# Economic Aspects of Prognostics and Health Management Systems in the Wind Industry

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## ABSTRACT

Since Wind Turbines are one of the most dynamically stressed structures, all parts should be subjected to Prognostics and Health Management System. This is especially true for the supporting structure since it is exposed to high fatigue loads. The current technical trend in the O&M business is to improve the life-time of these supporting structures. In particular, when considering the supporting structure of a wind turbine from a civil engineering perspective; a long term approach is most beneficial in financial, ecological and social aspects. To meet the challenge of managing the life-time of wind turbine supporting structures efficiently, it is necessary to develop technical concepts assessing the consumed life-time of a wind turbine. Future PHM systems of wind turbines must include this function.

The global O&M market in the wind energy industry grew in the period from 2005 to 2011 at a rate of around 18 per cent, annually. The main growth driver is the aging overall turbine park. Especially in the European onshore wind market there will be a profit migration of the O&M business at the expense of new construction until 2020. Until the year 2020, three quarters of the total profit in the wind energy industry will be occupied by O&M services (Oliver Wymann, 2011).

This paper discusses the special economic aspects of Prognostics and Health Management Systems focusing on a remaining lifetime prediction as a basic maintenance system in application within the wind industry. Besides studies of the future O&M market development, concepts to lower the levelized cost of energy through PHM from a macroeconomic perspective will also be discussed.

Keywords: Wind O&M market, Lifetime management, Levelized cost of energy, return on investment analysis.

## 1. INTRODUCTION

Europe is currently in the energy transition process from conventional and fossil power technologies to renewable energy technologies. Fossil fuels helped to build the modern world we know in Europe. But with the goal to preserve the ecological balance for future generations and not to continue robbing natural resources for blind growth, the task of the generations in this century is to transform our energy system into a renewable one. Additionally renewable resources also enable people in developing countries quick and useful access to energy for their daily lives. We live in a transformative moment in history in which we should not waste time anymore and use this unique gift of our planet.

In this context it is worthwhile to remember a famous quote of the theoretical physicist and mastermind Albert Einstein:

"Imagination is more important than knowledge. Knowledge is limited; Imagination encircles the world."

With this background the paper is concerned with the possibilities and potentials of PHM systems to economically optimize the operation of wind power plants.

## 2. GLOBAL WIND MARKET DEVELOPMENT

The global wind market is mainly characterized through a mature onshore market and a growing offshore market. The pioneers of the past in the onshore wind energy developments were the USA, Denmark, Germany and Spain (GWEC, 2012). Those countries represented the starting points for the global onshore wind energy development. Despite the growing Asian market, Europe is still the continent with the highest installed wind power capacity. Furthermore Latin America, India, Africa and Canada are also very dynamic markets. Until today roughly 80 countries contribute in developing the global onshore wind energy market. As shown in Figure 1 the current total global installed capacity accounts 282 GW. Average annual growth rates of about 28 % characterized the dynamic development (GWEC, 2012).
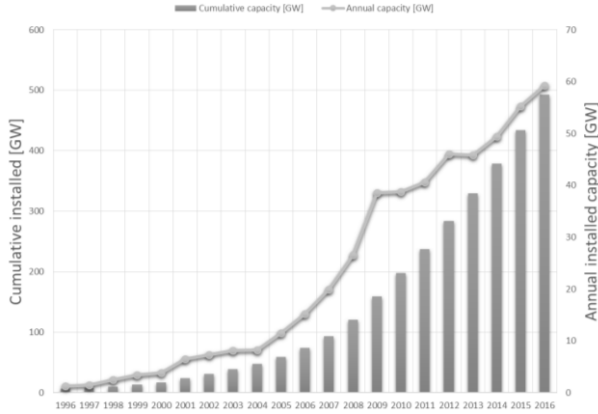
Figure 1: Global wind power capacity development
(GWEC, 2012).



Figure 3: Cumulative capacity forecast per region
(GWEC, 2012).

At the end of 2012 the European market added 108 GW to its installed wind power capacity. A share of 78 GW was installed in the leading markets, namely Germany, Spain, France, Italy and the UK. Within the major players, Germany is still the leading wind energy market in Europe and conducts 32 GW installed wind power. The new major finalized offshore projects on the British coast made UK the European country with the highest capacity growth rate (EWEA, 2013).

