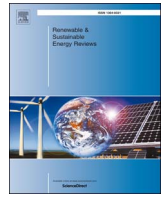




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## Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK



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### ABSTRACT

A significant number of wind turbines will reach the end of their planned service life in the near future. A decision on lifetime extension is complex and experiences to date are limited. This review presents the current state-of-the-art for lifetime extension of onshore wind turbines in Germany, Spain, Denmark, and the UK. Information was gathered through a literature review and 24 guideline-based interviews with key market players. Technical, economic and legal aspects are discussed. Results indicate that end-of-life solutions will develop a significant market over the next five years. The application of updated load simulation and inspections for technical lifetime extension assessment differs between countries. A major concern is the uncertainty about future electricity spot market prices, which determine if lifetime extension is economically feasible.

### 1. Introduction

In 2016, 12% of the installed wind turbine capacity in Europe was older than 15 years. This share increases to 28% by 2020 [1]. These wind turbines will soon reach the end of their designed service life, which is typically 20 years. As a consequence, the wind industry needs to prepare for upcoming challenges, such as maintenance of aging assets, assessment of structural integrity, lifetime extension decision making, and decommissioning of turbines. Lifetime extension is appealing in that it can increase returns on investment of existing projects, but experiences to date are limited.

Operators must decide which option is best for their aging wind farms; options include: i) lifetime extension, ii) repowering, and iii) decommissioning of the site. Technical, economic and legal aspects drive the decision-making process. For lifetime extension, wind turbines must have sufficient structural life remaining that their safety level is not compromised. In addition, wear-out of components translates into higher operation and maintenance (O & M) costs and turbine downtime. Wind farm operators must sell the produced energy at the spot market or find bi-lateral agreements if no governmental subsidies exist. Changes in legislation prohibit repowering of some existing wind farm sites. Uncertainties make the decision process complex and only

very limited literature is presently available.

On the technical side, recommendations for lifetime extension assessment were recently published by DNV GL [2], UL [3], Megavind [4], and the German Association of Wind Energy [5]. Holzmüller [6] applied generic aero-elastic models of onshore wind turbines to reassess fatigue loading in line with site-specific conditions. Ziegler and Muskulus [7] performed fatigue reassessment for offshore wind turbines. Loraux and Brühwiler [8] analysed two years of strain gauge measurements from a wind turbine tower and estimated the remaining fatigue life with this data set. The importance of load measurement campaigns to accurately depict the effect of wakes from neighboring turbines on the remaining fatigue lifetime was stressed by Karlina-Barber et al. [9]. On the economics side, drivers of lifetime extension were discussed by Rubert et al. [10]. Luengo and Kolios [11] review different end-of-life scenarios. A decision model on the optimal time to switch from lifetime extension to repowering was presented by Ziegler et al. [12]. To the knowledge of the authors, no study on the interaction of technical, economic, and legal aspects has so far been published.

The objective of this paper is to investigate the current trends, challenges, and research needs relating to lifetime extension of wind turbines. In order to achieve this goal, this paper reviews the current state-of-the-art for lifetime extension of onshore wind turbines based on

*Abbreviations:* O & M, Operation and maintenance; RUL, Remaining useful lifetime; SCADA, Supervisory control and data acquisition; IEC, International Electrotechnical Commission; NREL, National Renewable Energy Laboratory; DIBt, Deutsches Institut für Bautechnik

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available scientific literature, standards and guidelines, together with qualitative interviews with key market players. A comprehensive overview of the market as well as technical, economic, and legal aspects of lifetime extension is presented for the selected countries of Germany, Spain, Denmark, and the UK. Furthermore, the practice of technical assessment and decision-making is compared between the countries. Five challenges and further needs for research are derived from the results.

The remainder of this paper is organised as follows. Section 2 describes the research methodology combining literature review and expert interviews with country-specific market players. Background information on the wind energy market is presented in Section 3 for each country. Section 4 presents results on lifetime extension as an outcome of the review of scientific literature and standards; technical, economic, and legal aspects are discussed. The design of the expert interviews and achieved results are presented in Section 5. Results are discussed in Section 6 and conclusions presented in Section 7.

### 2. Research methodology

Publicly accessible sources like standards, scientific articles, and reports contain limited information on the current lifetime extension practice within the wind industry. To overcome this shortcoming, further data is gathered through the consultation of experts in the field using a consistent interview template. Fig. 1 illustrates the research approach, which combines a thorough literature review with expert interviews in order to collect information on the state-of-the-art of lifetime extension.

Germany, Spain, Denmark, and the UK were selected for the study since lifetime extension is either important for them today due to the age of the fleet (Denmark, Germany, Spain) or will be in the near future (UK). In addition, these countries have rather different contexts in terms of their subsidy schemes, legislation, market structure and scarcity of sites, which is expected to influence the application of lifetime extension. Further information on the market characteristics of these countries is given in Sections 3 and 4.

### 3. Background on wind turbines at end-of-life

In 2015, Germany, Spain, and the UK had the largest cumulative installed wind capacity in Europe [1]. In Denmark, the installed wind capacity is comparatively less due to its smaller geographical area. Denmark, however, is leading in terms of the wind energy contribution to the national electricity consumption with 42.1% in 2015 [1]. Although the countries selected for this study are pioneers in wind energy, their industry developed differently over the past years. The annual installed capacity in Germany is still increasing, while in Denmark,

Spain and the UK it is decreasing [1]. This reduction is driven by changes in political incentives, scarcity of sites for wind farm development in the case of Denmark, and problems with public acceptance as for example in the case of the UK [13]. In Spain, almost no new wind turbines have been installed since 2013 due to a drastic change of legislation, referred to as ‘Energy Reform’. The new regulation entailed a complete removal of subsidies and incentives, such as the prior feed-in tariff and feed-in premium schemes [14,15]. In summary, despite Europe’s 2030 renewable energy targets, new installations are dropping at a time when the fleet is aging.

Currently, Denmark, Germany and Spain have a significant capacity of old wind farms connected to the grid that are now facing the end of their planned service life. The situation is as follows:

- In 2016, roughly 3400 wind turbines had exceeded 20 years of operational life in Germany [16].
- The situation in Denmark is similar with 1250 turbines being older than 20 years in 2016 [17].
- More than 500 turbines had completed their 20-year lifetime in Spain in 2016, and this will increase to more than 4200 turbines in 2020 [18].
- In the UK only 19 onshore wind farms have exceeded 20 years of operation as of November 2016: of these eleven are still in operation (through lifetime extension), two were decommissioned, and five projects were repowered [19,20]. No public information was available for the one remaining wind farm. In total fourteen repowering projects have been completed or approved in the UK since 2010 [21].

The future age distribution of installed wind capacity almost looks dramatic. By 2020, 41% of the currently installed capacity in Germany will be over 15 years old, 44% in Spain, and 57% in Denmark. The UK has a comparatively younger fleet with a share of 10% of the current installed capacity that will be older than 15 years in 2020. These numbers refer to a scenario for 2020 projected from the installed capacity of the year 2016 without considering future installations.

Fig. 2 illustrates the annual number of wind turbines that will reach the end of their planned service life in Germany, Spain, Denmark, and the UK. It is clear that there is a significant market for end-of-life solutions for Germany, Denmark and Spain over the next decade, followed by the UK after 2024. For these countries, around 2000-4000 turbines per year will either need to be life extended, repowered or decommissioned.

In addition, Fig. 3 illustrates the rated power of turbines that reach their end of design lifetime at present and in near future. In 2016, turbines considered for lifetime extension were rated below 1 MW. From 2020 onwards, larger turbines will reach their 20th year of operation. In the future, it is expected that technology will progress less rapidly than over the past decades. Advances between existing and potentially repowered turbines diminish as time progresses and make lifetime extension more attractive.

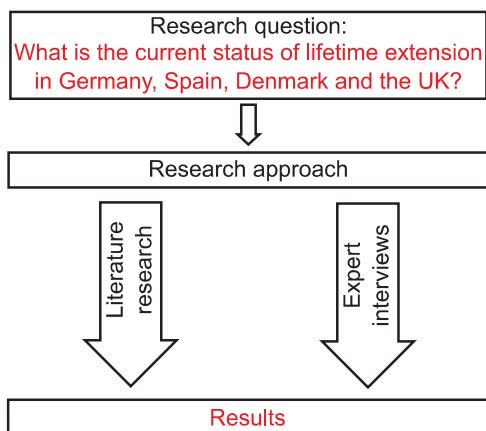


Fig. 1. Research methodology. Information of the current status of lifetime extension is gathered through a review of literature and qualitative expert interviews.

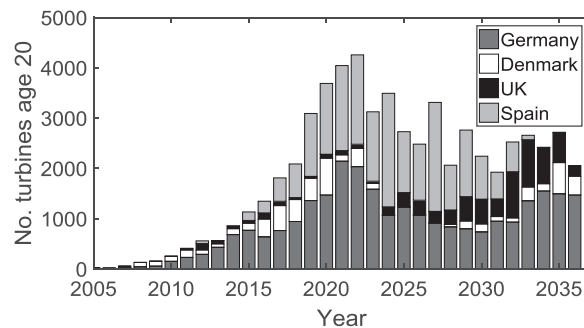


Fig. 2. Number of onshore wind turbines reaching 20-years of operation annually in Denmark, Germany, Spain and the UK. Data sources [16–18,22].

