# Life Extension for Wind Turbine Structures and Foundations

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## Abstract

This paper presents economic life extension scenarios for wind turbines as well as complimentary structural health monitoring of turbine foundations based on an advanced optical sensor network. Demand for this is driven by an ageing asset base and the overall reduction in governmental support towards wind energy in Europe, despite the agreed 2020 and extended 2030 renewable energy targets. Consequently, this paper displays early work on economic evaluation of levelised cost of energy (LCOE) under simple life extension scenarios and concludes that reductions within the order of 5% of LCOE can be achieved by extending a turbine's lifetime by up to 15 years. At the same time, an ongoing project is presented that aims to apply structural health monitoring to a wind turbine foundation aimed at providing operational load data that can justify or dictate lifetime extension of a wind turbine foundation.

## 1 Introduction

The renewable energy industry is driven by governmental policies and incentives, as in the past devices fuelled by wind and solar energy as well as biomass have not been economically competitive with fossil energy resources such as oil, gas, and coal. Policy making is "the process by which governments translate their political vision into programmes and actions to deliver 'outcomes' - desired changes in the real world" [1]. The difficulty here is that energy regulation is complex as the environment is under constant transition. Additionally there are competing aims; e.g., cost of energy, security of energy supply, clean energy, economic growth, etc. Furthermore, the government as well as the country's economy itself undergo changes too, since a legislative period is usually limited to four to five years and the economic situation can change considerably as well as rapidly. The latter can be triggered by slowing growth in emerging markets and its subsequent effects within today's globalised economy, or shocks within commodities as seen in 2015. Due to the nature of the wind resource; i.e., unsteady and difficult to predict much in advance, it is of high importance to review and scrutinise policies to maintain control of the various competing objectives briefly mentioned before. Such reviews' outcomes can either discard, maintain, scale up or scale down current policies. In general, reviews are positive mechanisms in order to control deliverables, especially if a program's expenses surpass estimations like photovoltaic (PV) applications in Italy and Germany. Unfortunately, this can result in governmental short-termism. Therefore, this dependency is quite severe as when jurisdicted by policies it is challenging to provide security and long term stability. As power plants are defined by high investment costs, such uncertainty can have negative influences concerning the likelihood of investors to invest in renewable energy sources due to increased perceived risk.

Stimulated by high subsidies in the beginning of the 21$^{st}$ century, aimed at meeting the European 2020 climate targets, the recent boom within the European wind energy market has led governments to actively discuss and challenge their policies. The philosophy here is to reduce over-subsidising and utilise governmental budgets more economically, while encouraging the industry to innovate so that wind energy continues to become more competitive. Figure 1 illustrates the total installed wind energy capacity of the European countries with the greatest wind energy investment between 2010 and 2015. A clear contrast emerges; installed capacity increased notably in Germany and France; on the other hand, it decreased significantly in Spain, Italy, and the United Kingdom. When looking into governmental policies of these countries with significant changes, it is further verified that there exist a strong correlation between a country's wind energy policy or policy review and its effects on wind energy installations.

With regards to France, the introduction of a new marked based subsidy scheme is expected in 2016. However, it is unclear whether this policy change will account for onshore wind too, since a new feed-in tariff (FIT) was introduced in March, 2014 which is valid for the next 10 years [2]. This happened because the old FIT was not compliant with European Union (EU) regulations. Nevertheless the current FIT is expected to be revised later on. In Germany wind turbine generators (WTG) receive compensation payments according to the revised German Renewable Energy Act (EEG) of 2014. Overall in Germany, there have been constant subsidies for the past fifteen years and are expected to remain constant in the future as pointed out in [3]. At the same time, a new onshore installation cap was introduced with an annual limit of 2.8 GW of newly installed capacity excluding re-powering investments [4]. This change is significant in comparison with previous installed capacity as illustrated in Figure 1. Concerning offshore energy, new installations have been capped to a total of 6,5 GW in 2020 and 15 GW in 2030 [5], thus there will be a limited amount of sites authorised. Also with the changes of the EEG in 2016, latest in 2017 a tendering and auction process will be implemented where investors compete like in the United Kingdom (UK) with contracts for difference (CfD) auctions [6]. Therefore, Germany and France are identifiable for continuity and secured investments resulting in growth in the installed capacity, although Germany has introduced factors to limit installed power in order to maintain affordability and France has yet to decide on how to move forward. Spain, Italy, and the UK present a different picture. In 2012, Spain declared an end to its subsidies that led to a halt of its entire wind industry as shown in Figure 1 with zero installations in 2015 [7]. This case study demonstrates well that at present wind energy cannot compete without subsidies, hence the industry came to a standstill.