In regards to the capacity growth rates, Asia beat the European growth rates for the first time in 2009. In 2010 Asia installed more new wind turbines than the USA and Europe combined. The main driver in Asia is the Chinese market. Figure 2 shows the distribution of the current global cumulative installed wind turbine capacity for the leading countries.
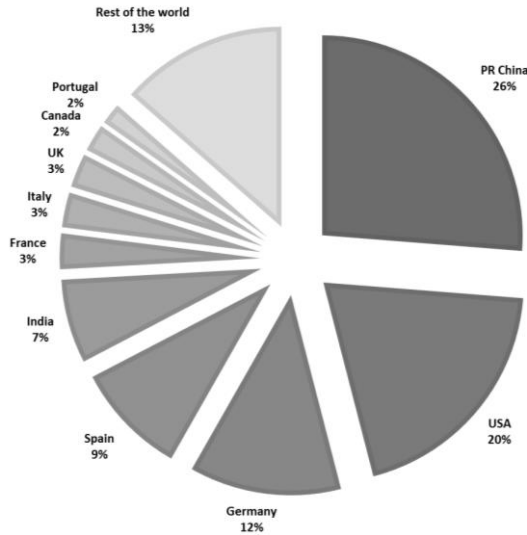
Besides the already mentioned rapid Asian market growth Figure 3 also shows the developing markets in Latin America, Africa and the Middle East region as well as the Pacific area. Especially in Morocco for example, there are excellent locations for converting wind energy. However the limiting factors in these regions are the unstable political and social frameworks.

The previously mentioned leading role of Germany in the European market is graphically expressed in Figure 4. The second largest wind market in Europe is located in Spain which undergone flourishing development in the early 2000s. Currently the restrictive and backward renewable energy policy in Spain leads the local wind energy market development almost to a deadlock.



Figure 2: Global wind turbine capacity distribution
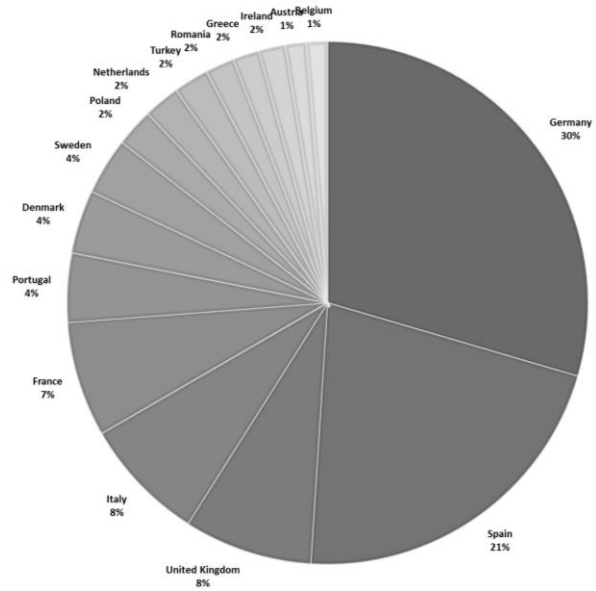(GWEC, 2012).



Figure 4: European wind turbine capacity distribution
(EWEA, 2013).

The European wind energy market can be subdivided into an onshore market segment and an offshore market segment. Figure 5 shows the market development in those areas considering the annual installations in the last decade. Despite the fact that there are plenty of research as well as market activities in the new offshore business, the lion's share considering real operative business is still clearly covered by onshore turbines. The presented European market setup is also valid for the German market as Table 1 points out. A special feature of the mature German market is the growing importance of repowering activities as more and more turbines reach their designed life-times. The alternative to repowering is plant life extension with the support of PHM systems in application. Special macro-economic aspects of this opportunity will be discussed later in the article.

Due to the fact that major players of the European wind energy market are currently revising their policies and subsidies – causing uncertainty on the investors' side – European market growth will decelerate.

However, new positive market developments are recognized in Latin America. In the last five years Brazil has gone from a fledgling wind market to a generic business development base. Brazil alone installed more than twice the amount of grid-connected turbines than all other Latin American countries combined.

Another future flourishing market will be South Africa. The South African government is currently tendering big wind turbine projects in the mountain regions northwest and northeast of Cape Town.
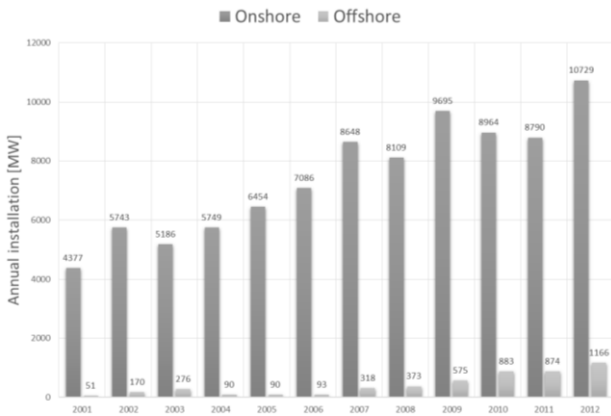
Table 1: German onshore wind market
(Deutsche WindGuard GmbH, 2013a).