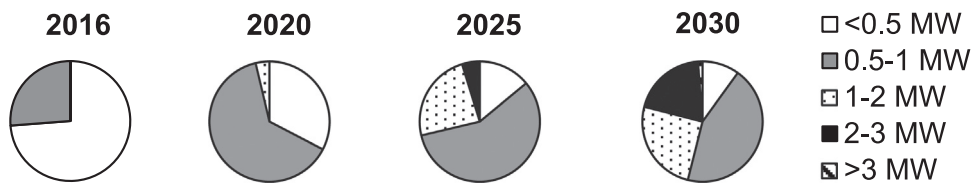


Fig. 3. Rated power of turbines reaching 20-years lifetime today and in the next five, ten and 15 years in Denmark, Germany, Spain and the UK. Data sources [16–18,22].

## 4. Literature review on lifetime extension

### 4.1. Key market players

Lifetime extension involves interests and competences of various players within the industry. *Operators* see the potential to increase return on investments in existing wind parks. On the other hand, they are responsible for the structural safety of their assets. Operators need to mitigate risks of an increase of failure rates of aged wind turbines causing additional downtime and expenses for repair. *Wind turbine manufacturers* have detailed knowledge regarding turbine design and share an interest in O&M strategies. They are able to execute site-specific assessments during project development phases to estimate the lifetime extension potential. *Governmental organizations* are concerned with the health and safety of citizens and are further challenged with implementation of renewable energy targets. Such institutions have to choose which incentives are suitable to achieve objectives. *Certifying agencies* provide security for investors and contribute to delivering operational safety. There is an emerging service market aimed at providing expert reviews for technical lifetime extension assessments. The safety reputation of wind energy technology is a major concern for the entire industry.

### 4.2. Technical aspects

#### 4.2.1. Design lifetime, structural safety and remaining useful lifetime

Wind turbines are designed to withstand operational and environmental loading for a specified design lifetime with an appropriate structural safety level. The design lifetime should be at least 20 years according to the International Electrotechnical Commission (IEC) standard [23]. Target safety levels specify an acceptable annual probability of structural failure. Safety levels are achieved by verification of ultimate and fatigue strength of the material against loading. Both, loading and material strength, are multiplied with partial safety factors [23]. According to DNV GL [2] and UL [3] the focus for lifetime extension is on the fatigue limit state. It is not necessary to reassess ultimate limit states when site conditions are less harsh than design assumptions.

Wind turbines are dynamic systems exposed to aerodynamic loading and quasi-periodic excitation from the rotor. Structural components typically face between  $10^8$  and  $10^9$  load cycles over their lifetime. Load cycles are compared to material SN-curves for the design of load-carrying components of the wind turbine [24,25]. SN-curves specify the number of cycles that a material can endure at a certain stress range until failure. The failure criterion is typically defined when a fatigue crack penetrates through the thickness of the specimen. Loading is calculated using structural dynamics models of the wind turbine with environmental conditions as input [23]. The operational environment of wind turbines is complex with turbulent wind fields, wind shear, wind veer, gusts, and wakes from surrounding turbines. Local conditions can differ significantly from one site to another (e.g. terrain complexity, neighboring wind farms, obstacles, atmospheric stability, etc.). Wind turbines are type certified according to IEC classes in order to simplify and standardize design and manufacture [23]. If a wind turbine is installed at a specific site, local wind conditions are assessed beforehand. The suitable wind turbine IEC class is determined so that local conditions do not exceed those used for turbine certification.

If a wind turbine is operating under more benign environmental

conditions than defined in the corresponding IEC class, remaining structural reserves can be left at the end of the design lifetime. In addition, structural reserves may arise if the capacity factor and operational hours of a turbine are below design assumptions. The time until structural reserves are consumed while maintaining the target safety level is denoted Remaining Useful Lifetime (RUL). As all load-carrying components have different RULs, the lowest one defines the potential for lifetime extension. Replacement of critical component may increase the RUL of the overall system.

Non-load carrying components do not endanger structural safety under the assumption that they do not cause critical cascade effects. Nevertheless, wear out of these components can increase failure rates. This results in higher costs for maintenance and repair in addition to production losses from turbine downtime. Ziegler et al. [12] showed that the business case for lifetime extension is very sensitive to modelling of wear out and failure rates. Bathtub curve models divide the operational life of repairable systems into early failures, constant failure rates, and wear out [26]. These models have been applied to wind turbines [27,28]; however, their applicability is questionable due to complexity of the system [29].

#### 4.2.2. Technical lifetime extension assessments

The option of lifetime extension must be based on the operating conditions of the turbine during its design lifetime. Technical assessments are needed to determine the RUL and ensure that target safety levels for the wind turbine are maintained during lifetime extension. All load-carrying components must be considered. Technical lifetime extension assessment can be analytical (simulation), practical (inspection), and/or data-driven (measurements) [2,5].

The analytical assessment is typically an updated load simulation undertaken using an aero-elastic model of the wind turbine [2]. Fatigue assessments are made for the original design basis and also for site-specific environmental conditions. The difference between these results is an estimate of the RUL available for lifetime extension. Ideally, the analytical assessment should use original design models calibrated with on-site measurements. In practice, a generic turbine model is often used because the original design assumptions are not available due to confidentiality. A generic turbine model approximates the real structure where design information is not available (e.g. rotor geometry, controller settings, modal parameters) [5]. Cooperation from turbine manufacturer is required for sharing of type certificates and other design information. The industry recognizes that generic models must

- use state-of-art for aero-elastic simulations,
- represent structural dynamics appropriately, and
- include uncertainty assessments and safety factors [3].

A reference project considered a 600 kW turbine assessed by eight independent experts using generic models; it showed acceptable agreement, however details were not disclosed [5]. On the other hand, sensitivity studies have shown that changes to the control system of wind turbines can significantly influence loading and fatigue life [30–32]. An overview of the effect of control strategies on service lifetime is given by Beganovic and Söffker [33]. Today, experimental measurements are not performed to validate generic models due to cost reasons. Large errors can occur in the calculation of RUL if model assumptions are invalid, e.g. due to undetected rotor imbalances [32]. Short-term load measurement campaigns can help to reduce

uncertainty with limited expenditure [9,34].

Site-specific conditions needed as input for the analytical method are

- environmental conditions: distribution of wind speed and direction, turbulence intensity (ambient and wake), wind shear, air density, and
- operational conditions: turbine availability, number of shut-downs and start-ups [5].

If these data are not available, conservative assumptions can be made [5]. Some of this data can be accessed from the Supervisory Control And Data Acquisition (SCADA) system. SCADA systems are used for control and performance monitoring of wind turbines [35]. For modern turbines, SCADA data is readily available at no additional cost. It must be used carefully as sensors might not be calibrated accurately and are subject to degradation over time [36]. Measurements from nacelle anemometers and power outputs are included in SCADA data by default. This may be used to reconstruct operational conditions and the wind history at hub height. However, nacelle anemometers are influenced by the rotor and the reliability of the reproduction of free stream wind velocities depends on the quality of its calibration [36,37]. The accuracy of turbulence intensity data obtained from the nacelle anemometer is questionable [38]. Ambient turbulence intensity can be determined from short-term meteorological mast data with long-term corrections based on statistical analysis [39]. Wake-added turbulence can be calculated using the Frandsen wake model [23,40]. Environmental data is always affected by uncertainty. Toft et al. [41] estimate the coefficient of variation for wind speed (3–7%), ambient turbulence intensity (7–9%), wake effects (10–20%), and air density (3%). For the 5 MW National Renewable Energy Laboratory (NREL) turbine uncertain wind conditions were found to contribute 1–3% to the total uncertainty of fatigue damage equivalent loads [41]. Uncertainty in material resistance and other factors were observed as more important. The source code for the aero-elastic model from the 5 MW wind turbine developed by NREL is publicly available and broadly accepted by the scientific community for research purposes.

Practical assessment comprises a detailed inspection of the turbine and review of its maintenance history. Details of components, failure modes, and inspection methods are given in [4]. The analytical method is able to quantify RUL, while practical methods can only confirm the current health status and may predict near future failures. Assessments using only practical methods must thus be repeated periodically [42].

The availability of data determines which assessment approach is applicable for lifetime extension. MegaVind [4] outlines four scenarios: (I) no design basis or operational measurements, (II) design basis but no operational measurements, (III) design basis with operational measurements, and (IV) design basis with operational and load measurements. Data-driven assessments are important for lifetime extension in categories III and IV. Data-driven assessments can be categorised into approaches using data from the operational phase and approaches that require temporary or permanent installation of additional sensors. Operational measurements are typically represented in SCADA data, such as turbine availability, power production, yaw direction, component status, etc. Today's research focuses on the use of SCADA data for

condition monitoring and fault detection [43]. For example, Gonzalez and Melero [44,45] scrutinised high-frequency SCADA data to monitor the performance of wind turbines. Further studies are needed to address the use of SCADA data in technical assessment of lifetime extension. In order to measure loads or monitor the health of structural components, additional sensors are required. Monitoring of load histories enables a direct comparison between design loads and occurred loads in order to calculate RUL [46]. Several techniques exist for structural health monitoring which are either local (monitoring of a specific component) or global (vibration-based monitoring of the entire structure). Structural health monitoring aims to fulfil four goals which are given in ascending order of difficulty: detection, localization, quantification, and prediction of damage. Further information on structural health monitoring is given in [33,47,48].