As a response to this severe outcome, Spain reintroduced a new subsidy in June, 2014 that caps earnings of all renewable energy plants with an aimed return of investment (ROI) of 7.5% [8]. This rate is based on the average interest rate of a ten years sovereign bond, plus an additional 3%, which is revised every three years. These measures are retroactively accountable (back to June 2013) to achieve the following three objectives: stability, to allow a reasonable return of investment (ROI), as well as to provide certainty. Italy experienced a rapid development of wind and solar power until 2012; however, active incentive mechanisms became too costly, resulting in a reduction of their FIT as well as an overall cap on total subsidy expenditure [9]. Despite high wind energy deployment rates, the UK is facing significant changes with regards to its onshore wind energy policy. The current FIT for installations below 5 MW will be reviewed and adjusted in 2016; overall, FIT rates have been constantly decreasing since 2012 [15].

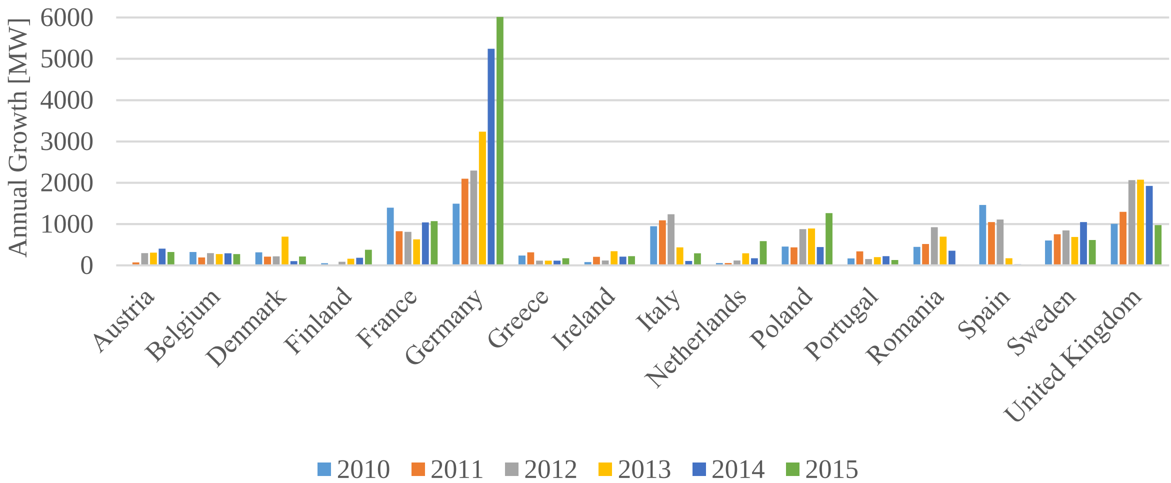


*Figure 1. Installed European Wind Energy, Source* [10]–[14]

Furthermore, the government decided to terminate the renewable obligation (RO) scheme one year early (first of April, 2016) for onshore wind deployment, with an unlikely transition into the second allocation round of the CfD mechanism [16]. With the successful introduction of the first CfD auction in 2015, results revealed that under competitive tendering the average strike price for onshore (~£80 per MWh) and for offshore (~£117 per MWh) was much lower than anticipated [17]. However, it is yet to discover whether these projects can be delivered in time as well as on budget.

