. The availability A is defined [5] as

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \tag{1}$$

where MTTF is mean time to failure and MTTR is mean time to recovery.

B. Maintenance

The purpose of maintenance is to enable desired component performance by maintaining or returning the component's ability to function correctly [6]. The maintenance concept does not provide only one correct operational solution. In this paper, it is divided into preventive and corrective maintenance [7]. Other examples of definitions on maintenance are presented by Endrenyi *et al.* [8] where maintenance is divided into, among other things, scheduled and predictive maintenance.

Preventive maintenance is the maintenance carried out before failures occur, and corrective maintenance is the maintenance

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carried out after failures occur. Preventive maintenance can further be divided into scheduled and condition-based maintenance. Scheduled maintenance is carried out in accordance with an established time schedule or established number of units in use [7]. Scheduled maintenance in wind power includes lubrication, tightening bolts, changing filters, and checking safety equipment. Condition-based maintenance is preventive maintenance that is based on performance and/or parameter monitoring and subsequent actions [7]. CMS is a tool for condition-based maintenance.

C. Reliability Centered Maintenance (RCM)

RCM is a systematic method to keep a balance between preventive and corrective maintenance. This method chooses the right preventive maintenance activities for the right component at the right time to reach the most cost-efficient solution [9]. RCM has its origin in the civil aircraft industry and the Boeing 747. The first description came in 1978 by Nowlan. It was introduced in nuclear power in 1980 and in hydro power in 1990 [6]. RCM is characterized by maintaining system function, identifying failure modes, prioritizing functions, and choosing efficient maintenance.

Reliability centered asset management (RCAM) is a development of RCM into a quantitative approach [10]. The aim of RCAM is to relate preventive maintenance to total maintenance cost and system reliability. The method was developed from RCM principles, and attempts to more closely relate maintenance's impact to system cost and reliability [10]. The aim is to use quantitative methods to see component-level preventive maintenance's effect on system cost and reliability. A central feature of the method is that the analysis moves from the system level to the component level and then back to the system level.

D. Life Cycle Cost (LCC)

LCC calculates the total cost for a technical system during its lifetime. The goal is to minimize the total lifetime cost [9].

The total cost involves planning, purchase, operation and maintenance, and liquidation. Power plant financial concerns could typically be investment, maintenance, down time, and remainder value. Within this study, it has been assumed that the total LCC (in euros per year) is defined as

$$\mathrm{LCC} = C_{\mathrm{Inv}} + C_{\mathrm{CM}} + C_{\mathrm{PM}} + C_{\mathrm{PL}} + C_{\mathrm{Rem}} \tag{2}$$

where C_{Inv} is the cost of the investment, C_{CM} is the cost for corrective maintenance, C_{PM} is the cost for preventive maintenance, C_{PL} is the cost for production loss and C_{Rem} is the remainder value.

The *present value method* compares all future payments over a certain time to one point in the present time. The present value PV means the amount of money that should be deposited into the bank now at a certain rate d to pay for an outlay C after n years. This means that all future payments are re-calculated to the equivalent value for the present time.

The present value of one outlay C to be paid after n years is gained by multiplying it with the *present value factor* $\mathrm{PV}_f(n,d)$ as [6]

$$\mathrm{PV} = C\,\mathrm{PV}_f(n,d) \Leftrightarrow C(1+d)^{-n} \tag{3}$$

where C is the outlay in (euros), n is the number of years from the present to the date of the outlay, and d is the discount rate, where, for example, a discount rate of 7% gives $d = 0.07$.

III. Maintenance Management of Two Case Studies

This paper describes how operation and maintenance is performed at two wind farms owned by two different companies:

1) Näsudden, Gotland, Sweden, owned by Vattenfall;
2) Kentish Flats, U.K., owned by Elsam.