| Development in the German Onshore Wind Market | | Number | Capacity [MW] |
|---|---|---|---|
| **2012** | Cumulative installed wind turbines - 31.12.2012 | 22907 | 30989 |
| Develop-ment 2012 | Gross new installed wind turbines in 2013 | 1154 | 2998 |
| | - Repowering | 269 | 766 |
| | Dismantling in 2013 | 416 | 258 |
| **2013** | Cumulative installed wind turbines - 31.12.2013 | 23645 | 33730 |

## 3. DEVELOPMENTS IN THE WIND O&M MARKET

In Europe the general market environment is characterized by a mature onshore market and a growing offshore market. In future the European market will experience a profit migration from new installations to O&M services. The European wind service market currently has a size of 2.3 bn. €. Furthermore the European wind energy servicing market occupied in recent years roughly half of the global wind energy servicing market size. The European market will grow up to 2.7 bn. € until 2020, as shown in Figure 6. From 2005 until 2011 the European O&M market grew about 18 % annually on average. Germany's maintenance market will be the largest and reach 1 bn. € in 2020.

The main market players in the European O&M business in the wind industry are the service departments of the Original Equipment Manufacturers (OEM), Independent Service Providers (ISP) and the Wind Farm Owners (WFO). ISPs currently mainly concentrate their business activities on special turbine types and regional areas. Due to the decreasing margins in production of wind turbines, the OEMs build increasingly their businesses on complete packages of wind power plants including all services over a life-time of 20 years. In doing so, they secure their market positions facing new business models such as ISPs (BWE, 2012).



Figure 5: European new business onshore/offshore
(EWEA, 2013).



Figure 6: European service market development
(Deloitte / TaylorWessing, 2012).

Looking into the latest statistics of the German wind energy association – Bundesverband WindErnergie e.V. – it can be seen that the OEM service concepts still dominate the market with a 90 % share of OEM service contracts in the German wind energy market (BWE, 2012). However, different studies predict that the current 10 % market share of the ISPs will rise up to 30 % in 2020 (Oliver Wymann, 2011). Additionally the ISPs are also searching for new market possibilities in Poland, France and Italy.

From a macro-economic perspective this represents positive development. The growing number of competitors in the O&M market will lead to increased price pressure and lower the current high maintenance costs.

Until now the onshore market clearly dominated the O&M business. In the year 2012 about 91 % turnover was reached in the onshore market and 9 % turnover in the offshore market. The increasing average age and the large number of turbines in the onshore market provide a good basis for future business developments. In the coming years more and more turbines will exceed their designed lifetime of 20 years. In the year 2012 about 860 turbines were older than 20 years. Predictions say that in the year 2020 we will have 8,200 turbines over 20 years in operation (Fraunhofer IWES, 2013). Despite having relatively less turbines, the offshore sector still offers market potential for players in the O&M market. The core problem which needs to be solved soon in the offshore maintenance business is the high maintenance cost – 2 to 4 times higher than in the onshore sector (IRENA, 2012).

## 4. COST STRUCTURE OF A WIND TURBINE PROJECT

Prior to analyzing economic concepts of PHM systems in the wind industry it is necessary to get a clear understanding of the cost structure in that business branch. On the highest level the cost structure can be subdivided into investment costs and operation costs. Furthermore, the investment costs are categorized into primary investment costs and secondary investment costs.

The main investment costs come directly from the wind turbines' physical components. Main cost drivers are the following subsystems: gear box, rotor blades, generators and particularly the towers. The specific investment costs of wind turbines rise with increasing hub heights but decrease with increasing power of the turbine. This correlation is mainly lead by the influencing high costs of the supporting structure of turbines. The specific tower costs rise with increasing turbine power. On average the primary investment cost shares of the tower structure range from 24 % to 32 % for a wind turbine in the onshore market. In comparison rotor blades on average cost from 21 % to 24 % of primary investment, and the gearboxes cost from 10 % to 18 % of primary investment. Those three subsystems represent the most important cost shares of the wind turbine

and therefore are important working points for the installation of a PHM system.