Conclusively, wind energy investors, operators, and ultimately wind turbine manufacturers are now under increased pressure due to the transformation from an over-subsidised environment to a more competitive allocation. This will have significant impacts on economic wind energy parameters such as internal rate of return (IRR), and ROI. Ultimately this will then reflect upon the decision whether to invest in wind farms or capitalise in alternative options.

These changes are well observed within the industry too. Gamesa declared this transition as the 'credit crunch' within the wind industry and highlighted the requirement for wind turbine life extension as of 2014, stating: "new alternatives such as reliability-centred maintenance and reconditioning programs play an ever increasingly important role. However, these improvements are just the first glimpse of a much more ambitious and promising opportunity: turbine life extension" [18]. In addition, Gamesa has been the first original equipment manufacturer (OEM) to make use of the recently introduced life extension certificate provided by Det Norske Veritas and Germanischer Lloyd (DNV GL). The certificate extends the operation of onshore and offshore wind turbines and was first issued on the 16th of December 2014 [19], [20].

Figure 2 displays the installed wind energy capacity for onshore (green) and offshore (blue) installations until 2015, as well as the total cumulative installed capacity. Beyond 2015, the installed capacity is mirrored in order to graphically represent annual capacity that is reaching its end of lifetime, where the operator must decide how to move forward; i.e., to demolish, re-power, or recondition (life extension). As one can see there will be a significant capacity reaching its end of lifetime from 2018 onwards for onshore and 2035 for offshore turbines.

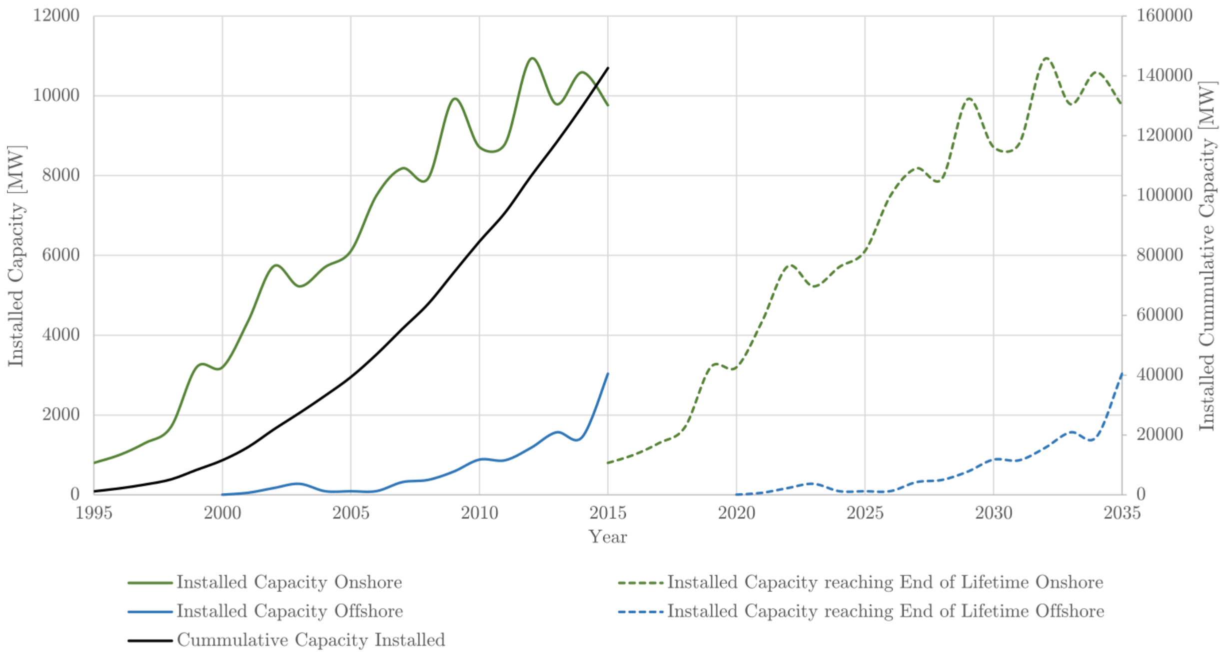


*Figure 2. Installed European Wind Energy, Source* [10]–[14]. *The annually installed capacity is on the left axis and the cumulative capacity is on the right axis.*