### 4.3. Economic aspects

#### 4.3.1. Operators and operational costs

In Germany and Denmark wind farms are generally owned by small operators with few assets, whilst in Spain the majority of wind turbines are owned by a handful of large operators, namely Iberdrola, Acciona Energía, EDP Renováveis, and Enel Green Power [49]. This has a significant impact on the lifetime extension strategy as larger operators have more operational data available. Moreover, they have extensive experience with older assets in their fleet and benefit from a holistic fleet assessment approach. Danish operators have low costs for O & M compared to the other countries [50]. This may be due to generally good wind conditions of Danish sites and economies of scale, but also due to low fixed and variable costs. In Germany, O & M costs in years 11–20 were approximately 10% higher than for years 1–10 according to [51].

Important market characteristics for the four countries are summarised in Table 1. O & M costs are given as a sum of fixed costs (administration, insurance, maintenance contracts, grid fees, land lease, etc) and variable costs (expenses for non-covered maintenance, repair, material, labour) in agreement with [50].

#### 4.3.2. Subsidy schemes

In Germany, wind energy subsidies are regulated by the Renewable Energy Act [55]. Wind farms commissioned before April 2000 receive a fixed feed-in tariff until 2020 regardless of the asset age. This means that all wind farms operating in lifetime extension remain subsidised by the fixed feed-in tariff until 2020. After 2020, all lifetime extended wind farms are required to sell their electricity at the spot market. Turbines commissioned after 2000 are guaranteed a fixed feed-in tariff for only 20 years. Thus, they are dependent on the energy spot market as soon as they enter lifetime extension (or even before if the design lifetime is above 20 years). Since January 2016 the subsidy depends on the amount of newly installed capacity in order to limit annual growth to 2.8 GW [55]. The latest change of the Renewable Energy Act introduces a tender model starting in 2017 [56].

At present, the wind industry in Spain is subject to a significant degree of uncertainty. In 2012, the Spanish government suspended previous economic incentives by abolishing the remuneration scheme applied for 'Special Regime' production facilities (including

**Table 1**  
Characteristics of the wind energy market in Germany, Spain, Denmark, and the UK.

Parameter	Sources	Germany	Spain	Denmark	UK
Installed capacity [GW] (2015)	[1]	45	23	5.1	13.6
% of electricity consumption (2015)	[51,52]	9.7%	17.9%	42.1%	13.3%
O & M costs [cent/kWh] (2013–14)	[50,53]	3.1	2.9	1.7	2.8
Operators	[54]	Many/ small	Few/ large	Many/ small	Many/ small-large
Site availability	–	Limited	Many	Limited	Many

cogeneration, waste and renewable energy plants) [14,57]. This resulted in stagnation of the wind industry (cf. Section 3). Spain's current remuneration scheme is set in the Law 24/2013 [58]. This scheme retroactively modified the remuneration of existing and future projects, based on a theoretical concept of 'reasonable profit'; the profitability is fixed by law at 7.5% throughout the whole regulated lifetime of the project. According to this scheme, energy is sold at the spot market and might be supplemented if the level of 'reasonable profit' is not reached. Each regulatory period lasts for 6 years, but estimates of revenues and profitability might be revised every 3 years. In practice, lifetime extension, repowering and investments in new wind farms face the same economic environment. In each scenario, the investor/operator has to cope with the uncertainty of the spot market price.

In Denmark, wind turbines commissioned after January 2014 are guaranteed a bonus payment per kWh on top of the market price ('premium tariff') [59]. The regulation for turbines commissioned before 2014 depends on the date of connection and turbine size. In general, the premium tariff is either limited to 10 years or a pre-defined number of full load hours [59]. Entering lifetime extension does not change the economics of aging turbines in Denmark as their electricity is sold on the spot-market beforehand.

In the UK, fixed feed-in tariffs are only applicable for wind farms with a total capacity of less than 5 MW. Feed-in tariffs are guaranteed for 20 years but rates have been decreasing constantly since 2012 [60]. Wind farms above 5 MW are subsidised under the renewable obligation (RO) scheme introduced in 2002. For onshore wind farms the RO scheme was terminated in 2016 with a grace period active until 2019 [10,61]. Subsidies for existing wind turbines under the RO scheme will potentially continue until 2037 (independent of turbine age). A change towards a fixed RO pricing is agreed by the government and scheduled for market introduction in 2027 [62]. A contract for difference (CfD) regime was introduced in 2015 which is comparable to the future auctions in Germany [10,63]. Subsidies from the tender system are only guaranteed for 15 years; lifetime extension and repowering are not considered.

In summary, electricity generation during lifetime extension is not subsidised in Denmark and Spain. Germany will face the same situation from 2020 onwards. In these cases, the electricity spot market determines the revenue during lifetime extension. Fig. 4 shows the development of spot prices in Germany, Spain, Denmark, and the UK over the past four years. Markets in Germany and Denmark experienced a decrease in price level. Yearly average spot prices changed up to 15€/MWh between 2012 and 2015. These fluctuations make the business case uncertain. A fixed-price for the next ten years is estimated as 22€/MWh in Denmark [4]. This is below the current price level and shows that market players are pessimistic about future price developments.

#### 4.4. Legal aspects

##### 4.4.1. Legal requirements for lifetime extension

Requirements for lifetime extension are country-specific as there is

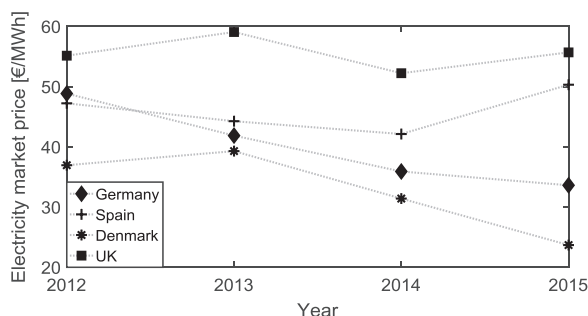


Fig. 4. Development of spot prices at the electricity market for Germany, Spain, Denmark and the UK in €/MWh [64–70].

no international regulation in place. Wind turbines are type certified for their design lifetime [23]. Once this type certification expires, turbines are governed by country-specific regulations to ensure structural safety during any period of lifetime extension (if available). Fig. 5 illustrates legal requirements for Germany, Spain, Denmark and the UK.

In Denmark, certification of wind turbines is regulated in Executive Order No. 73 [42]. It requires that wind turbines subjected to lifetime extension must receive extended service inspections from certified companies. Such inspections must consider all structural components and cover at minimum:

- annual inspections of the machine frame, tower, foundation for cracks, main shaft for dents and rust, yaw bearing for wear, and inspection and tightening of bolts, as well as
- a visual inspection of rotor blades every three years [42].

In Germany, wind turbines are classified as fixed structures and require certification of structural safety. This is regulated in the standard for wind turbines by the German institute for construction technology (DIBt) [71]. This standard requires an assessment of structural stability for lifetime extension and refers to the Germanische Lloyd 'Guideline for the Continued Operation of Wind Turbines' [72]. The Germanische Lloyd guideline is now replaced by [2] but the link to it in the DIBt document remains valid. In addition, DIBt requires that an independent, qualified expert performs the lifetime extension assessment based on an analytical as well as practical approach [72].

In contrast to Denmark and Germany, there is no official guidance that regulates lifetime extension in Spain and the UK. The general regulatory framework for industrial safety applies, independent of the age of the wind farm.

##### 4.4.2. Regulations for repowering

The goal of repowering is to replace old wind turbines with a new generation that have higher energy yields and improved ancillary services such as frequency response that can contribute to the stability of the power system. Repowering is important if a country faces a scarcity of sites with suitable wind conditions, such as in Germany and Denmark (cf. Section 3). This was part of the political motivation for repowering subsidies. However, today no political repowering subsidies exist in Germany, Spain, Denmark, and the UK. Repowering bonuses were removed in Germany in 2014 [73] and 2016 in the UK (grace period until 2019) [10]. In Spain, repowering bonuses were announced in the Renewable Energy Plan PER 2011–2020 [74], but never materialised due to subsequent suspension of the plan. Repowering projects are similar to new projects apart from the available grid connection and historical records of wind conditions. Repowering projects require the same detail of documentation and due diligence, such as environmental impact assessments, legal consent, and public acceptance.