The secondary investment costs contain on a basic level the foundation of the wind turbine, the grid connection as well as the prior planning activities and during the turbine construction phase. The main cost share of on average 18 % is occupied by the foundation costs. Together with the above-mentioned importance of the supporting structure from an economic perspective, the supporting structure components tower and foundation are of particular interest for PHM future systems in application in the wind industry.

Figure 7 illustrates the investment cost structure of an example 3 MW onshore wind turbine in Southern Germany.

The second main cost category of wind turbines is the operating costs. By definition the operating costs contain all expenses necessary to ensure a safe and reliable operation of the turbine over the whole life span. Core expenses are maintenance and repair, leasing costs, commercial and technical operation management, insurance costs, savings and miscellaneous costs.

Due to the importance of maintenance and repair costs in the distribution of the operating costs the majority of the wind turbine owners prefer full service contracts. The duration of those full service contracts for wind turbines range from 10 years to 15 years. Full service contracts include the benefits of all maintenance and repair costs by default defined in the wind industry as well as all unplanned maintenance and repair activities beyond the warranty of the Original Equipment Manufacturer (OEM). Additionally providers of such full service contracts guarantee a certain level of availability of the wind turbine over the lifetime. The guaranteed availability levels range from 95 % to 99 %. The main providers for full service contracts are on the one hand the OEMs and on the other hand the so called Independent Service Providers (ISPs). In particular, the wind turbine owners profit in this framework from a calculable cash flow plan of their wind turbine project with minimized risks.
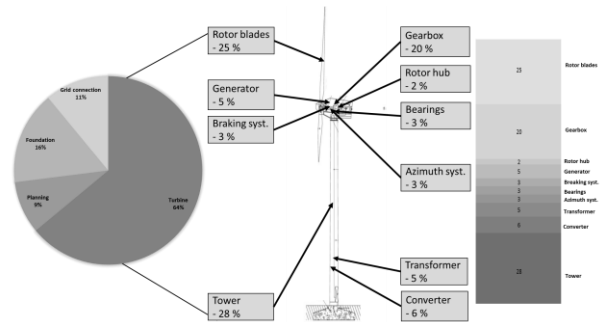
Figure 7: Distribution of investment costs – Onshore.

A recent poll of the German wind energy association – Bundesverband WindEnergie e.V. - came to the result that

34 % of the overall wind turbines in the German market are serviced in standard service contracts and 64 % of the turbines in full service contracts (BWE, 2012).

To proceed with the analysis of the distribution of the operating costs it is appropriate to subdivide operations costs in to the first half of the planned lifespan of a wind turbine project and the second half of the lifespan.

Figure 8 shows the proportional distribution of operating expenses of an average onshore wind turbine project. Most importantly, the high amount of maintenance and repair as well as the increasing development in the second half of the life span is remarkable. In the second half of the lifetime wind turbines cause 30 % to 43 % more O&M costs compared to the first half.

The whole renewable energy branch in Europe is currently under cost pressure in the energy transition process. On the route to a renewable energy system the basic challenge is to further reduce the energy production costs of the different technologies. PHM systems can certainly help to solve these complex problems on a technical basis.

To illustrate this point; Germany spends in 2013 23 bn. € for feed-in tariffs and other subsidies for renewable energy sources. Those costs have to be optimized and the technologies will have to be further developed to marketability. However, the wind energy technology already covers an important and economical part of the renewable capacities in the power system and represents therefore a valuable development base. The key concept from a macro economic standpoint is to reduce the Levelized Cost of Energy (LCOE) of a specific generation technology – in this case, wind energy.
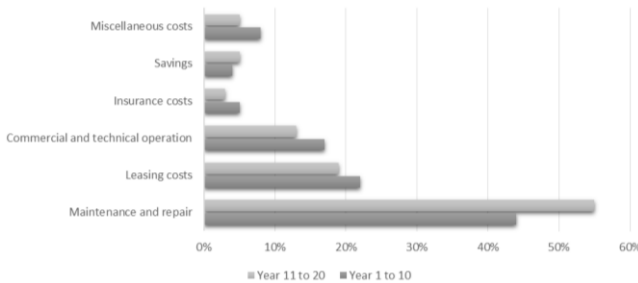


Figure 8: O&M cost dependence from turbine age (Deutsche WindGuard GmbH, 2013b).

## 5. PHM TO LOWER THE LEVELIZED COST OF ENERGY

In order to evaluate the total costs of production of electricity the concept of Levelized Cost of Energy (LCOE) can be applied.

In the case of wind energy this concept describes the costs incurring for the conversion of wind energy into electricity.