The following maintenance process description is based on communication with A. Andersson, Operation Manager at Vattenfall, Näsudden,[1] and with T. K. Hansen, Project Team Manager at Kentish Flats for Elsam.[2] A description follows the two case studies in terms of system data, maintenance contracts, scheduled maintenance, manuals, and CMS.

A. System Data

At Näsudden, more than 100 wind turbines are installed, owned by different companies. Vattenfall owns about 30 of those wind turbines from different manufacturers. Some of the turbines at Näsudden are part of research projects and are prototypes. Here, the turbine *Olsvenne2*, a Vestas V90, has a CMS developed by Vestas called VCMS.[3] This is a prototype, and data from this system cannot be accessed by the personnel of Vattenfall, only by Vestas. Vattenfall has wind turbines in other places in Sweden, e.g., on the West Coast and one in Lappland, and there are plans for several new farms to be built mainly offshore. They also have activities in other countries in Europe like Germany, Poland, and Denmark.

The operation of Kentish Flats, an offshore farm with 30 × 3-MW turbines placed in the North Sea, U.K., has recently been taken over by Elsam, which also operates several turbines and farms in Denmark. Kentish Flats was completed in September 2005. The majority of Elsam's wind turbines in Denmark were taken over by Vattenfall in the summer of 2006. The CMS system VCMS [13] has been installed at Kentish Flats in the summer of 2006. Elsam has access to data from the CMS on this site.[2]

B. Maintenance Contracts

Vattenfall has contracts for maintenance with several companies. They have maintenance contracts with Vestas, Siemens, and Enercon. Maintenance contracts are valid for one year at a time and the decision has been made not to have any of the turbines insured.

For all new farms under Elsam, a five-year contract with full maintenance is signed with the manufacturer. This is in line with

[1] Interview with A. Andersson, Operation Manager at Vattenfall, Gotland, Sweden. January, 2006.

[2] Interview with T. K. Hansen, Project Team Manager, Turbines, Kentish Flats Offshore Wind Farm, Elsam Engineering, Denmark. January 2006.

[3] List of certifications, CMS/control centers for CMS, Germanischer Lloyd, January 1, 2006.

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TABLE I
SIMILARITIES AND DIFFERENCES BETWEEN THE TWO WIND FARMS

System	Number of turbines	CMS	Access to data	Scheduled maintenance	Contract on maint.
1.Näsudden/ Vattenfall	30 of different manufacturers	VCMS*on Olsvenne2	No	With half a year interval	1 year
2.Kentish Flats/ Elsam	30 Vestas	VCMS*	Yes	With half a year interval	5 years with Vestas

*Vestas CMS.

the five-year warranty period on the wind turbines. For Kentish Flats, a five-year contract was signed with Vestas.

C. Scheduled Maintenance

Today's wind power maintenance is mainly scheduled maintenance.

At Vattenfall, scheduled maintenance is carried out approximately twice a year in general. The maintenance is categorized as either minor or major. Minor maintenance takes about 4 h for two people and major maintenance takes about 7 h for two people. One hour costs about € 54, that is the hourly cost of a maintenance worker from Vestas.

At Elsam, scheduled maintenance is carried out in three to six month intervals, for older and smaller turbines. Newer, larger turbines have intervals of six months to a year. Older turbines are maintained by Elsam's own maintenance division, Elsam Wind Service, which has 10–15 workers. For larger tasks, Elsam rents external independent services. At Kentish Flats, scheduled maintenance requires two people working two days per turbine per year, all at a cost of € 750 per person per day if maintenance is scheduled, and a cost of € 850 per person per day if it involves a major overhaul. These costs include all labour-related costs such as training, safety equipment, pensions, offices, transportation, etc.

D. Maintenance Manuals

Vattenfall use a maintenance manual by Vestas.[4] The manual includes general rules, safety procedures, changing oil filters, and controlling leakages.

At Elsam, there is a manual for scheduled maintenance that is followed when maintenance is carried out. For corrective maintenance, there is no manual in use.[2] Manuals are often of varying quality and as a result interest groups in Germany now want to establish standards for maintenance manuals.