Sites with existing wind farms are often impossible to repower due to lack of availability of the site, legal consent, changes in subsidies, environmental protection, public acceptance, or insufficient wind conditions. From the technical side, new turbines may result in modified spacing to accommodate wakes. In Germany, the state of Bavaria introduced in 2014 a regulation that sets a new minimum distance of ten times the tip-height between a wind turbine and the closest residential areas [75]. In the UK, the repowering market is now 'more or less gone' [21] due to the termination of the RO scheme (although the RO scheme is still open until 2019 for sites with planning permission received prior to the 18th of June 2015). Repowering was discussed as an alternative in Spain by Colmenar-Santos et al. [76], leading to the conclusion that it appears to be a feasible option within a specific technical and remunerative framework. Repowering needs long-term financial stability and legal security to justify investment. Unfortunately, Spain presently suffers from significant political instability and uncertainty that in practice undermines repowering as an option [15,54].

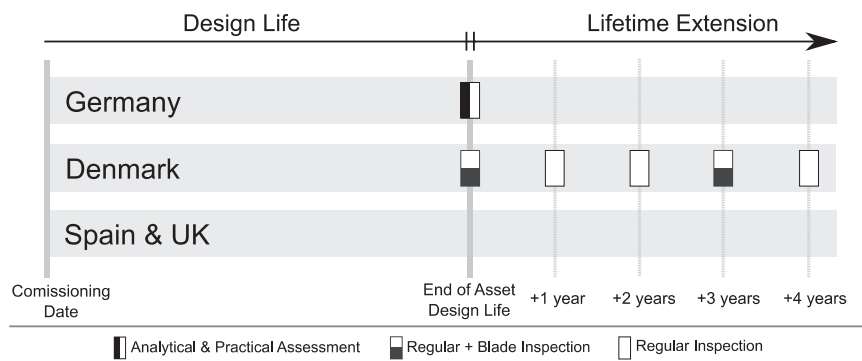


Fig. 5. Legal requirements for lifetime extension in Germany, Denmark, Spain, and the UK.

## 5. Expert interviews

### 5.1. Design of interviews

Expert interviews were used to supplement information gathered from literature review presented in the previous section. Guideline-based expert interviews were chosen as a qualitative research method. Qualitative research is commonly applied in social sciences if quantitative methods are not feasible due to the lack of available data and their representativeness [77,78]. Lifetime extension is still an immature industry and sufficient data to allow statistical analysis is not yet available.

Bogner et al. [79] grouped expert interviews into three categories: exploratory, systemizing, and theory generating. Exploratory interviews are guided openly and aim to provide a framework of a new research field. Systemizing interviews use structured guidelines to reconstruct knowledge with the target to be comparable, repeatable, and complete. Theory generating interviews collocate specialised knowledge from highly experienced professionals [79]. The reader is referred to [77,79] for details on qualitative research and expert interviews.

In this study, the interviews were designed following the steps illustrated in Fig. 6 (left). The research question was to compare the current industrial practice of lifetime extension in the wind industry between Germany, Spain, Denmark, and the UK. Therefore, the objective of the interviews was to identify motivations for lifetime extension, technical assessments, activities to understand the health status of the asset, and decision making and uncertainties for each country.

This study applies systemizing expert interviews so that results are comparable between countries. An interview guideline was developed consisting of introductory questions, filtering questions, and key questions [80]. Each question is followed-up with a specified question in order to systemize participant's responses while keeping the interview adaptable to the expert's specialization area. Table 2 presents the interview guideline and exemplar responses from an expert. The interview guideline was summarised into keywords for a comprehensive overview in this paper.

In this study, wind energy experts are defined to have more than three years of working experience. Experts must currently be working in an organization that deals with an aspect of lifetime extension such as remaining useful lifetime calculations, inspection, monitoring, financing, and certification. A list of potential interview partners was developed with the goal to cover different market players.

Overall, 36 suitable candidates were contacted via email, telephone and one to one meetings. The initial contact introduced the research objectives, use of data, a summarised interview guideline, as well as the partners and funding bodies of the study. As an incentive for participation, the interviewed experts were promised a report of the study and an executive summary containing relevant results. The response rate was 66.7%, hence 24 experts agreed to be interviewed. The interviewed experts worked in the following sectors: operators (8), developers and independent experts (6), wind turbine manufacturers (4), certifying

agencies (2) and other institutions (4). In total 22 of the interviewed candidates are currently involved in projects dealing with lifetime extension. The companies of the remaining two interviewees have no projects on lifetime extension so far. However, they have run case studies and consider this as a field for future business development. Project experiences of the selected experts included operation and maintenance of lifetime extended wind turbines, technical assessments, commercial evaluation of business cases, and the development of guidelines and standards. Fig. 6 (right, top) shows the distribution of the working experience; on average, participants have worked 10.5 years in the wind industry. 23 out of 24 interviewees (96%) have a Master of Science or Master of Engineering degree (or equivalent); one interviewee has a Bachelor degree. Although having a technical background, the majority of interviewees work now in high-level management. The remaining participants were senior engineers, project managers, and advisors. Statistics for job categories of the interviewees are presented in the bottom right of Fig. 6.

The interviews took on average 45 min. 71% of the interviews were conducted via phone and 29% through one to one meeting. The interviews were transcribed by handwritten notes into a structured template according to the interview guideline. Interview results were compared with data from literature and standards or guidelines whenever possible. Results of the interviews were sent back to all interviewed experts for feedback.

### 5.2. Interview results

#### 5.2.1. Motivation for lifetime extension

The interviews revealed two settings for which lifetime extension is relevant: (I) for existing wind farms approaching the end of their design lifetime and (II) for new projects.

Overall, the motivation for existing wind farms is similar for all countries:

1. Interviewees agreed that the driving motivation for lifetime extension is to maximize the return on investment.
2. Lifetime extension is mainly performed when the site is impossible or uneconomic to repower (cf. Section 4.4.2).
3. Public acceptance for lifetime extension of existing wind farms is perceived to have less local opposition than repowering with larger rotors and hub heights. This argument was mainly stressed by participants from the UK.
4. Refinancing of wind projects was mentioned to ensure pay back of borrowed capital by modification of interest rates.

In Germany, the guaranteed feed-in tariff until 2020 is a large motivation for lifetime extension. This is similar for British wind farms under the RO scheme until 2027/2037. In Spain, wind farms are not governed under any form of subsidy during lifetime extension but the situation is comparable to new wind farms. Since new wind projects are more capital intensive than lifetime extension, the latter was stated as

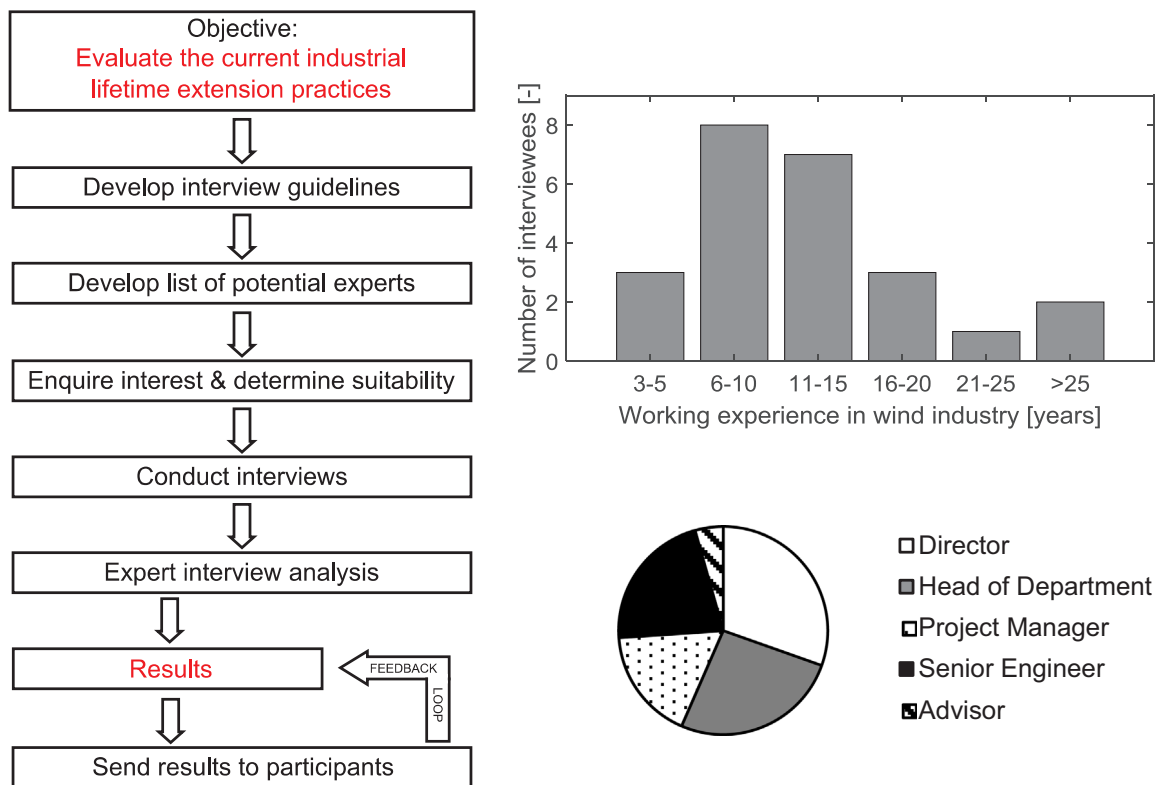


Fig. 6. Left: Flowchart of the design of expert interviews. Right, top: Years of working experience of interviewed experts in the wind industry. Right, bottom: Distribution of job categories of participants.

the preferred option in the interviews. Scarcity of available sites with good wind conditions in Germany and Denmark is a driver for repowering, while there are still suitable sites available in Spain and the UK.

