REPORT FROM MEGAVIND
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Strategy for Extending the Useful Lifetime of a Wind Turbine

MEGAVIND

Contents

Front page: Courtesy of Siemens Wind Power

Preface

Megavind is Denmark's national partnership for wind energy and acts as a catalyst and initiator of a strengthened strategic agenda for research, development, and demonstration (RD&D).

Established in 2006, Megavind aspires to strengthen public–private cooperation in order to accelerate the innovation processes in the areas of wind energy that hold the greatest potential for technological development.

Vision and objective

Megavind's vision is to maintain and enhance Denmark's position as the global wind-energy hub and home of the world's leading companies and research institutes for wind energy.

Megavind's objective is to facilitate and accelerate the Danish wind industry's journey towards delivering competitive wind energy on market terms.

Work on the present strategy was carried out by a working group consisting of:

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1. Executive summary

Today, with a significantly large number of wind turbines reaching operational life spans longer than 15 years, it is essential that wind-turbine and wind-farm owners take informed decisions regarding the end of the turbines' operational life, life extension, or decommissioning. To do so, the wind-turbine components must be inspected to ascertain their integrity and the risk of failure during continued operation. The type of inspection may vary, based on the extent of operational data available and the problems encountered previously by the turbine's components. Extending a turbine's life beyond its usual design life of 20 or 25 years requires the owner to demonstrate – through inspections, operational data, or both – that the annual probability of failure of structural components is still acceptable, considering the maintenance history and component-failure modes.

The following sections describe the strategy for determining potential life-extension solutions, based on a component-by-component analysis, along with necessary inspection requirements and recommendations, that can demonstrate the feasibility of life extension. The strategy is applicable to wind turbines nearing the end of their design lives and is based on the level of operational data available, allowing informed decisions. The current scenario of wind energy in Denmark and the legal requirements for life extension are also highlighted.

2. Recommended actions

The remaining lifetime must be assessed, based on the amount of data available on the turbine design parameters and the operational history.

Four scenarios based on the level of information are described below.

Four levels of data affecting the ability to determine possible lifetime extensions
No design basis (for example, as used in type certification) or operational measurements available.
System-level turbine parameters (used in the initial design basis) are available without any operational measurement history.
Along with the design-basis information, SCADA-based measurements are available for at least a few years.
Multiyear load measurements, wind speed, and turbulence-intensity measurements and/or condition-monitoring measurements are available along with the design basis.

A combination of the above data types in varying amounts may also be available in some circumstances, which must also be assessed with appropriate tools.

Based on the four levels of data, the following recommendations should be considered in determining possible lifetime extensions.

1) *Scenario 1: No design basis (for example, as used in type certification) or operational measurements available.*
   When no data is available – that is, design basis and operational history are not available – software tools should be developed that use information gathered from frequent and rigorous inspections to allow quantification of the risk of component failure and approximate remaining life extension. The goal should be to:
   a. Define potential failure scenarios and optimal inspection points to determine the condition of the components as input to the life-estimation tool;
   b. Develop cost-effective inspection methods for different types of components and materials (e.g. glass fibre, carbon fibre, welded joints, etc.);
   c. Gain an improved understanding of the connections between inspection methods and the life-estimation process (e.g. how fast a crack will propagate for different materials);
   d. Quantify the risk of failure, likelihood of failure, and approximate consequences for relevant components using relevant methods.

2) *Scenario 2: System-level turbine parameters (used in the initial design basis) are available without any operational measurement history.*
   When the design basis of the turbine is available with some knowledge of environmental conditions leading to the IEC class for the site, the remaining life needs to be assessed at a turbine level, based on load calculations for which relevant computational tools should be developed. The goal should be to:

a. Define specific failure scenarios and optimal inspection points to determine the condition of the components as input to the life-estimation tool;
b. Develop cost-effective inspection methods for specific components and different types of materials (e.g. glass fibre, carbon fibre, welded joints, etc.);
c. Gain an improved understanding of the annual reliability of the critical structural components and remaining life;
d. Quantify the risk of failure and determine required partial safety factors using simulated loads to establish an annual reliability target level.