The streams of costs for wind energy are converted to a net present value using the time value of money. In general the LCOE represent the price at which electricity must be generated from, at a specific source to break even over the lifetime of the project. All costs over the lifetime of a given project are summarised and included, discounted to the present time $t = t_0$ and levelized based on the annual energy production of the particular project.

In case of wind turbines the generated electricity represents future income and is discounted cash flow in the model. In $C_t$ the annual overall costs are summarized. The parameter includes: General fixed and variable costs of the wind turbine project, all costs incurring from maintenance activities, insurance costs as well as recycling costs of the wind turbine. In case of wind energy projects there are no fuel costs to consider, which would normally represent an important parameter in economic evaluations of conventional power plants. The used discount rate for the study is exemplary derived from the theory of Weighted Average Cost of Capital (WACC). Under consideration of the current financial market the WACC discount rate depends from the amount of equity capital in the certain project, the calculative return of equity capital and the amount of bonded capital (Berk, J., 2011).

One applicable formula to calculate the LCOE with this international known approach is the following:

$$\frac{I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Y_{el}}{(1+i)^t}}$$

(1)

The goal of this approach is to enable the comparison of the energy production costs from different conventional and renewable sources from a macro-economic perspective. The method of levelized cost of energy is not suited to give evidence to the cost effectiveness of a certain wind turbine project. For those purposes one needs a defined cash flow calculation over the lifetime of the certain project. Furthermore, the resulting prices of the LCOE approach also can not be compared to current energy prices in the energy stock market – e.g. at the European Energy Exchange (EEX) in Leipzig, Germany. The stock prices are dependent on weather and grid conditions and mainly influenced by the global market conditions in short term. Those effects cannot be represented with LCOE prices.

Figure 9 compares the different energy converting technologies which are currently available in the energy system.

Considering specific investment costs between 1000 and 1800 € / kW in the onshore area the levelized cost of energy of onshore wind turbines range between 45 and 107 € /

MWh. At good wind locations onshore wind turbines are already able to produce power cheaper than conventional new coal and gas power plants. If this positive development continues, in future onshore wind turbines might be possibly cheaper than average brown coal capacities in the energy system. Offshore wind turbine technology costs currently between 119 and 194 € / MWh providing specific investment costs ranging from 3400 € / kW to 4500 € / kW Fraunhofer ISE, (2013). Here, LCOE of offshore technologies are approximately double the LCOE of onshore wind technologies. The expensive installation process especially, and the high O&M costs contribute to that setting. But in general the LCOE of renewable energy sources decrease in preparation of the future renewable energy system, while the LCOE of conventional power plants will continue to rise.

Figure 10 describes on top level how the LCOE of a wind turbine project come together on an annual basis. The left side represents the cost side subdivided in the annual capital cost as well as the annual operation and maintenance cost. The right side represents the denominator side.
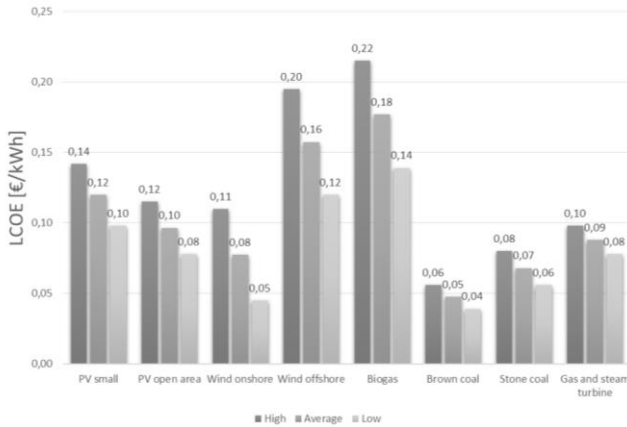


Figure 9: Comparison of renewable energy LCOE
(Fraunhofer ISE, 2013).



Figure 10: LCOE setup of an onshore wind project
(IRENA, 2012).

The annual energy yield is dependent on the specific turbine characteristics as well as the location characteristics. Derived from technical and mathematical relationships in order to optimize and reduce the levelized cost of energy of wind turbine technologies, three main strategies connected with PHM systems can be clarified:

1)  Lower O&M costs.

2)  Increase power output.

3)  Increase the lifetime of wind turbines.

Consequently PHM systems for the wind industry in future will have to focus holistically in those three dimensions according to Figure 11.

To analyze the economic impact of optimizing those three parameters it is worthwhile to conduct a generic sensitivity analysis.