Regarding new wind farms, the majority of interviewees stated that it is important to know the total service life possible for their assets in order to fit contracts for financing of capital, land lease, and grid connection. The turbine manufacturer may offer an estimation of the total

operational time at a specific site. Planning for extended service duration is also seen as a competitive advantage for lowering the price bid in tender systems, in agreement with previous publications [10].

### 5.2.2. Lifetime extension assessment performed in Germany, Spain, Denmark, and the UK

The interviews revealed large differences on how lifetime extension

Table 2

Interview guideline, paired with an example of participants' responses that are transformed into keywords. The guideline consists of introductory questions (intro), filtering questions (filter), key questions (key), and follow up questions.

Type	Content	Follow-up questions	Exemplar responses
Intro	Name, country, job title	Focus on technical or commercial aspects	John Doe, Germany, Senior Engineer
Filter	Role of company in lifetime extension	Selection from list of 10 categories	Operator, OEM, certification body
Filter	Motivation for lifetime extension	Focus on operating assets or future projects	Increase return on investment of operating assets
Filter	Experience with lifetime extension	Technical assessments, internal decisions, financial transactions, or due diligence	Internal decision of an operator for an aging wind park
Key	Maintenance	Preventive, predictive, corrective maintenance Full or partial service contracts Record of O & M history	Preventive and corrective maintenance Full service contract with OEM Logbook available for every turbine
Key	Monitoring	Type and target values	SCADA, no load or vibration monitoring
Key	Assessment of RUL	Parties involved Data used, data sources, uncertainty Models used Costs	Independent expert, OEM Wind conditions, SCADA, logbook Design model not available, use of generic turbine model 10000€ for single turbine
Key	Retrofit	Critical components	Tightening of bolts required
Key	Certification	Application Motivation	Report for structural stability, no certification Certification not required
Key	Decision making	Use of standards/ guidelines Factors in decision making Selection of three most important uncertainties from list of 12	Application of DNV GL guideline required through DIBt RUL, site impossible to repower Future market price electricity, performance degradation, availability of spare parts
Key	Investments	Difficulties and concerns	Access to design information
Key	Outlook	Technical, commercial, legal Developments needed	Report for structural stability Data-driven assessments

**Table 3**  
Lifetime extension assessments performed in industry today (compiled from interviews).

Parameter	Germany & Spain	Denmark	UK
<b>Analytical assessment</b>	Use of generic aero-elastic turbine models to reassess fatigue loading for specific sites	–	Assessment of wind history; occasionally load analysis
<b>Practical Assessment Approach</b>		Extended inspection; O & M history Individual assessment of every turbine	
<b>Monitoring</b>		SCADA; No short-term load measurements or monitoring, (few exceptions)	
<b>Assayer</b>	Independent expert (DE: legally required, ESP: voluntary)	Maintenance provider certified	In-house quality assurance
<b>Frequency</b>	Analytical part performed once; Inspection scope may be periodically	Annually	Every 3–5 years
<b>Advantages</b>	Analytical part gives long-term RUL	Avoid costs of load analysis	
<b>Limitations</b>	Estimated costs 5000–15000€ for single turbine (DE); no cost data available for Spain	Estimated costs 1500€ per turbine	No cost data available
			Assessment cannot predict long-term RUL

assessments are performed. The differences are driven by country-specific regulations (cf. Section 4.3 and 4.4), policies of operators, as well as the extent of their assets. Key findings are summarised in Table 3.

The assessment structure in Germany is set by legal requirements. For Spain, a similar assessment approach was reported which is motivated by (I) reduction of risk on structural safety and (II) more certainty for financial planning as the total RUL is obtained from analytical assessment. Interview partners stated that the use of original design models for analytical assessments is not feasible due to confidentiality of turbine manufacturers. The common approach was to consult an independent expert who does the assessment using a generic model of the turbine. Verification and validation of the generic models are still unsolved issues in practice.

Feedback from the UK was scattered as some parties use load re-assessment. The majority, however, seem to focus on practical assessment supported by analysis of the history of environmental condition and maintenance incidents. In Denmark, it is common practice to use only practical assessments for cost reasons. Practical inspections cannot confirm that target safety levels are maintained during lifetime extension. A comparison of loads and material properties is needed for this. According to the interview feedback, inspections are repeated periodically if no analytical assessment is made.

Experimental measurements are rarely performed, as this is hardly cost-effective. The interviewees confirmed that the level of data available for lifetime extension projects today is typically either category (I) no design basis or operational measurements or category (II) design basis but no operational measurements (cf. Section 4.2.2). Small-size wind turbines (below 1 MW rated power) approaching lifetime extension today often have no continuous backup of SCADA data. Participants from Germany stated that data-driven assessments do not play a role in practice up to now as insufficient data is available.

### 5.2.3. Health status and maintenance of assets

The health status of wind turbines depends critically on both site environmental conditions and maintenance strategy. Interviewees confirm a good knowledge of asset health after 15 years of operation. Turbine and site specific issues are well known and prognosis of future O & M costs is not seen as a major challenge. Interviewed operators estimate slightly increasing O & M costs for aging assets, in agreement with published data [51] and bathtub curve models [26].

Maintenance of wind turbines is either performed by the original turbine manufacturer, a maintenance provider or directly in-house by the operator. Maintenance contracts may consist of full or partial coverage. No clear trend towards either type could be identified between the interview participants. Interviewees stated, however, that standard full maintenance contracts are not affordable for lifetime extension. Suggested alternatives are to exclude the guarantee for large components and make the contract terminable at any point in case a major investment is needed. Maintenance audits are uncommon; operators

rely on their O & M contracts.

Typical maintenance activities include performance monitoring using SCADA data, preventive maintenance with routine inspections, and corrective maintenance after failure. One interviewee used high-frequency SCADA data (sampling interval between 1 and 10 s). The remaining interviewees either had only access to 10-min statistics or no SCADA data at all for turbines below 1 MW rated power. Predictive maintenance based on operational data is desirable but still in the early stages of commercialization. A good record of O & M including failure occurrences is understood as an advantage for faster, cheaper and more reliable lifetime extension assessment.

### 5.2.4. Decision and uncertainties

The decision on lifetime extension is influenced by (I) the technical asset health status, (II) requirements for lifetime extension, (III) regulations for repowering, and (IV) subsidy schemes for existing as well as new wind farms. The end-of-life situation requires a decision between lifetime extension of the old wind farm, repowering with a new set of wind turbines, and decommissioning of the site. If the site is suitable for repowering (cf. Section 4.4.2), the optimal point in time to replace old turbines has to be determined. If repowering is not possible, lifetime extension should be assessed. The key questions is whether operational costs are balanced by revenues for the produced energy assuming that capital costs are paid back at the end of the design lifetime. Revenues either come from subsidies or the electricity market directly (cf. Section 4.3.2).

The technical assessment indicates the possible period for lifetime extension from a structural safety point of view (cf. Section 4.2). Interview partners emphasised the following uncertainties on the technical side amongst others: original design assumptions and on-site wind conditions (turbulence intensity, wind speed). Increase of failure rates of non-load carrying components can make lifetime extension uneconomic. Uncertainty about future failure rates was not a major concern of operators. Since lifetime extension requires only low investments, a common approach is to terminate turbine operation if costly repairs become necessary.

On the economic side, large uncertainty regarding electricity market prices was seen as most critical. Uncertainty in annual energy production was stated to be well below market price uncertainties. If the market price is below 3 cent/kWh, continued operation of small wind turbines is considered infeasible by the majority of interviewed parties. Concerns of the interview participants regarding lifetime extension are summarised in Table 4.

## 6. Discussion

The executed study revealed a lack of certainty regarding lifetime extension decision making. German interviewees see a potential for lifetime extension until 2020. However, they are sceptical what



**Table 4**  
Concerns of interviewees regarding lifetime extension projects.

Technical	Economic	Others
<ul style="list-style-type: none"> <li>● Missing documentation</li> <li>● Access to design information</li> <li>● Wind history</li> <li>● Change of wind conditions due to new surrounding wind farms and other changes in the neighbourhood</li> </ul>	<ul style="list-style-type: none"> <li>● Uncertainty in electricity market price</li> <li>● Unavailability of spare parts</li> <li>● Costs of non-load carrying parts</li> </ul>	<ul style="list-style-type: none"> <li>● Unclear authority requirements</li> <li>● Extension of land lease</li> <li>● Security of maintenance technicians</li> <li>● Negative image for wind industry from potential failure due to low-quality assessments</li> </ul>

happens to the market after subsidies vanish. Lifetime extension is primarily important for sites without the ability to repower since subsidies for new wind farms remain economically attractive today. The situation is the opposite in Spain, where lifetime extension is labelled as ‘the only option’ due to a lack of incentives for new wind farms. In the UK, repowering is not considered as a viable future option due to the termination of the RO scheme, and hence wind farms which are already subsidised under the RO scheme are attractive for lifetime extension.