E. Similarities and Differences Between the Two Wind Farms

Similarities and differences between the two wind farms are listed in the table above (Table I). The farms are listed according to; number of turbines, CMS installed, whether the company has access to data or not, how often scheduled maintenance is carried out and valid time on maintenance contracts.

[4]Review, Mechanical part, Vestas, EDB nr.: 942285.R2, 1997.

IV. LCC ANALYSIS

A. Overview of the Approach

In this paper, LCC has been made for different scenarios comparing the effect of implementing different maintenance strategies. These strategies are based on the assumption that a CMS is implemented for two different case studies. First, one turbine onshore at Näsudden, and second, one average turbine at the offshore farm Kentish Flats.

At first, three strategies where preventive/corrective maintenance is affected are presented. Then, two strategies where only corrective maintenance is affected are presented. Finally, one strategy in which only the production loss is affected is presented. The last three strategies are only carried out for the offshore farm while the first three strategies are carried out both for the farm offshore, where an average turbine is observed, and the single turbine onshore. The strategies are based on the following assumptions.

1) The cost of preventive maintenance is compared to the cost of preventive maintenance and a CMS. The cost of corrective maintenance and the cost of production loss are set to zero.
2) The cost of preventive/corrective maintenance is compared to the cost of preventive/corrective maintenance and a CMS. The cost of production loss is set to zero.
3) The cost of preventive/corrective maintenance is compared to the cost of preventive maintenance, when corrective maintenance is set to zero, and a CMS. The cost of production loss is also set to zero.
4) Man-days are reduced and corrective maintenance becomes preventive because of better planning with CMS. The point at which a certain amount of unscheduled maintenance becomes preventive is determined in order to see when a CMS is profitable.
5) Man-days in the cost of major component replacements are reduced when the components are replaced two at a time instead of one at a time.
6) Availability increases and the cost of production loss is thereby decreased.

The purpose of these strategies is to evaluate the benefit of implementing CMS. In the first three strategies, a percentage for how much the cost must be decreased to make CMS profitable is calculated. The last three strategies give a direct indication of whether the price of a CMS is covered when implementing the strategy.

Possible benefits with CMS are that maintenance could be planned better, the right maintenance can be carried out at the right time, and unnecessary replacements can be minimized [2]. Downtime could be reduced as failures are discovered more easily.

The costs that could be saved with a CMS include costs for transportation to a wind farm offshore. Repairs can be planned in a new way. If one gearbox needs repair, then another gearbox that might go down at a later stage could be repaired at the same time, thanks to the CMS information. This saves money for transportation. On Kentish Flats, it is assumed that the installation of a CMS after a certain period of training time

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should allow both scheduled and corrective maintenance to be optimized.[2] The replacement of major components is of special interest here. The cost of a man-day includes all labor-related cost including training, safety equipment, pensions, offices, and transportation. In the two strategies where man-days are reduced at the farm because of better planning with a CMS, the difference in the total sum of the present value of LCC before and after is calculated.

B. Approach for the LCC Analysis

The sum of the costs for each year's LCC is calculated and multiplied with the present value factor $\mathrm{PV}_f(n, d)$. This gives the present value for the sum of LCC, PV(LCC) for each year, which is then summarized over the years as the total sum of present value for the LCC, TPV(LCC). This is at first done without a CMS.

The cost of a CMS is then added and the effect of different strategies is calculated. This is first done in three strategies where one wind turbine onshore versus one average wind turbine offshore is observed. Then, one wind farm offshore where maintenance is planned using a CMS is observed. Lastly, conclusions are drawn on the possible benefits of using a CMS.