As general setup of the sensitivity analysis the study focuses on a typical onshore wind turbine class ranging from 2 to 3 MW. The overall operating costs in the years one to ten are fixed to 25.1 € / MWh on average according to Deutsche WindGuard GmbH, (2013b) in the study presented here. In the years eleven to twenty the operating costs are fixed to on average 26.3 € / MWh for the analyzing calculation conducted here. Furthermore the discount rate is defined by 3.8 % after the WACC-approach over the whole sensitivity analysis.
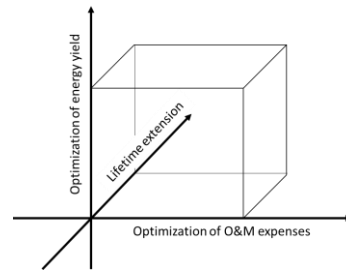


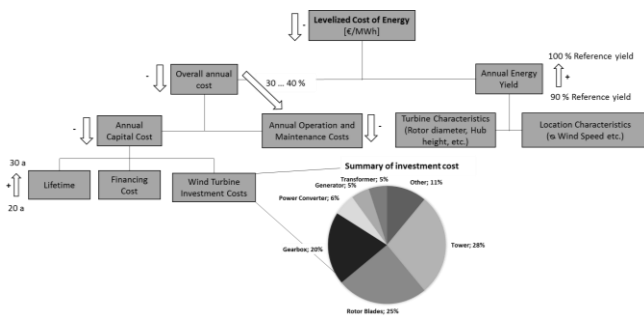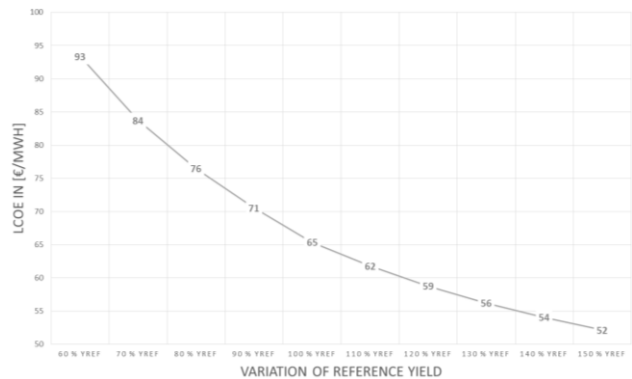Figure 11: Focusing dimensions of PHM for wind turbines.



Figure 12: Effect on LCOE by enhancing reference yield.

Firstly the study is modifying the annual energy yield which corresponds to the PHM function of helping to increase the annual power output – e.g. through higher availability in the power grid. A typical value of 2,882 MWh/kW/a as 100 % reference value for the ideal onshore wind turbine was set.

As shown in Figure 12, the annual energy yield has a high impact on the LCOE. With every 10 % increase of annual energy yield the technology costs of onshore wind turbines fall about 4.65 € / MWh on average.

In the next step the variation of the production costs was conducted, corresponding to the PHM function of lowering the O&M expenses.

This time a fixed typical onshore turbine characteristic was set as object of investigation, which is defined in Table 2. With an 80% reference yield of 2,537 MWh/kW/a the 2.45 MW onshore turbine with specific investment costs of 1785 € / kW is typical for Southern German wind farm locations Deutsche WindGuard GmbH, (2013b).

In a total of ten steps the annual operation costs were decreased in steps of 5% relating to the initial configuration. Corresponding to the formulas, every 5 % economization in the annual operating costs – mainly maintenance costs – reduces the technology costs by about 1.28 € / MWh. As shown in Figure 13 this variation has a linear decreasing effect on the LCOE. It has to be said that an operating cost reduction of about 50 % might be difficult to reach with PHM support – furthermore the operating costs will have fixed cost components which will have to remain – however the trend and influence of this parameter can be derived in that part.

Table 2: Turbine param. for LCOE effects var. $C_t$

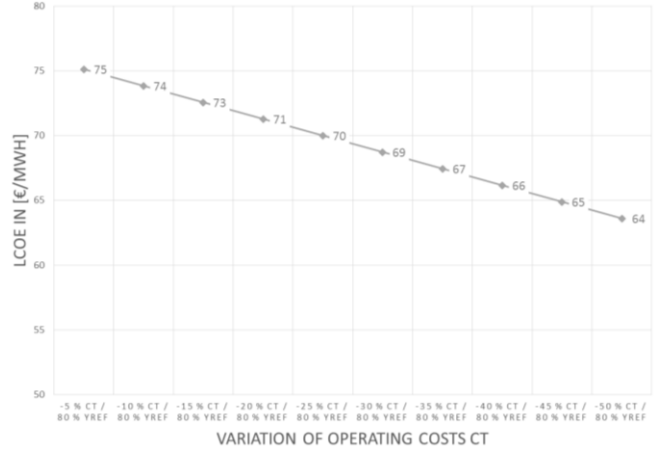| Turbine characteristic | | |
|---|---|---|
| Power | 2,45 | MW |
| Specific investment costs | 1785 | €/kW |
| Reference yield | 2,537 | MWh/kW/a |



Figure 13: Effect on LCOE by reducing the operating costs.