This leads to the conclusion that countries with favourable legal and economic conditions for repowering (e.g. profitable subsidy schemes for new wind farms, scarcity of sites, etc.) and with market prices of electricity uneconomic for small wind turbines are likely to experience less interest in lifetime extension in the next years. On the other hand, interest in lifetime extension is expected to increase in countries where conditions for new wind parks are unfavourable. Technical assessments performed for lifetime extension vary across the countries investigated. The form of assessment used is either determined by legal requirements (Germany, Denmark) or by the internal motivations of market players regarding risk management and financial planning if legal requirements are absent (Spain, UK). It is expected that there will be further consolidation of the industry towards consistent assessment methods as more guidelines are emerging.

### 6.1. Limitations

The main limitation of the current study is the lack of quantitative data. Quantitative results could not be presented since limited experience in the field does not offer sufficient data for statistical analysis. In addition, technical and economic project performance is often confidential, highly case-specific and cannot be generalised. The study showed that there is no clear approach for lifetime extension; concepts differ considerably in their details. This made it impossible to quantify existing concepts. Literature on the topic of lifetime extension was very limited making it necessary to supplement this review with information gathered by qualitative expert interviews. A weakness of the executed interviews is that only a small database of experts was interviewed due to the limited availability of suitable experts. Once the lifetime extension market matures, a larger database may be established by transforming the personal interviews into online surveys. In addition, interviews are prone to response bias, interaction between interviewer and interviewee, and communication difficulties. The interview guideline was designed to overcome these weaknesses. For example, filtering questions were used to identify subjectivity of the experts due to their job positions and interests of the companies.

The study is limited to the status of lifetime extension in Germany, Spain, Denmark, and the UK. Results show that the motivation and assessments for lifetime extension are strongly linked to country-specific aspects, such as the subsidy scheme, repowering characteristics, and legal requirements. Care must be taken when generalizing the results to other countries not investigated in this study.

### 6.2. Challenges and research needs

Results from literature and interviews indicate that there are still significant challenges regarding lifetime extension of wind turbines.

The key challenges identified are uncertainties regarding lifetime extension assessments and market prices (cf. Section 5.2.4). This leads to several research needs as discussed in the following.

1. What level of detail is needed in technical lifetime extension assessment in order to balance costs and benefits? This study revealed that there is no consensus at present. Lifetime extension requires a precise business case considering the expected revenues of less than 3 cent/kWh in future electricity markets. Sophisticated assessments might not be economically feasible. Future research should address the question of how target safety levels can be maintained with minimum expenditure. Can inspection-only strategies fulfil this goal? Must generic models be validated? How accurate are lifetime extension estimates taken in the pre-build phase by manufacturers?
2. How are long-term site conditions obtained reliably and cost-effectively? Methodologies to determine site conditions from long-term operational turbine data should be improved. SCADA data is attractive for this as it is readily available. Further research is needed to assess the potential of new measurement devices such as lidar [81] and spinner anemometers [82].
3. How should a data-driven approach to lifetime extension assessment best be undertaken? Data-driven assessment can be favourable if cost-effective or if analytical approaches do not provide sufficiently accurate estimates of RUL. This is the case when large safety factors are required due to uncertainties in the analytical assessment. Structural health monitoring can help to identify additional structural reserves.
4. How can lifetime extension be profitable if wind farms are exposed to the electricity market without subsidy? Both levers – decreasing operational costs and increasing revenues – should be addressed here. The optimization of maintenance concepts for aging turbines is an identified key aspect where predictive maintenance has a key role. Future research should examine operational strategies that optimize the economic value of produced power rather than simply maximizing power production. Examples are preferential operation of turbines during high market prices, or load reduction strategies.
5. How are future experiences with lifetime extension to be used effectively? Current as well as upcoming lifetime extension experience may help to reduce uncertainty on the degradation and failure rates of aging turbines. Ideally, these experiences will be well documented in a database. Furthermore, international standardization of methodologies for lifetime extension assessment is important to promote its practice.

## 7. Conclusions and outlook

The market for end-of-life solutions is still in its infancy, but is expected to grow significantly in the next five years. Germany and Denmark are leading the consolidation of industry towards a consistent technical lifetime extension assessment process initiated by legal requirements. The German procedure (analytical and practical assessment) is costlier than the Danish inspection based approach.

Analytical assessment is performed using structural models and real site conditions in order to verify the safety level of turbine components. The use of generic models is problematic if calibration data is missing.

Real site conditions are difficult to obtain using cost-effective methods. Data-driven methodologies can complement or even substitute for analytical models but more research is needed to obtain low-cost solutions. The practical approach can only confirm the current health status of the wind turbine but not the level of structural safety or RUL.

Standardised procedures to document the operational history of the wind turbine and site conditions, access to design data (e.g. inclusion in purchase agreement), and stable and clear legal frameworks would help in deciding on lifetime extension of aging wind farms. The business case of lifetime extension is driven by the electricity spot market price, which is uncertain. This is a major concern of the interview participants. New O & M strategies are needed to maintain turbines at their optimal health and to reduce loads on turbine components during operation.

Today's procedure for lifetime extension assessment suits smaller turbines (less than 1 MW) with limited monitoring data, and large structural reserves. Future wind turbines reaching their end of life will increase in size as time progresses, and are part of larger wind farms. This may increase the attractiveness of lifetime extension since operational costs can be reduced due to economies of scale. On the other hand, new challenges will arise, since:

- Modern turbine are more optimal due to improved design. Consequently, these turbines have reduced structural margins. The search for RUL will require increasingly detailed and accurate analysis.
- It is doubtful that design information will be available for large-scale turbines in order to calibrate generic models. Larger turbines are more sensitive to dynamic excitation from the rotor and settings of the controller, which increases the importance of validation of generic models. Both matters complicate analytical assessments.
- Detailed operational data is readily available for modern wind turbines. New methodologies to process this data for lifetime extension purposes are needed.
- The individual assessment approach is not cost-effective as new wind farms increase in size. Data-driven approaches may be able to reduce costs of lifetime extension assessments. The importance of data-driven approaches increases further when operators have a larger number of similar assets.