Consequently, market interest as well as offered services are growing in order to facilitate life extension decision making.

Summing up, operators and investors of wind parks are under increased pressure due to reductions in governmental support and further there are significant numbers of turbines reaching their end of designed lifetime that require decision making, where life extension could become a beneficial consideration.

Recognising the need as well as market potential for lifetime extension, this paper will look into this topic using a hybrid approach; on the one hand it will discuss economic modelling that can be used to justify decisions for investment in methods aiding lifetime extension. On the other hand, the application of advanced sensing and diagnostics based on fibre Bragg gratings (FBG) to monitor operation of onshore wind turbine foundations is presented. In addition, offshore wind turbine performance degradation results based on ROC certificates as well as possibilities to apply FBG sensors in offshore applications are discussed.

# 2 Wind Turbine Life Extension

As discussed wind turbine life extension is an active field of research; however, there are many factors enclosing the suitability to enable wind turbine life extension as illustrated in Figure 5 of the Appendix. In this section LCOE figures are derived and subsequently applied to simple life extension scenarios to investigate its effects on the economics of wind energy. At the same time, advanced optical sensors are presented that will be embedded in a wind turbine foundation in late 2016 for structural health monitoring and evaluation of FEM modelling.

## 2.1 Economical Approach

### 2.1.1 Methodology

LCOE is an important metric to determine and compare cost for different types of electricity generation. It can also be applied to scrutinise different operational strategies. LCOE figures are reproduced from the Department of Energy and Climate Change (DECC) for onshore wind farms based on 3 MW class turbines in a park installation above 5 MW. Results are obtained by combining DECC's published operational data with turbine characteristics illustrated in Table 3 of the Appendix that operational yield is in agreement with [21].

### 2.1.2 Results

LCOE was calculated as £99.60 per MWh for the previously mentioned onshore wind farm. This result was then subjected to a sensitivity analysis where different parameters are reduced by 10% as illustrated in Table 1 and where possible compared with [22].

*Table 1. LCOE Sensitivity Analysis*

| Case [-10%] | LCOE [£] | Δ Baseline | Blanco 2009 [54] |
|---|---|---|---|
| Investment Costs | 92.22 | -7.41% | -7.6% |
| O&M | 97.01 | -2.60% | -2.4% |
| Capacity factor | 109.88 | 10.32% | 8.5% |
| Interest Rate[1] | 94.11 | -5.51% | -2.1% |
| Lifetime[2] | 98.41 | -1.19% | -4.0% |
| Weibull Shape Factor | 97.95 | -1.66% | N/A |
| Mean Wind Speed | 127.63 | 28.14% | N/A |