The cost of a CMS is a part of the cost of preventive maintenance C_{PM}. The cost of replacing major components is a part of the cost of corrective maintenance C_{CM}. The cost of preventive maintenance C_{PM} could be divided into a cost for a CMS, C_{CMS}, and a cost for scheduled maintenance C_S

$$C_{\mathrm{PM}} = C_{\mathrm{CMS}} + C_S. \tag{4}$$

The cost of preventive and corrective maintenance $C_{\mathrm{PM}} + C_{\mathrm{CM}}$ and a CMS is

$$C_{\mathrm{CMS}} + C_S + C_{\mathrm{CM}}. \tag{5}$$

The LCC has been made for different cases with a cost for CMS. The cost for production loss is C_{PL}. The first three strategies are presented below.

Strategy 1: C_{CM} and C_{PL} are set to zero and C_{PM} is decreased so that TPV for the decreased C_{PM} with a CMS equals TPV of C_{PM} without a CMS

$$\mathrm{TPV}(C_{\mathrm{CMS}} + A_1 C_S) = \mathrm{TPV}(C_S) \tag{6}$$

where A_1 is a factor that decreases C_S.

Strategy 2: C_{PL} is set to zero and $C_{\mathrm{PM}} + C_{\mathrm{CM}}$ is decreased, so that TPV for the decreased $C_{\mathrm{PM}} + C_{\mathrm{CM}}$ with a CMS equals TPV of $C_{\mathrm{PM}} + C_{\mathrm{CM}}$ without a CMS

$$\mathrm{TPV}(C_{\mathrm{CMS}} + A_2(C_S + C_{\mathrm{CM}})) = \mathrm{TPV}(C_S + C_{\mathrm{CM}}) \tag{7}$$

where A_2 is a factor that decreases $C_S + C_{\mathrm{CM}}$.

Strategy 3: C_{PL} is set to zero and C_{CM} is at first set to zero, so that C_S within C_{PM} with a CMS can be increased so that TPV of an increased C_{S} within C_{PM} with a CMS equals TPV of $C_{\mathrm{PM}} + C_{\mathrm{CM}}$ without a CMS

$$\mathrm{TPV}(C_{\mathrm{CMS}} + A_3 C_S) = \mathrm{TPV}(C_S + C_{\mathrm{CM}}) \tag{8}$$

where A_3 is a factor that increases C_S.

TABLE II
COSTS FOR REPLACEMENTS OF MAJOR COMPONENTS

Component	Cost [EUR]
Gearbox	300 000
Generator	150 000
Transformer	100 000
Blade	200 000

C_{CM} can be divided into cost for unscheduled service C_{US} and cost for replacing major components C_{MC}

$$C_{\mathrm{CM}} = C_{\mathrm{US}} + C_{\mathrm{MC}}. \tag{9}$$

C_{US} can be divided into a cost for man-days C_M and a cost for spare parts C_{SP}

$$C_{\mathrm{US}} = kC_M + C_{\mathrm{SP}} \tag{10}$$

where k is the number of man-days.

C_{MC} can be divided into a cost for man-days C_M and a cost for replacing major components C_R

$$C_{\mathrm{MC}} = kC_M + C_R \tag{11}$$

where k is the number of man-days.

The cost C_{CM} has been compared for different scenarios. The next two strategies where the man-days are affected are presented below.

Strategy 4: In C_{US}, kC_M is decreased because the man-days can be reduced in unscheduled service when we plan it better with a CMS. Unscheduled service becomes preventive. The point B_1 at which a certain amount of unscheduled service becomes preventive is found to see where a CMS is profitable

$$C_{\mathrm{US}} = kC_{M,\mathrm{US}} + C_{\mathrm{SP}} \text{ becomes } C_{\mathrm{US}} = kC_{M,S} + C_{\mathrm{SP}}.$$

Strategy 5: The major components are replaced two at a time instead of one at a time because of a CMS. This means that in C_{MC}, k becomes $k/2$ and kC_M becomes $kC_M/2$. $C_{\mathrm{MC}} = kC_M + C_R$ becomes

$$C_{\mathrm{MC}} = (kC_M/2) + C_R.$$

The cost for a CMS affects the production loss. The final strategy in which the availability increases is presented below.