Last but not least the lifetime of the wind turbine project was varied addressing the PHM function of optimal lifetime management. The lifetime enhancement was modelled in ten steps increasing 5 years with every step - starting with the default lifetime of 20 years. Due to the fact that the operating costs of older wind plants will rise, the calculation used a linear increase of operation costs of 1.2 € / MWh per decade extra lifetime as shown in Table 3.

As shown in Figure 14 on average every five years lifetime enhancement reduces the LCOE of onshore wind energy by about 1.53 € / MWh. It well could be that in reality the operating costs do not increase in a linear manner with every decade. Assuming proper use of the installed PHM system might lead to a lower increase of operating costs of older wind turbines. The vision of lifetimes of 50 years and beyond has so far not been technically proved in the wind energy market, but considering typical civil engineering buildings with a similar number of load cycles – e.g. bridges – from a macro economic standpoint it is worthwhile to work on that vision enabled to PHM systems. This vision is especially challenging for PHM engineers because from a technical point of view wind turbines can be defined as aero generation systems including many mechanical and electro technical elements with different fault modes to be detected and managed via PHM systems. Certainly the human safety level must not be influenced in a negative way considering enhanced lifetimes of wind turbines.

Table 3: Increase of operating costs over lifetime

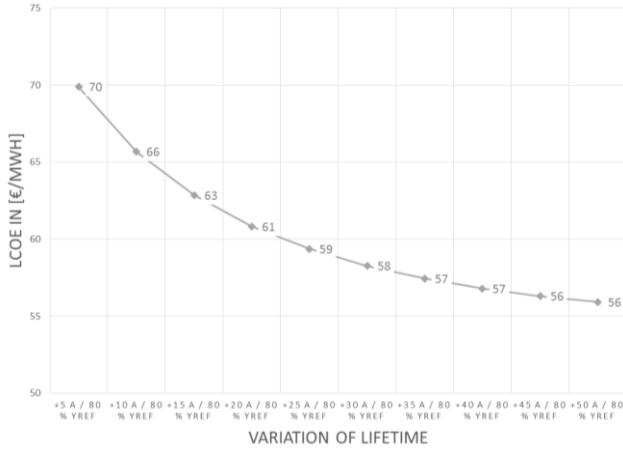| Lifetime | $C_t$ - Operating costs €/MWh |
|---|---|
| Year 1 … 10 | 25,1 |
| Year 11 … 20 | 26,3 |
| Year 21 … 30 | 27,5 |
| Year 31 … 40 | 28,7 |
| Year 41 … 50 | 29,9 |
| Year 51 … 60 | 31,1 |
| Year 61 … 70 | 32,3 |

Figure 14: Effect on LCOE by enhancing the lifetime.

Finally Figure 15 displays all three investigated PHM functions at wind turbines and their optimizing effect on the wind energy production costs in the energy system. Theoretically the effects of the functions in the LCOE parameter study here were separated, but in reality the effects will have to be combined – e.g. enhancing the turbine's lifetime in reducing operation loads can certainly also lead to reduced maintenance and repair costs because e.g. the main shaft bearings see lower load amplitudes – which would lead to further LCOE cost optimizations enabled to those generated synergies of PHM functions.
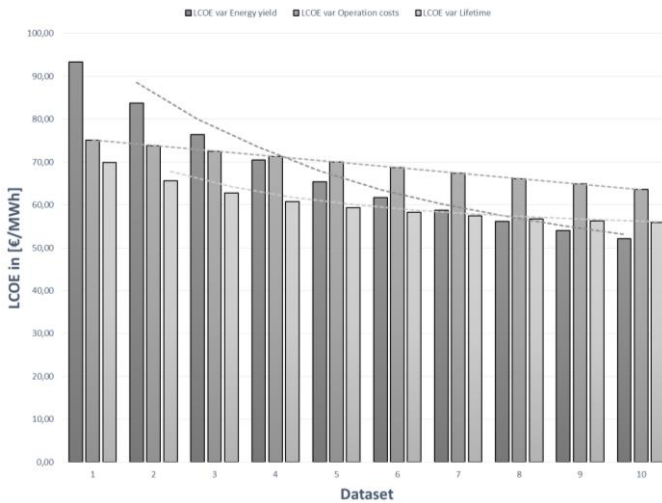