[1]Blanco based on 7.5%, [2] +10%

The first two sensitivity cases (investment costs, O&M) are in agreement with findings from Blanco, whereas the sensitivity case of interest rate, capacity factor and life extension deviate. These changes could be introduced due to the differences in the applied model as Blanco models 20 years of lifetime, with a specified debt/equity ratio and a split interest rate for debt and equity. Also, the model's methodology is not disclosed, hence it is difficult to evaluate if there are fundamental differences in calculating LCOE. Overall the analysis reveals that the greatest sensitivity to LCOE is annual fluctuation in mean wind speed that based on a reduction of 10% can increase LCOE by 28.14%. At the same time it is important to notice the unlikelihood of such a significant change over 25 years as research suggests by [23], [24]. The LCOE's sensitivity to the wind resource is also in agreement with the reduction in capacity factor that can be caused by a reduction in mean wind speed or a reduced availability due to downtime caused by faults. These findings are in agreement with Blanco "the wind resource – which matters the most" [22]. Further, a turbine's investment costs can impact LCOE significantly as seen with a reduction in LCOE of 7.41% which is anticipated as initial investment costs are the greatest cost factor [25]. It is quite interesting to see that a 10% reduction in operation and maintenance (O&M) costs contributes to a small proportion of LCOE, which findings are also in agreement with Blanco. It is important to note here that parameters are not decoupled; i.e., changes in O&M expenditure impact downtime and availability that also changes LCOE parameters, hence reducing O&M costs could potentially reduce LCOE, although increased downtime might equalise or even increase LCOE eventually. Based on overall results and its comparison to available published data, the DECC's replicated LCOE model is validated. Therefore, this model is subjected to simple life extension scenarios.

Preliminary findings concerning life extension, based upon the LCOE model that is in agreement with DECC's metric are also available. Under simple life extension scenarios where the final operational year is assumed to economically continue constantly for five additional years results in a reduction of LCOE by 2.6% (10 years – 4%; 15 years – 4.9%).

Although DECC's LCOE metric does not include the effect of wear and tear, its effect can potentially result in wind turbine performance degradation and thus the reduction in efficiency [26]. In fact there is evidence that this effect can be observed on a national level [27].

Based on a simple scenario with an annual linear reduction of energy yield by 1.6%, LCOE is increased by 12.62% (0.8% - 6.5%; 0.2% - 1.6%). Therefore, if observed over the course of a turbine's lifetime, a reduction in energy conversion efficiency can significantly affect LCOE. A practical model would then require to take this into account. Recent work by Rubert and Staffel has looked into the rate of performance degradation of onshore as well as offshore wind turbines based upon the applied methodology by Staffel and Green [27] for turbines with a capacity above and equal to 3 MW. Although in both cases (onshore/offshore), operational data is only available for eight years, preliminary findings show no evidence of performance degradation within this capacity range. However, since results are only available for the first 8 operational years and most wind farms are operated under performance based maintenance contracts following their warranty period, it is likely that performance degradation is triggered at a later stage. Potential causes are numerous, for example the impact of hail on blades can cause pits in the paint and coating layers that subsequently form gouges and if untreated may result in delamination and thus deteriorate aerodynamic characteristics [28]. Work by Rubert and Staffel is currently exploring this area further in order to evaluate performance degradation and model it accordingly.

So far this paper has presented the tightening of European wind energy subsidies, revealing that a zero subsidy regime will halt the industry altogether as observed in the case of Spain as well as the fact that the European wind fleet is aging with significant numbers of installations reaching the end of designed lifetime as exemplified in Figure 2. Informed decision making is crucial near the end of the design lifetime to determine a turbine's future, thus potential economic benefits of life extension are presented in section 2. However, in order to enable life extension from a reliability point of view it is important to enable structural health monitoring to ensure safe operation. Wind turbine foundations are difficult to inspect and although generally considered over-engineered, there is wide interest to assess their operational health and evaluate its actual load spectrum. In the following a project is presented aimed at enabling foundation conditioning monitoring based on an advanced optical sensor network.

## 2.2 Technical Approach

Advantages and disadvantages of FBGs are summarised in Table 2. Due to the ability to multiplex and its immunity to EMI and RFI, FBGs have been successfully applied in different engineering components as reviewed by Higuera [29] with the application in wind turbine blades [30], real estate foundation piles [31], gearboxes [32], [33], and accelerometers [34]. Based upon this work, Higuera suggests to apply optical sensors in onshore wind turbine foundations; however, to our knowledge there is no evidence that this has been performed by other researchers at present. Also, there is great interest by wind turbine operators to evaluate foundation loading in order to verify FEM simulations, assess propagating structural dynamics, as well as to determine a foundation's unique fatigue loading. Therefore, the technical aim of this work is to embed an advanced optical sensor network in an onshore wind turbine foundation to evaluate operational loading and apply condition monitoring.