Strategy 6: If availability increases to B_2 from 97.5%, the total sum of the present value of the cost increases by $\mathrm{TPV(LCC)}_{\mathrm{Before}}$–$\mathrm{TPV(LCC)}_{\mathrm{After}}$ because of a CMS.

C. Application Studies

The analyses have been made based on estimates of the costs for the single turbine onshore, Olsvenne2[1] and the farm offshore, Kentish Flats.[2]

The task of estimating costs is difficult especially as prices can vary a lot. Table II shows costs of different major components.[1,2] The assumed investment cost for one CMS is € 20 000.[5]

A present value of the total LCC for every year has been calculated, which are then summarized as the total sum of the present value of LCC. The discount rate d is set to 7% and the life of a turbine N is 20 years.

[5]Interview with Fredrik Larsson, Managing Director on SKF Condition Monitoring Center. February 2006.

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The total sum of the present value of LCC has been calculated in different strategies. In strategy 1, preventive maintenance must decrease by a certain amount to make a CMS profitable. In strategy 2, preventive and corrective maintenance must together decrease by a certain amount to make a CMS profitable. In strategy 3, preventive maintenance with a CMS could increase by a certain amount when corrective maintenance is zero because of a CMS. In strategy 4, the cost for man-days kC_M is decreased as unscheduled service becomes preventive, i.e., the cost for man-days decreases from € 1000 per man-day into € 750 per man-day. The point where a certain amount of unscheduled maintenance becomes preventive is found to see where a CMS is profitable. In strategy 5, major components are replaced two at a time and this means that the man-days k is reduced to $k/2$ in the cost for replacements C_{MC}. In the final strategy 6, where production loss is affected, *availability* increases into a certain percentage. The cost for production loss is thereby decreased.

D. Input Data for Olsvenne2

The investment cost is placed in year zero. Connection cost is included in the investment cost. Preventive and corrective maintenance for two years are included in the investment cost. There is also a cost for basic maintenance-materials in both years. These costs are included in the costs for preventive maintenance C_{PM} and the corrective maintenance C_{CM} for year one and two. C_{PM} and C_{CM} from year three are estimated for each year. A cost for production loss has been calculated as income times *unavailability* from year one and is called C_{PL}. Commercial *availability*, i.e., 97.5%, has been used in this calculation. *Unavailability* is calculated as $1-$*availability*. A cost for demolition and recycling C_{Rem}, has been estimated for the last year.

Costs for major component replacements have been calculated. The gearbox is changed twice during a lifetime. The generator is changed once during a lifetime. The transformer and blades are changed 1/10th time during a lifetime. These costs are combined under cost of replacements C_R, according to

$$C_R = C_{R,\mathrm{GB}} + C_{R,G} + C_{R,T} + C_{R,B} \tag{12}$$

where

$C_{R,\mathrm{GB}}$ cost of replacing gearboxes for a year;
$C_{R,G}$ cost of replacing generators for a year;
$C_{R,T}$ cost of replacing transformers for a year;
$C_{R,B}$ cost of replacing blades for a year.

The investment cost in one CMS is C_{CMS} in year zero. $C_{\mathrm{CMS}} =$ € 20 000. The input data include no CMS and are for one single turbine.

E. Input Data for Kentish Flats

The cost of the first year is the investment cost, which includes connection cost. From year 1 to 20, costs for scheduled service are included and are the same every year. Major overhaul is included in scheduled maintenance for most of the years but is entered as a cost in years 4, 6, 9, 13, and 14. This is included in the preventive maintenance cost C_{PM}.

Unscheduled maintenance costs decrease from year one for four years and then increase at the end. They include one visit to each turbine every month in year one, reduced to one visit every three months in year four. This is included in the corrective maintenance cost C_{CM}. A cost for production loss C_{PL} has been calculated as income times *unavailability* from year one. These costs are calculated together. Here, commercial *availability* has been used, that is 97.5%. *Unavailability* is calculated as $1-$*availability*.