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## References

- [1] European Wind Energy Association. Wind in power - 2015 European statistics; 2016.
- [2] DNV GL. Lifetime extension of wind turbines. DNVGL-ST-0262, <<https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-03/DNVGL-ST-0262.pdf>>; 2016 [Accessed 20 December 2016].
- [3] UL. Outline of investigation for wind turbine generator life time extension (LTE). UL-4143; 2016.
- [4] Megavind. Strategy for extending the useful lifetime of a wind turbine. Report, <<http://www.vindmoellegodkendelse.dk/media/1163/strategy-for-extending-the-useful-lifetime-of-a-wind-turbine.pdf>>; 2016 [Accessed 21 December 2016].
- [5] BWE. BWE Grundsätze zum Weiterbetrieb. Für die Durchführung einer Bewertung und Prüfung über den Weiterbetrieb von Windenergieanlagen (BPW) an Land. RL-BPW-17; 2017.
- [6] Holzmüller J. Analysing the lifetime of a wind turbine – operation past design life. In: Proceedings of Wind Europe Summit 2016, Hamburg, Germany; 2016.
- [7] Ziegler L, Muskulus M. Fatigue reassessment for lifetime extension of offshore wind monopile substructures. J Phys Conf Ser 2016;753:92010. <http://dx.doi.org/10.1088/1742-6596/753/9/092010>.
- [8] Loraux C, Brühwiler E. The use of long term monitoring data for the extension of the service duration of existing wind turbine support structures. J Phys Conf Ser 2016;753:72023. <http://dx.doi.org/10.1088/1742-6596/753/7/072023>.
- [9] Karlina-Barber S, Mechler S, Nitschke M. The effect of wakes on the fatigue damage of wind turbine components over their entire lifetime using short-term load measurements. J Phys Conf Ser 2016;753:72022. <http://dx.doi.org/10.1088/1742-6596/753/7/072022>.
- [10] Rubert T, Niewczas P, McMillan D. Life extension for wind turbine structures and foundations. In: Proceedings of International Conference on Offshore Renewable Energy, Glasgow; 2016.
- [11] Luengo M, Kolios A. Failure mode identification and end of life scenarios of offshore wind turbines: a review. Energies 2015;8:8339–54. <http://dx.doi.org/10.3390/en8088339>.
- [12] Ziegler L, Lange J, Smolka U, Muskulus M. The decision on the time to switch from lifetime extension to repowering. In: Proceedings of Wind Europe Summit 2016, Hamburg, Germany; 2016.
- [13] Department of Trade and Industry (DTI). Renewable energy awareness and Attitudes Research. GfK NOP Social Research, 12th May 2006. London; 2006.
- [14] España. Real Decreto-ley 1/2012, de 27 de enero, por el que se procede a la suspensión de los procedimientos de preasignación de retribución y a la supresión de los incentivos económicos para nuevas instalaciones de producción de energía eléctrica a partir de cogeneración, fuentes de energía renovables y residuos. Boletín Oficial del Estado, 28 de enero de 2012, 24; 2012. p. 8068–72.
- [15] Deloitte. La eólica en la economía española. Informe. Asociación Empresarial Eólica, <[https://www.aeeolica.org/uploads/Estudio\\_La\\_eolica\\_en\\_la\\_economia\\_espanola\\_2012\\_2015.pdf](https://www.aeeolica.org/uploads/Estudio_La_eolica_en_la_economia_espanola_2012_2015.pdf)>; 2016 [Accessed 21 December 2016].
- [16] Fraunhofer Institute for Wind Energy and Energy System Technology. Windmonitor, <[http://windmonitor.iwes.fraunhofer.de/windmonitor\\_en/3\\_Onshore/2\\_tech/6\\_alterstruktur](http://windmonitor.iwes.fraunhofer.de/windmonitor_en/3_Onshore/2_tech/6_alterstruktur)>; 2016 [Accessed 21 December 2016].
- [17] Danish Energy Agency. Stamdateregister for vindkraftanlæg; 2016.
- [18] Asociación Empresarial Eólica (AEE). Database on age distribution of onshore wind turbines in Spain enquired per email. [received 20 January 2017].
- [19] RenewableUK. Database on decommissioned onshore wind farms in the UK enquired per email. [received 17 January 2017].
- [20] Everoze life extension assessment framework - LEAF, <<http://www.everozeleaf.com>>; 2016 [accessed 21 December 2016].
- [21] Megaw N. UK energy groups warn subsidy cuts threaten old wind farms. Financ Times 2015 [Accessed 21 December 2016]. <<https://www.ft.com/content/591b0cc8-7d61-11e5-98fb-5a6d4728f74e>>.
- [22] UKWED. Renewable UK wind energy database, <<http://www.renewableuk.com/page/UKWEDSearch>>; 2016 [Accessed 03 January 2017].
- [23] International Electrotechnical Commission. IEC 61400-1 Wind Turbines - Part 1: Design requirements; 2005.
- [24] DNV GL. Support structures for wind turbines. DNVGL-ST-0126, <<http://rules.dnvgl.com/docs/pdf/dnvgl/ST/2016-04/DNVGL-ST-0126.pdf>>; 2016 [Accessed 21 December 2016].
- [25] Eurocode CEN. 3: Design of Steel Structures, Part 1-1 General Rules and Rules for Buildings. BS-EN 1993-1-2; 2005.
- [26] Rigdon SE, Basu AP. Statistical methods for the reliability of repairable systems. New York: Wiley; 2000.
- [27] Spinato F, Tavner PJ, van Bussel GJW, Koutoulakos E. Reliability of wind turbine subassemblies. IET Renew Power Gen 2009;3:387–401. <http://dx.doi.org/10.1049/iet-rpg.2008.0060>.
- [28] Carroll J, McDonald A, McMillan D, Bakshi R. Offshore wind turbine sub-assembly failure rates through time. EWEA 2015 annual event; 2015.
- [29] Carroll J. Reliability comparison of wind turbines with DFIG and PMG drive trains. In: Proceedings of the IEEE Power Energy Soc Gen Meet. 30:1–1; 2015 <<http://dx.doi.org/10.1109/PESGM.2015.7286449>>.
- [30] Bossanyi EA. Individual blade pitch control for load reduction. Wind Energy 2003;6:119–28. <http://dx.doi.org/10.1002/we.76>.