3) *Scenario 3: Along with the design-basis information, SCADA-based measurements are available for at least a few years.*
When the design basis and general operational history of the turbine are available, including power production, wind speeds, and rotor speeds as commonly recorded in the SCADA system, a probabilistic design approach at the turbine level can be followed to estimate the remaining expected life of the structural components and the frequency of inspection required for different turbine components. Under this scenario, the goal should be to:
a. Define specific failure scenarios based on past maintenance records and required inspection methods, frequencies, and focus points to determine the condition of the components as input to the life-estimation tool;
b. Improve (i) necessary inspections and condition monitoring for specific components and different types of materials and (ii) the methodology of incorporating information about existing physical damage (e.g. crack sizes) into material-fatigue S-N curves used in life estimation;
c. Gain an improved understanding of the annual reliability of the critical structural components and remaining life, based on operational measurements;
d. Quantify the risk of failure and required partial safety factors using simulated loads for an annual reliability target level.

4) *Scenario 4: Multiyear load measurements, wind speed, and turbulence-intensity measurements and/or condition-monitoring measurements are available along with the design basis.*
When detailed measurement data is available, such as load measurements from different components (e.g. blades and towers), as well as condition-monitoring information (e.g. gearbox oil temperature, vibrations, etc.), a component-specific reliability estimation can be made with specific inspection and life-estimation procedures as described for each component in Section 5. Under this scenario, with detailed information, the goal should be to:
a. Define specific failure scenarios based on past maintenance records, wind measurements, and load history to determine the condition of the components as input to the life-estimation tool;
b. Implement (i) advanced wind- and load-measurement capabilities, (ii) a necessary schedule for inspection and maintenance of specific components, (iii) different types of materials, and (iv) new inspection technologies for a target extended lifetime. Further, increase the frequency of inspections, depending on the technology used and the benefits accrued from early detection of possible failures;
c. Gain an improved understanding of the annual reliability of the critical structural components, fatigue life of different materials, and the uncertainty in the remaining life;
d. Quantify the risk of failure and the reduction in partial safety factors allowable, using measured loads for an annual reliability target level.

General recommendations

5) Initiate research into repair methods for each relevant component for life extension of the turbine, including structural and non-structural components, as well as for improved power production and safety.
6) Develop a method to categorise wind-turbine failures in a database structure for failure records and root causes.
7) Develop a process tool for certifying lifetime extension.
8) Adapt knowledge from other industries, such as the automotive sector, offshore sector, or civil engineering sector, to the wind-energy industry.
9) Develop a new IEC TC88 standard for wind-turbine life extension to broaden the application and requirements for life extension on a global level.
10) Develop a method for verification of tension in prestresssed bolt connections.
11) Development of standardized methods for assessment of remaining lifetime for major components using operational and/or measured data.

3. Methodology

The present strategy is based on the outcome of a series of meetings of the Megavind working group during 2015–2016.

Throughout its work, the working group has endeavoured to find the right balance between areas to which technological and/or functional solutions and recommendations are most beneficial and areas where filling important knowledge gaps is fundamental to progress and lower costs.

The present strategy focuses on extending the useful lifetime of wind turbines, including all sizes and ratings, except those specific to households.

The strategy is especially applicable to wind turbines that are near the end of their design life and is based on the level of operational data available to make informed decisions. The strategy, therefore, covers both onshore and offshore wind turbines. However, onshore turbines form the largest potential target group, because more onshore wind turbines than offshore wind turbines are reaching an age at which lifetime extension is relevant.

The content of the report has been peer reviewed by the Megavind steering committee.