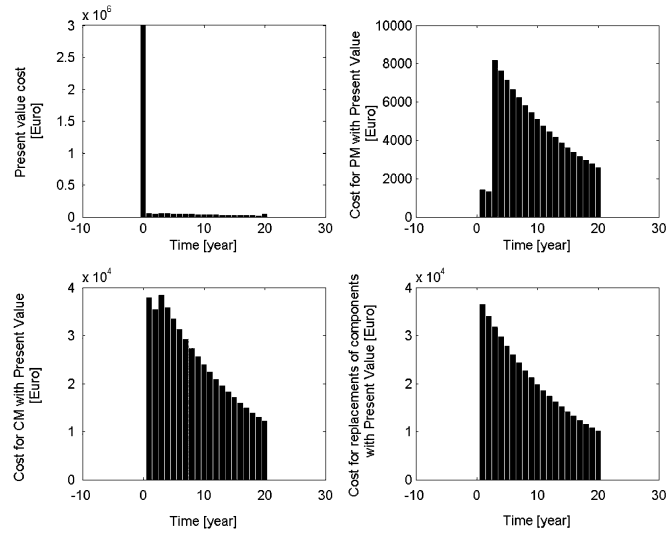

Fig. 1. Results of the LCC analysis for Olsvenne2. Present value cost and costs for preventive maintenance C_{PM}, corrective maintenance C_{CM}, and replacements C_R of major components with replacements every year for Olsvenne2. The cost of replacements of major components is included under C_{CM}. The discount rate was set to 7%.

The major component replacements have been estimated per year for 20 years. For example, 11 gearboxes are to be replaced out of 30 during the turbine's lifetime, 20 generators are to be replaced during a lifetime, 3 transformers and 3 blades are to be replaced out of 30 during a lifetime, etc. These costs are included under cost of replacements C_R, according to Eq. (10) and are part of the cost of corrective maintenance C_{CM}.

The investment cost in 30 CMS is 30 C_{CMS} in year zero. 30 $C_{\mathrm{CMS}} =$ € 600 000. One scheduled man-day costs € 750 at Kentish Flats, $C_{M,S} =$ € 750. One unscheduled man-day costs € 1000 at Kentish Flats, $C_{M,\mathrm{US}} =$ € 1000.

The number of man-days k is 43; this means that 43 components are replaced in 43 days including 11 gearboxes, 20 generators, 3 transformers, 3 blades, etc. Thus, 43 components will be replaced during the wind farm's lifetime. The input data include no CMS for the entire farm.

F. Results of the LCC Analysis

Results from the calculations of the two cases Olsvenne2 and Kentish Flats are presented in Figs. 1 and 2. For Olsvenne2, the results of the total sum of the present value for the LCC, and the strategies 1–3 are presented. For Kentish Flats, the results of the total sum of the present value for the LCC, and the strategies 1–6 are presented. In strategies 4–6, the man-days at the farm are affected by a CMS and this changes the maintenance cost C_{CM}.

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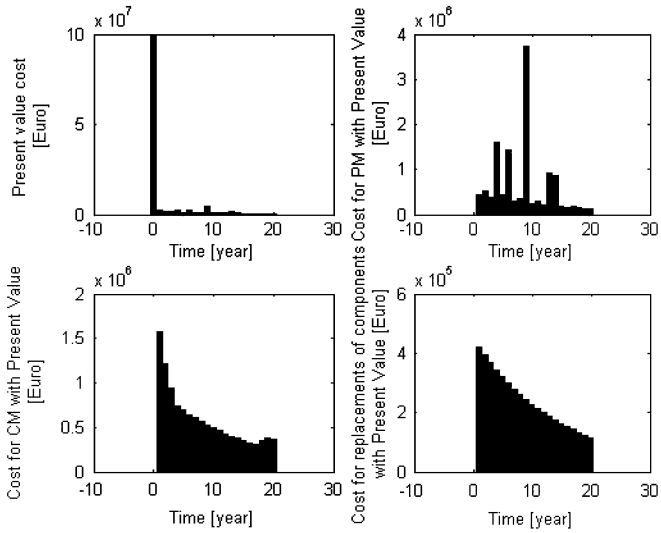