*Table 2. Advantages and Disadvantages of FBG*

| Advantages |
|---|
| • Multiplexing (up to 100 FBGs [35])<br>• Multi-functionality (temperature, strain, pressure, etc.)<br>• Long transmission distance - several km [29]<br>• Immune to electromagnetic interference (EMI)/ radio frequency interference (RFI)<br>• Electric isolation<br>• Signal integrity<br>• Fatigue Resistance [30], [36]<br>• Size/weight/integration in tight areas [37]<br>• Linear response [38]<br>• Direct physical correlation between wavelength and strain [37]<br>• Recalibration of sensor, even after signal-processing unit has been exchanged, not necessary [37]<br>• Spectral shift by temperature small vs. spectral shift by strain in civil engineering application [39] |
| **Disadvantages** |
| • Erasing of sensor when exposed to temperatures above 500℃<br>• Costs |

### 2.2.1 Methodology

The applied strain sensor design originates from Niewczas and Fusiek [40] and is schematically illustrated in Figure 3.

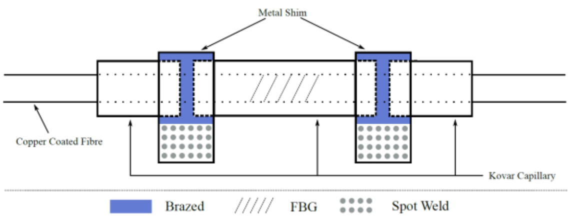


*Figure 3. FBG Strain Sensor*

With regards to sensor dimensions the strain sensor has a total length of 47 mm and a width of 8.5 mm. These dimensions are flexible though, hence depending on requirements parameters can deviate. For this project the sensor is designed to be spot welded to reinforcement bars with a varying diameter of 16-32 mm. The layout for the sensor manufacture is illustrated in Figure 4. The commercially sourced metal coated optical fibre comprises standard single mode glass fibre (⌀ 125 µm) coated in copper (⌀ 170 µm) and equipped with an FBG of the length of 7 mm, written in a 10-15 mm stripped fibre section.

The FBG is placed inside a kovar capillary (⌀I 200 µm; ⌀O 700 µm) and sealed at both ends with a silver alloy (melting point: 610-850℃). During brazing, high frequency current (200-300 A, 400 kHz) is passed through the induction heating coil for a total duration of 30 s.

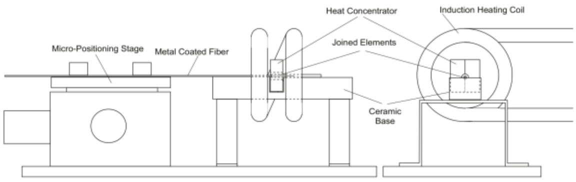


*Figure 4. Layout of Sensor Manufacture* [40]

Thus, temperatures of 610-620℃ are reached in order to melt the silver solder. With this set-up the curie point of kovar (430℃) is exploited, thus protecting the FBG from excessive thermal stress that could potentially cause the grating to erase. Overall, approximately 50% of reflected FBG intensity is lost throughout this heating process, which is acceptable from the point of view of peak detection by the optoelectronic sensor interrogation system. As presented in Table 2, the FBG's reaction to thermal as well as mechanical stress can be characterised by a linear response making it mathematically simple to use; however, any FBG measurement will be a combination of temperature and mechanical induced strain. Therefore the wavelength change $\Delta\lambda_B$ of an FBG can be defined as:

$$\Delta\lambda_B = (C_\varepsilon \Delta\varepsilon + C_T \Delta T)\lambda_B \qquad (1)$$