| Dataset | LCOE var Energy yield | | | LCOE var Operation costs | | | LCOE var Lifetime | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 60 % Yref | 93,35 | €/MWh | -5 % Ct / 80 % Yref | 75,11 | €/MWh | +5 a / 80 % Yref | 69,89 | €/MWh |
| 2 | 70 % Yref | 83,70 | €/MWh | -10 % Ct / 80 % Yref | 73,83 | €/MWh | +10 a / 80 % Yref | 65,67 | €/MWh |
| 3 | 80 % Yref | 76,45 | €/MWh | -15 % Ct / 80 % Yref | 72,55 | €/MWh | +15 a / 80 % Yref | 62,85 | €/MWh |
| 4 | 90 % Yref | 70,54 | €/MWh | -20 % Ct / 80 % Yref | 71,27 | €/MWh | +20 a / 80 % Yref | 60,82 | €/MWh |
| 5 | 100 % Yref | 65,37 | €/MWh | -25 % Ct / 80 % Yref | 69,99 | €/MWh | +25 a / 80 % Yref | 59,36 | €/MWh |
| 6 | 110 % Yref | 61,78 | €/MWh | -30 % Ct / 80 % Yref | 68,71 | €/MWh | +30 a / 80 % Yref | 58,26 | €/MWh |
| 7 | 120 % Yref | 58,77 | €/MWh | -35 % Ct / 80 % Yref | 67,43 | €/MWh | +35 a / 80 % Yref | 57,44 | €/MWh |
| 8 | 130 % Yref | 56,21 | €/MWh | -40 % Ct / 80 % Yref | 66,16 | €/MWh | +40 a / 80 % Yref | 56,79 | €/MWh |
| 9 | 140 % Yref | 54,05 | €/MWh | -45 % Ct / 80 % Yref | 64,88 | €/MWh | +45 a / 80 % Yref | 56,30 | €/MWh |
| 10 | 150 % Yref | 52,17 | €/MWh | -50 % Ct / 80 % Yref | 63,60 | €/MWh | +50 a / 80 % Yref | 55,91 | €/MWh |

Figure 15: Summary of LCOE optimizing effects of PHM functions at wind turbines.

## 6. CONCLUSION

The last paragraph is dedicated to a short summary of the main findings of the contributed work here as well as a quick forecast for future research activities.

As pointed out in chapter 2 the global wind industry is already an important business branch in Europe, especially in Germany, France and UK. Under the provision of supporting policies its positive development will continue in the coming decades.

Furthermore, mainly due to the aging overall wind park and limited locations in Europe in the future there will be a business migration in the wind industry from new installations to O&M services. The O&M market for wind turbines is not yet settled and offers various opportunities for market entries of new players. The Independent Service Providers especially, currently use this situation and cause dynamic market development. As for onshore wind turbines, they currently occupy the lion's share in the O&M area.

As we saw in the cost structure of a wind turbine project in chapter 4, the supporting structure, beside the rotor blades and the powertrain is a core element. The operating costs of a turbine are dominated by the O&M expenses, increase with the turbine's lifetime and represent a center leverage point to optimize wind turbine systems with PHM.

Chapter 5 presented the concept of Levelized Cost of Energy as a method to evaluate cost effectiveness from a macro economic standpoint and to compare wind energy with other energy conversion technologies. It was derived that PHM systems should be developed in three dimensions for the use of economizations of wind turbines, they are: Lower the O&M expenses, increase power output and increase the lifetime of wind turbines.

A conducted parameter study analyzed the three PHM functions and their effects on the macro-economic production cost of wind energy separately. Increasing the energy yield as well as enhancing the lifetime of wind turbine projects had crucial effects on the cost effectiveness. However in reality those effects should be combined in a suitable way in a PHM system for wind turbines to leverage reasonable and connected synergies.

Future research activities should continue considering wind energy as a main pillar in our energy system and therefore develop technologies enabling cost effective energy production from renewable energy sources. PHM systems are a core tool to reach that goal in case of wind turbines. Knowledge already acquired from PHM systems in the automotive, aviation and space area will have to be merged for the application for wind turbines.

## NOMENCLATURE

| | |
|---|---|
| $I_0$ | total investment costs |
| $C_t$ | operating costs at time t |
| $Y_{el}$ | annual energy yield |
| i | discount rate |
| $n$ | year in operating life |

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