Fig. 2: Results of the LCC analysis for Kentish Flats. Present value cost and costs for preventive maintenance C_{PM}, corrective maintenance C_{CM}, and replacements C_R of major components with replacements every year for Kentish Flats Wind Park. The cost of replacements of major components is included under C_{CM}. The discount rate was set to 7%.

TABLE III
CHANGES NEEDED TO COVER THE COST OF A CMS

Strategy	**Onshore, 1 turbine**	**Offshore, 1 average turbine**
1 – A change in Preventive Maintenance.	23 %	4.5 %
2 – A change in Preventive –and Corrective Maintenance.	3.5 %	2.5 %
3 – How much Preventive Maintenance can increase if Corrective Maintenance is set to zero.	6.3 times	1.85 times
	Change at a Wind Farm, 30 turbines	
4 – How much of the Corrective Maintenance needs to be Preventive Maintenance.	47 %	
5 – How much can be saved by replacement of two at a time.	EUR 230 000	
6 – How much availability must increase.	0.43 %	

1) Olsvenne2: The sum of the present value for 20 years, the total sum of the present value for the LCC, was about € 3.72 million for Olsvenne2 when the discount rate was set to 7%. For present value cost every year as well as preventive maintenance cost C_{PM}, corrective maintenance cost C_{CM}, and cost of replacements C_R, see Fig. 1.

2) Kentish Flats: For Kentish Flats wind farm, the total sum of the present value for the LCC would be about € 4.25 million per turbine with the discount rate set to 7%. For present value cost every year as well as preventive maintenance cost C_{PM}, corrective maintenance cost C_{CM}, and cost of replacements C_R, see Fig. 2.

3) Summary of Results for Implementation of the Strategies: The implementation of the different strategies shows several ways to cover the cost of a CMS, especially if the calculations are carried out for a large-scale wind farm offshore. For the separate turbine, corrective maintenance has to be included, but if only the preventive maintenance is included, it has to be decreased significantly. Table III shows the changes needed to cover the cost of a CMS in the separate turbine onshore versus an average turbine offshore, and how a CMS is justified when maintenance could be better planned for the wind farm offshore.

V. CONCLUSION

A LCC analysis has been carried out to gain an understanding of whether a CMS is profitable for the separate wind turbine onshore and the wind farm offshore. The LCC is compared for different alternative maintenance strategies.

The results from the first three strategies show that for a single turbine, preventive maintenance would have to decrease by 23% if only preventive maintenance is affected. The result for the farm was 4.5%. If corrective maintenance is also affected, preventive and corrective maintenance together would not have to decrease by more than 3.5% for the single turbine and 2.5% for the farm. A decrease in corrective maintenance is needed to justify a CMS, at least for the turbine onshore.

When an entire farm was observed, the conclusions were that a change from scheduled to unscheduled maintenance of 47% would be enough to make a CMS profitable. Replacing components two at a time instead of one at a time would not be enough to make CMS profitable, but it would have a significant impact. Availability would not have to be increased by more than 0.43% to reduce the cost of production loss to cover the cost of a CMS. There are many ways to cover the cost of a CMS, especially for the wind farm offshore where maintenance could be planned more efficiently with a CMS.

VI. FUTURE WORK

In future work, it would be interesting to study how to combine CMS and RCM in wind power. To follow the development of wind farms offshore, and see the possibilities and benefits of RCM and CMS in a farm with the same type of turbine would be a further step. To be able to plan maintenance with RCM, a system that collects data is needed. CMS here enters as a good tool.

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