where $C_\varepsilon$ and $C_T$ are the strain and temperature coefficient and $\Delta\varepsilon$ and $\Delta T$ the change in mechanical strain as well as the change in temperature. The common methodology aimed at extracting mechanical induced stress or strain readings from $\lambda_B$, is to deploy two sensors in close proximity; one that measures mechanical and thermal induced strain and the second that only measures temperature. Based on this set-up, the change in mechanical strain can be calculated by:

$$\Delta\varepsilon = \frac{1}{C_{\epsilon 1}}\left[\frac{\Delta\lambda_1}{\lambda_1} - \frac{C_{T1}}{C_{T2}}\frac{\Delta\lambda_2}{\lambda_2}\right] \qquad (2)$$

where $C_{\epsilon 1}$, $\Delta\lambda_1, \lambda_1, C_{T1}$ are the parameters of the strain sensor, hence defined by a combination of temperature and strain coefficients and $\Delta\lambda_2$, $\Delta\lambda_2$, $C_{T2}$ of the temperature sensor.

Concerning the implementation, we aim to equip the concrete embedded reinforcement cage of a wind turbine foundation with a network of multiple sensors along the prevailing wind direction. Before the installation, sensors will be subjected to various tests in order to ensure reliability. With regards to general marine applications, such sensors could be deployed in various applications in order to monitor loads and apply structural health monitoring. Due to the in-house sensor design and manufacture, strain and temperature sensors could be spot welded to multiple locations and based upon individual requirements the geometry could potentially be adjusted towards specific needs.

# 3 Future Work and Limitations

As this paper presents early research on wind turbine life extension, there are multiple limitations to its current usage. Modelled LCOE within the region of £99.6 per MWh seem outdated, especially in relation with presented average CfD auction results. One significant factor is the discount rate of 10%. In fact the discount rate represents a projects risk and although controversially discussed onshore wind farm's perceived risk has reduced substantially. Also, LCOE parameters depend on various assumptions and estimations that can vary significantly, hence results offer a guideline of average achievable cost reductions. Future work will look into modifying this paper's LCOE model in order to establish a more reliable as well as practical tool which then can be adjusted to more detailed life extension scenarios. Another potential option is to estimate ROI or IRR; however, this is quite challenging as revenue cash flows have to be predicted for a turbine's lifetime and poentially beyond.

Limitations concerning the preliminary findings on life extension and its impact on LCOE are that from a reliability point, some components might require re-conditioning in order to ensure safety as well as reliability, which will impact expenditure. Also, at the time of decision making of lifetime extension, construction of a new farm with its LCOE implications and re-conditioning with its diverging LCOE implications are two competing scenarios. A practical approach would be to compare both in order to allow a sensible comparison to facilitate decision making. This will also be tackled in future work.

Concerning structural health monitoring, the sensor's reliability under dynamic loading is under evaluation, as well as planning the embedding procedure to ensure sensible and successful placement. The sensor network is expected to be implemented in late 2016.

# 4 Conclusion

Overall, this paper has demonstrated ongoing research of wind turbine life extension, revealing the origin and potential upcoming market, its effects on LCOE under simple considerations, as well as a potential method to apply structural health monitoring of onshore wind turbine foundations. Concerning the latter long-term sensor data can help to justify lifetime extension of wind turbines from a structural perspective. In addition, the applicability to equip marine structures with in-house manufactured advanced optical sensors is presented.

# Acknowledgments

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# 5 Appendix

*Table 3. LCOE Wind Turbine Parameters*

| Parameter | Value |
|---|---|
| Rotor Radius | 50 [m] |
| Mean Wind Speed | 6.6 [m/s] |
| Cut-In Wind Speed | 3 [m/s] |
| Cut-Out Wind Speed | 23 [m/s] |
| Turbulence Intensity | 0.1 |
| Cp-Max | 0.48 |
| Drive Train Efficiency | 0.85 |
| Weibull Shape Factor | 2 |
| Weibull Scale Factor | Gamma Function |