4. Wind turbines installed in Denmark and their legal basis

Today, wind energy contributes with a significant portion of the Danish and European electricity generation. At the end of 2015, the accumulated installed wind-power capacity was 142 GW, producing 315 TWh in 2015, contributing to 11.4% of the EU's electricity consumption[1]. In Denmark, this figure in 2015 was 42.1%[2].

Wind turbines are conventionally designed for a lifetime expectancy of 20 to 25 years and, according to the Danish Energy Agency, 4,300 turbines have been in operation for more than 10 years in Denmark, including both onshore and offshore[3]. Of these, 1050 have already been operating for more than 20 years.

Figure 1 shows the number of turbines installed per year in Denmark. It shows that many turbines are reaching the end of their expected lifetimes and therefore fall within the scope of the present strategy.

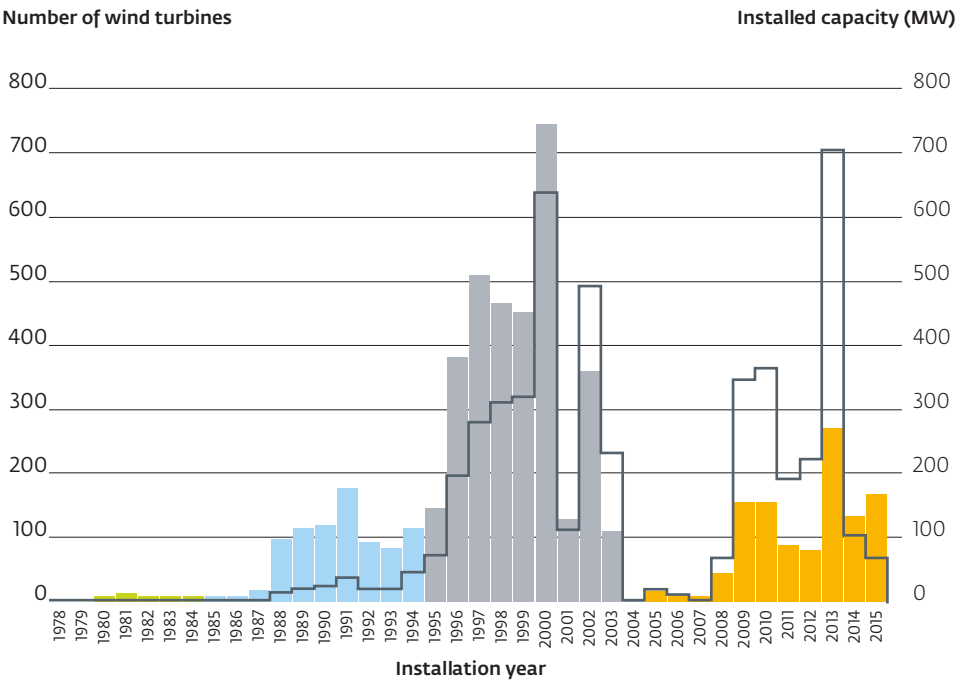

Figure 1[4]
Installations of wind turbines in Denmark.

- 30+
- 20-30
- 10-20
- 0-10
- Capacity (MW)

1 Wind Europe, 2015: Wind in power: 2015 European statistics
2 Energinet.dk, 2015: Dansk vindstrøm slår igen rekord – 42 procent
3 The Danish Energy Agency, 2015: Stamdataregister for vindkraftanlæg
4 Figure based on data from the Danish Energy Agency, 2015: Stamdataregister for vindkraftanlæg

Figure 2 shows the number of turbines installed per year in Denmark between 1978 and 2014, distributed by turbine size. Two major trends have emerged: (i) turbine capacity is increasing to more than 2.5 MW (orange bars), and (ii) the number of turbines with a capacity of less than 600 kW is increasing (green bars).