- [31] Selvam K, Kanev S, van Wingerden J, van Engelen T, Verhaegen M. Feedback-feedforward individual pitch control for wind turbine load reduction. *Int J Robust Nonlinear Control* 2009;19:72–91. <http://dx.doi.org/10.1002/rnc.1324>.
- [32] Leithead WE, Neilson V, Dominguez S. Alleviation of unbalanced rotor loads by single blade controllers. *Eur Wind Energy Conf Exhib.* Red Hook, NY: Curran Associates, Inc.; 2009. p. 576–615 (<https://strathprints.strath.ac.uk/id/eprint/28424>).
- [33] Beganovic N, Söffker D. Structural health management utilization for lifetime prognosis and advanced control strategy deployment of wind turbines: an overview and outlook concerning actual methods, tools, and obtained results. *Renew Sustain Energy Rev* 2016;64:68–83. <http://dx.doi.org/10.1016/j.rser.2016.05.083>.
- [34] Kamieth DR, Liebich PR, Melsheimer M, Grunwald DA, Heilmann C, Berlin TU, et al. Validierung einer Lastmessungs-gestützten Methode zur Restnutzungsdauer-Ermittlung von Windenergieanlagen. *Fachtagung Schwingungen von Windenergieanlagen, Düsseldorf. Germany: VDI Verlag; 2014*.
- [35] Burton T, Sharpe D, Jenkins N, Bossanyi E. *Wind energy handbook*. John Wiley & Sons; 2001. <http://dx.doi.org/10.1002/0470846062>.
- [36] Noppe N, Iliopoulos A, Weijtjens W, Devriendt C. Full load estimation of an offshore wind turbine based on SCADA and accelerometer data. *J Phys Conf Ser* 2016;753:72025. <http://dx.doi.org/10.1088/1742-6596/753/7/072025>.
- [37] Frandsen S, Sørensen JN, Mikkelsen R, Pedersen TF, Antoniou I, Hansen K. The generics of wind turbine nacelle anemometry. *Eur Wind Energy Conf Exhib*; 2009.
- [38] Barthelmie RJ, Frandsen ST, Nielsen MN, Pryor SC, Rethore PE, Jørgensen HE. Modelling and measurements of power losses and turbulence intensity in wind turbine wakes at middelgrunden offshore wind farm. *Wind Energy* 2007;10:517–28. <http://dx.doi.org/10.1002/we.238>.
- [39] IEC. Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines. IEC 61400-12-1; 2005.
- [40] Frandsen S. Turbulence and turbulence generated structural loading in wind turbine clusters [PhD thesis]. Roskilde, Denmark: Risø NationalLaboratory; 2007 [Accessed 21 December 2016]. ([http://orbit.dtu.dk/feodora/objects/orbit:79899/datastreams/file\\_269c3f19-0001-4e41-b754-b5b322a826cb/content](http://orbit.dtu.dk/feodora/objects/orbit:79899/datastreams/file_269c3f19-0001-4e41-b754-b5b322a826cb/content)).
- [41] Toft HS, Svenningsen L, Sørensen JD, Moser W, Thøgersen ML. Uncertainty in wind climate parameters and their influence on wind turbine fatigue loads. *Renew Energy* 2016;90:352–61. <http://dx.doi.org/10.1016/j.renene.2016.01.010>.
- [42] Danish Energy Agency. Executive order on a technical certification scheme for wind turbines no. 73; 2013.
- [43] Tautz-Weinert J, Watson S. Using SCADA data for wind turbine condition monitoring - a review. *IET Renew Power Gen* 2016. <http://dx.doi.org/10.1049/iet-rpg.2016.0248>.
- [44] Gonzalez E, Melero JJ. Wind turbine fault detection by monitoring its performance using high frequency SCADA data. In: *Proceedings of the 30th international congress and exhibition on condition monitoring and diagnostic engineering COMADEM*; 2017.
- [45] Gonzalez E, Melero JJ. Use of high-frequency SCADA data for improved wind turbine performance monitoring. *Wind. Conf. Exhib*; 2017. Submitted for publication.
- [46] Ziegler L, Smolka U, Cosack N, Muskulum M. Brief communication: Structural monitoring for lifetime extension of offshore wind monopiles: can strain measurements at one level tell us everything? *Wind Energy Sci* 2017;2:469–76. <http://dx.doi.org/10.5194/wes-2-469-2017>.
- [47] Wymore ML, Van Dam JE, Ceylan H, Qiao D. A survey of health monitoring systems for wind turbines. *Renew Sustain Energy Rev* 2015;52:976–90. <http://dx.doi.org/10.1016/j.rser.2015.07.110>.
- [48] Martinez-Luengo M, Kolios A, Wang L. Structural health monitoring of offshore wind turbines: a review through the statistical pattern recognition paradigm. *Renew Sustain Energy Rev* 2016;64:91–105. <http://dx.doi.org/10.1016/j.rser.2016.05.085>.
- [49] Asociación Empresarial Eólica. La eólica en España. Potencia instalada, (<http://www.aeeolica.org/es/sobre-la-eolica/la-eolica-en-espana/potencia-instalada/>); 2016 [Accessed 21 December 2016].
- [50] Deutsche Windguard. Kostensituation der Windenergie an Land - Internationaler Vergleich. Report, ([http://www.windguard.de/\\_Resources/Persistent/80d4d53fe8cdeff21edc7b0d4de1bfcf2e5e18cf/2014-04-03-Kostensituation-der-Windenergie-an-Land-intlA3-FinalReport.pdf](http://www.windguard.de/_Resources/Persistent/80d4d53fe8cdeff21edc7b0d4de1bfcf2e5e18cf/2014-04-03-Kostensituation-der-Windenergie-an-Land-intlA3-FinalReport.pdf)); 2014 [Accessed 21 December 2016].
- [51] Fraunhofer IWES. Wind Energy Report Germany 2014, (<http://publica.fraunhofer.de/dokumente/N-354656.html>), 2015 [Accessed 21 December 2016].
- [52] Red Eléctrica de España. Estadísticas del sistema eléctrico, (<http://www.ree.es/es/estadisticas-del-sistema-electrico-espanol/>); 2016 [Accessed 21 December 2016].
- [53] DECC. Electricity Generation Costs 2013. *Dep Energy Clim Chang*; 2013. p. 1–67, ([https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/223940/DECC\\_Electricity\\_Generation\\_Costs\\_for\\_publication\\_-\\_24\\_07\\_13.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf)). 25 May 2010.
- [54] Asociación Empresarial Eólica. Eólica 2016, ([https://www.aeeolica.org/uploads/ANUARIO\\_2016\\_baja.pdf](https://www.aeeolica.org/uploads/ANUARIO_2016_baja.pdf)); 2016 [Accessed 21 December 2016].
- [55] Erneuerbare-Energien-Gesetz (EEG 2014) vom 21. Juli 2014 (BGBl. I S. 1066), das durch Artikel 2 des Gesetzes vom 22. Dezember 2016 (BGBl. I S. 3106) geändert worden ist. §29.
- [56] Fachagentur Windenergie an Land. EEG 2017: Ausschreibungsbedingte Neuerungen für Windenergieanlagen an Land. Report, ([http://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA\\_Wind\\_EEG-2017\\_Ausschreibungen\\_11-2016.pdf](http://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA_Wind_EEG-2017_Ausschreibungen_11-2016.pdf)); 2016 [Accessed 21 December 2016].
- [57] España. Real Decreto 661/2007, de 25 de mayo, por el que se regula la actividad de producción de energía eléctrica en régimen especial. *Boletín Oficial del Estado*, 26 de mayo de; 2007. 126. pp. 10556.
- [58] España. Ley 24/2013, de 26 de diciembre, del Sector Eléctrico. *Boletín Oficial del Estado*, 27 de diciembre de; 2013. 310. pp. 13645.
- [59] § 35a-43 Lov om fremme af vedvarende energi; 2015.
- [60] OFGEM. Feed-in tariff generation and export payment rate table for non-photovoltaic installations FIT year 6 (1 April 2015 to 31 March 2016), ([https://www.ofgem.gov.uk/sites/default/files/docs/2015/01/fit\\_non\\_pv\\_tariff\\_table\\_for\\_1\\_april\\_2015\\_0.pdf](https://www.ofgem.gov.uk/sites/default/files/docs/2015/01/fit_non_pv_tariff_table_for_1_april_2015_0.pdf)); 2015 [Accessed 21 December 2016].
- [61] OFGEM. Renewables obligation: closure of the scheme to onshore wind (England, Wales, and Scotland), URL: ([https://www.ofgem.gov.uk/system/files/docs/2017/03/ro\\_onshore\\_wind\\_closure\\_gb.pdf](https://www.ofgem.gov.uk/system/files/docs/2017/03/ro_onshore_wind_closure_gb.pdf)) [Accessed 07 August 2017].
- [62] DECC. Government response to the consultations on the renewables obligation transition and on grace period, ([https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/289078/Transition\\_and\\_Grace\\_Periods\\_Government\\_Response\\_-\\_12\\_Mar\\_2014.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/289078/Transition_and_Grace_Periods_Government_Response_-_12_Mar_2014.pdf)); 2014 [Accessed 21 December 2016].
- [63] UK Government. Electricity market reform: contracts for difference, Department for Business, Energy & Industrial Strategy, (<https://www.gov.uk/government/collections/electricity-market-reform-contracts-for-difference>); 2015 [Accessed 22 September 2016].
- [64] NordPool. N2EX Day Ahead Auction Prices 2012–2016 Daily GBP, (<http://www.nordpoolspot.com/historical-market-data/>); 2009 [Accessed 03 January 2017].
- [65] Fraunhofer Institute for Solar Energy System. Monthly electricity spot market prices in Germany, ([https://www.energy-charts.de/price\\_avg.htm](https://www.energy-charts.de/price_avg.htm)); 2016 [Accessed 21 December 2016].
- [66] Energinet DK. Wholesale market data, (<http://www.energinet.dk/en/el/engrosmarked/udtraek-af-markedsdata/Sider/default.aspx>); 2016 [Accessed 21 December 2016].
- [67] Operador del Mercado Ibérico de Energía - Polo Español. Informe de Mercado – 2012, (<http://www.omie.es/inicio/publicaciones/informe-annual>); 2013 [Accessed 21 December 2016].
- [68] Operador del Mercado Ibérico de Energía - Polo Español. Informe de Mercado – 2013, ([http://www.omie.es/files/omie\\_2013\\_mercado\\_electricidad.pdf](http://www.omie.es/files/omie_2013_mercado_electricidad.pdf)); 2014 [Accessed 21 December 2016].
- [69] Operador del Mercado Ibérico de Energía - Polo Español. Informe de Mercado – 2014, ([http://www.omie.es/files/informe\\_mercado\\_espanol.pdf](http://www.omie.es/files/informe_mercado_espanol.pdf)); 2015 [Accessed 21 December 2016].
- [70] Operador del Mercado Ibérico de Energía - Polo Español. Informe de Mercado – 2015, ([http://www.omie.es/files/omie\\_es\\_0\\_0.pdf](http://www.omie.es/files/omie_es_0_0.pdf)); 2016 [Accessed 21 December 2016].
- [71] Deutsches Institut für Bautechnik. Richtlinie für Windenergieanlagen - Einwirkungen und Standsicherheitsnachweise für Turm und Gründung, ([https://www.dibt.de/en/Departments/data/Aktuelles\\_Ref\\_I\\_1\\_Richtlinie\\_Windenergieanlagen\\_Okt\\_2012.pdf](https://www.dibt.de/en/Departments/data/Aktuelles_Ref_I_1_Richtlinie_Windenergieanlagen_Okt_2012.pdf)); 2012 [Accessed 21 December 2016].
- [72] Germanischer Lloyd. Guideline for the Continued Operation of Wind Turbines. 2009.
- [73] Fachagentur Windenergie an Land. Status des Windenergieausbaus und Repowering in Schleswig-Holstein. Report, ([http://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA-Wind\\_RepoweringSituation\\_SH\\_02-2016.pdf](http://www.fachagentur-windenergie.de/fileadmin/files/Veroeffentlichungen/FA-Wind_RepoweringSituation_SH_02-2016.pdf)); 2016 [Accessed 21 December 2016].
- [74] Instituto para la Diversificación y Ahorro de la Energía. IDAE. Plan de Energías Renovables 2011–2020, ([http://www.idae.es/uploads/documentos/documentos\\_11227\\_PER\\_2011-2020\\_def\\_93c624ab.pdf](http://www.idae.es/uploads/documentos/documentos_11227_PER_2011-2020_def_93c624ab.pdf)); 2011 [Accessed 21 December 2016].
- [75] Bayerische Bauordnung (BayBO) in der Fassung der Bekanntmachung vom 14. August 2007 (GVBl. S. 588, BayRS 2132-1-I), die zuletzt durch § 3 des Gesetzes vom 24. Juli 2015 (GVBl. S. 296) geändert worden ist. § 35.
- [76] Colmenar-Santos A, Campiñez-Romero S, Pérez-Molina C, Mur-Pérez F. Repowering: an actual possibility for wind energy in Spain in a new scenario without feed-in-tariffs. *Renew Sustain Energy Rev* 2015;41:319–37. <http://dx.doi.org/10.1016/j.rser.2014.08.041>.
- [77] Yin RK. *Case study research design and methods*. Thousand Oaks, CA: Sage; 2009.
- [78] Patton MQ. *Qualitative research and evaluation methods. Integrating theory and practise* Fourth Ed. Sage Publications; 2014.
- [79] Bogner A, Littig B, Menz W. *Interviews mit Experten. Eine praxisorientierte Einführung*. Wiesbaden: Springer VS (Qualitative Sozialforschung); 2014.
- [80] Gläser J, Laudel G. *Experteninterviews und qualitative Inhaltsanalyse. Als Instrumente rekonstruierender Untersuchungen*. 4. Aufl. Wiesbaden: VS Verlag für Sozialwiss Lehrbuch; 2010.
- [81] Bardal LM, Sætran LR, Wangsnæs E. Performance test of a 3 MW wind turbine – effects of shear and turbulence. *Energy Procedia* 2015;80:83–91. <http://dx.doi.org/10.1016/j.egypro.2015.11.410>.
- [82] Pedersen TF, Demurtas G, Sommer A, Højstrup J. Measurement of rotor centre flow direction and turbulence in wind farm environment. *J Phys Conf Ser* 2014;524:12167. <http://dx.doi.org/10.1088/1742-6596/524/1/012167>.