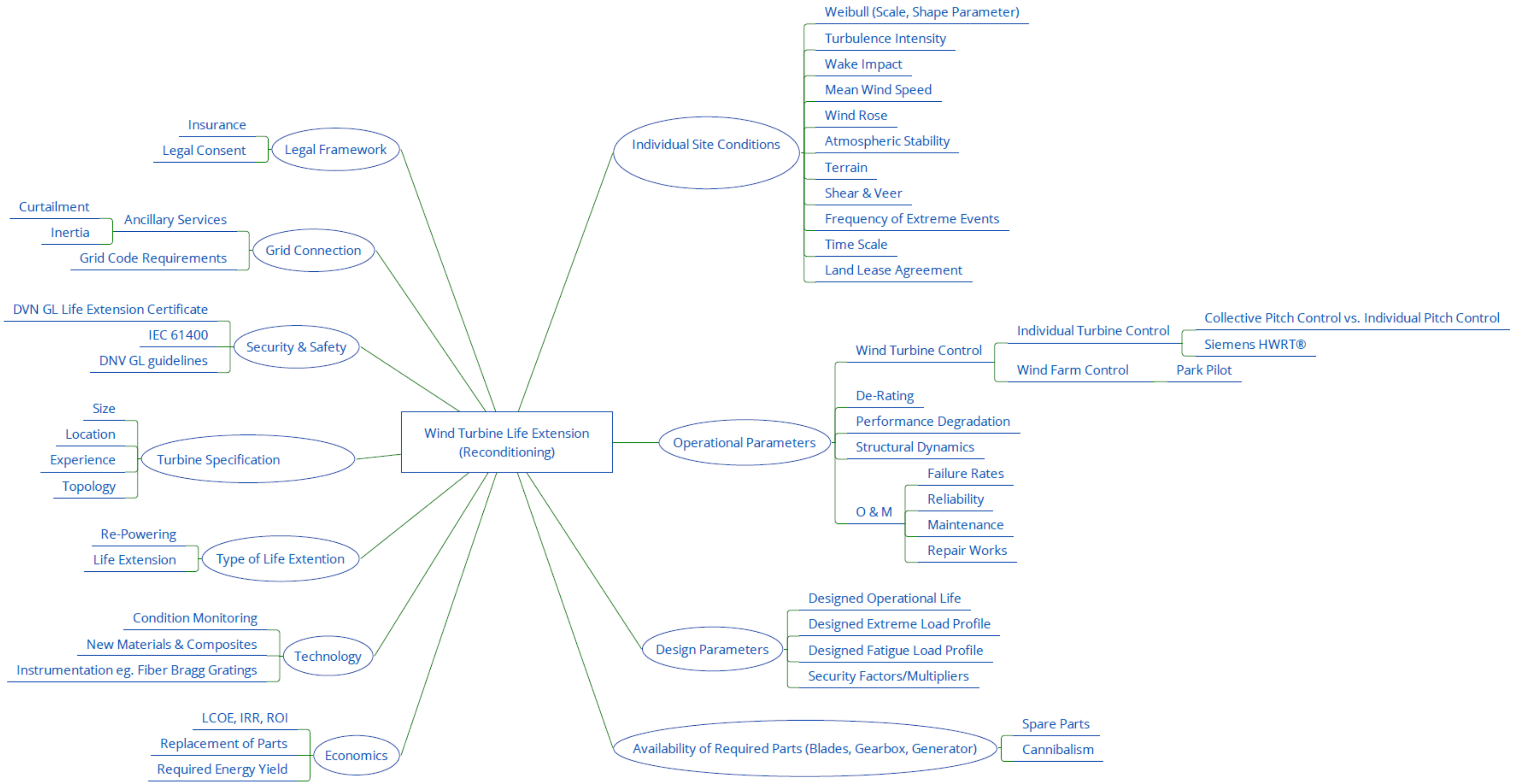


*Figure 5. Parameters for Wind Turbine Life Extension*

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