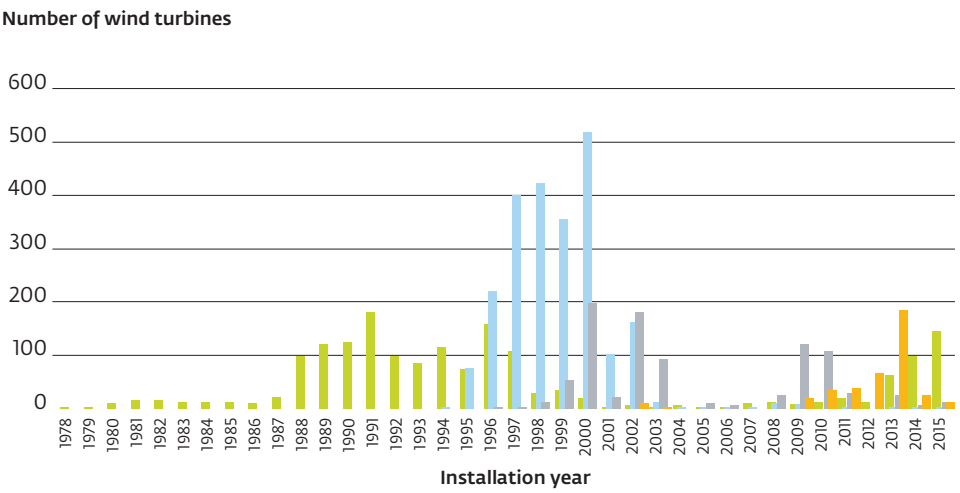

Figure 2[5]
Capacity (kW) of wind turbines installed in Denmark.

- 0-600
- 600-1000
- 1000-2500
- 2500+

Figure 3 shows the number of decommissioned wind turbines in Denmark and their age when decommissioned.

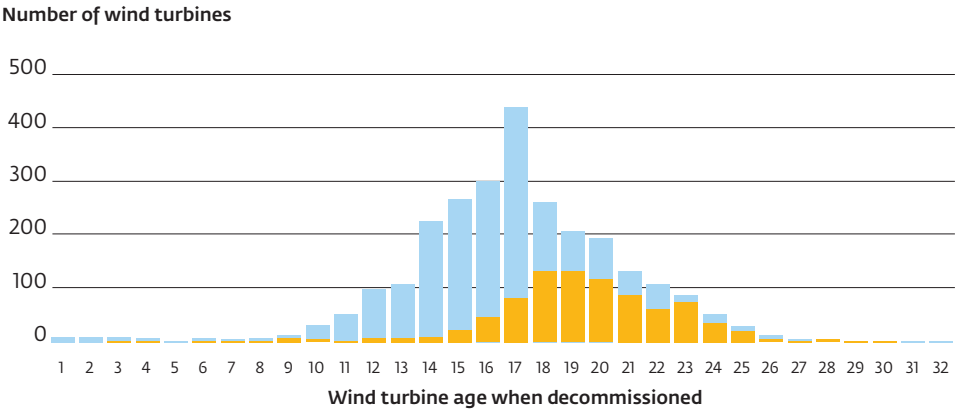

Figure 3[6]
Age of wind turbines when decommissioned.

- All turbines
- Scrapping scheme

Fewer than 3,000 wind turbines were scrapped in Denmark between 1984 and 2015 and, of these, 900 were under the scrapping scheme that ran from 2004 to 2011. This is shown in Figure 3, where blue bars represent the sum of all decommissioned turbines, and orange bars represent the number of turbines decommissioned based on the scrapping scheme. The x-axis shows the age of the turbine when decommissioned.

5 Figure based on data from the Danish Energy Agency, 2015: Stamdataregister for vindkraftanlæg

6 Figure based on data from the Danish Energy Agency, 2015: Stamdataregister for vindkraftanlæg

Figure 4 shows that many turbines will need to be decommissioned over the next eight years and, after that, many more will need to be decommissioned. The present strategy is especially valuable for these turbines.

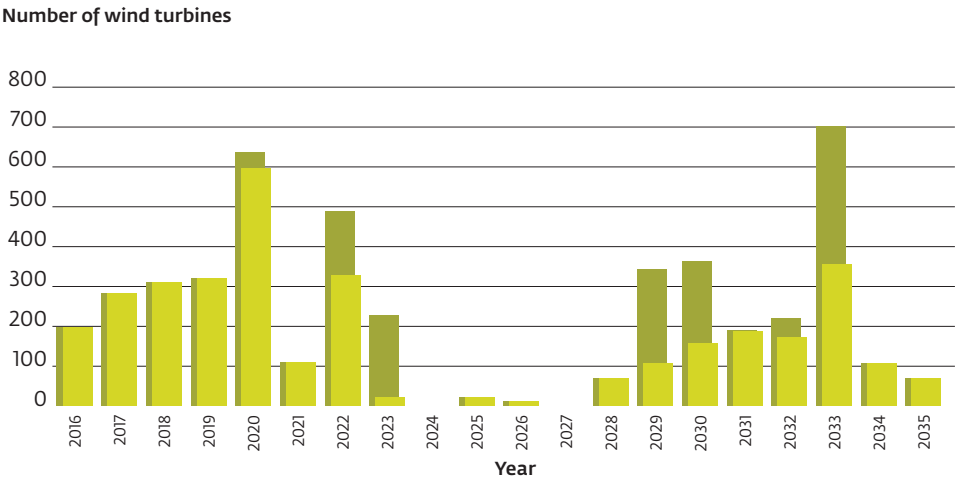

Figure 4[7]
Number of onshore and off-shore wind turbines reaching a 20-year lifetime.

- Total
- Onshore

The business model for the life extension of turbines depends largely on spot electricity pricing. Figure 5 suggests an upward price trend; however, projections show otherwise. For example, in their 2014 annual report, Vattenfall estimated a future spot price of DKK 0.225/kWh[8]. Today, however, a ten-year, fixed-price agreement would be set at approximately DKK 0.16/kWh.

Figure 5[9]
Spot-price trend for wind power in Denmark.

- Vestdanmark
- Østdanmark
- Vattenfall prediction
- Fix ten years

7 Figure based on data from the Danish Energy Agency, 2015: Stamdataregister for vindkraftanlæg

8 Vattenfall, 2014: Annual Report

9 Figure based on data from Nord Pool, 2015

Comparing the spot-market development with the consumer price index, Figure 6 shows a slight increase in the price of electricity.

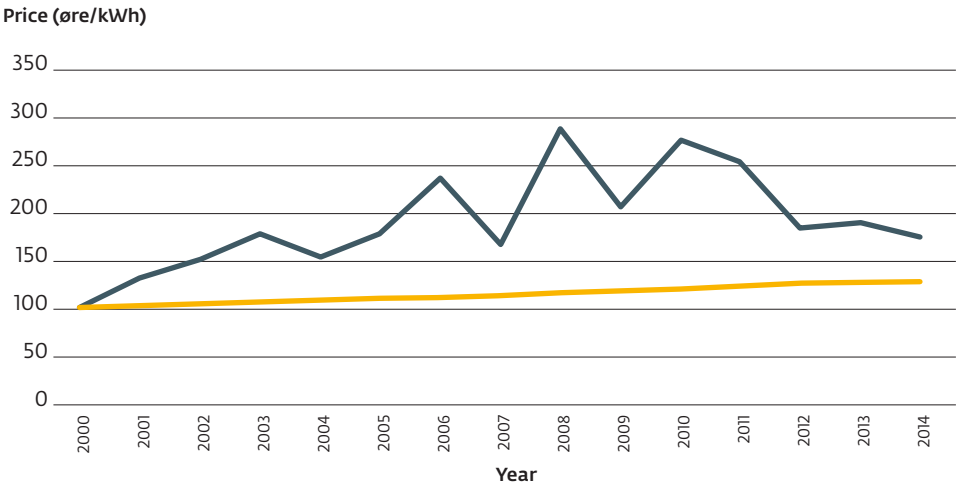

Figure 6[10]
Comparing the average spot price with the consumer index.

Average spot price
Consumer index

Onshore turbines in Denmark have an expected capacity factor of approximately 20–35%, depending on the site and turbine type, while offshore turbines often have a capacity factor of 35–50%. This means that a 1 MW onshore turbine (with a capacity factor of 25%) generates a yearly income of approximately (0.25*8760*1000*0.16) DKK 350,000, excluding taxes. This means that, if the operation and maintenance costs exceed the revenue, the owner will lose money by keeping the turbine operational, implying that life extension is not economically viable.

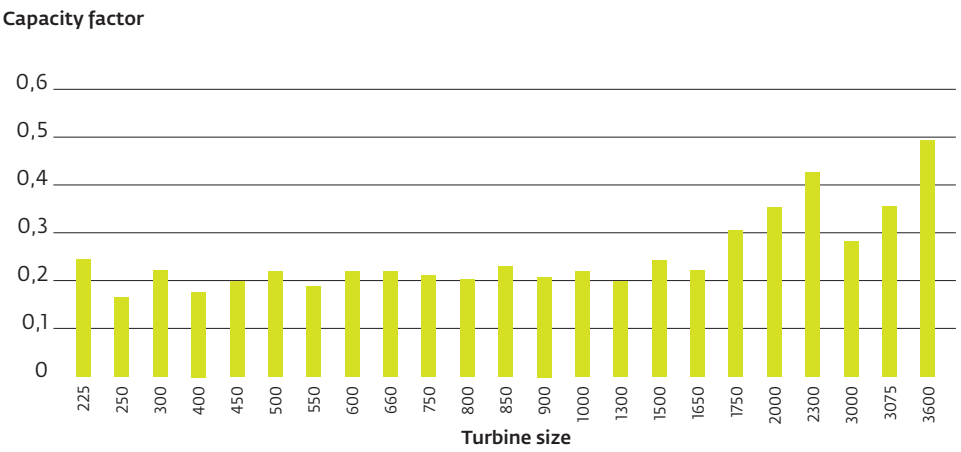

Figure 7[11]
Average capacity factor of turbines in Denmar k, based on turbine size in 2014.

10 Figure based on data from Nord Pool, 2015

11 Naturlig Energi, 2015

4.1. Executive Order on a technical certification scheme for wind turbines

Executive Order No. 73 of 25 January 2013[12] covers the requirements and procedures for technical certification, maintenance, repair, and service of wind turbines erected onshore, in Danish territorial waters and the Exclusive Economic Zone.

The order specifies that a wind turbine that has been in operation for longer than its design lifetime, as stated in the manufacturer's documentation or in the certificate issued, shall be subject to extended service[13].

Figure 8 shows that the extended service of wind turbines covers, at a minimum, the service inspection performed in accordance with the service manual as well as an inspection and assessment of the wind turbine's structural parts, based on the turbine's continued operation.

Figure 8
Wind turbines in operation longer than the design lifetime shall be subject to extended service, including inspection and assessment of the wind turbine's structural parts.

Extended service inspections of wind turbines must include the following minimum requirements.

Annually

- Inspect the machine frame for cracks in areas subject to heavy loads as well as in all welds.
- Inspect all bolted joints.
- Inspect the main shaft for dents and rust. The area in front of the foremost trunnion bearing is important. This area shall not have dents and rust, i.e. stress raisers.
- Inspect the yaw bearing for wear and measure the amount of play in the bearing. Inspect important parts of the yaw system.
- Inspect the tower for cracks in all welds.
- Tighten bolts in joints (in particular on blades) in accordance with the manual.
- Inspect the foundation for cracks in the concrete. Inspect and, if necessary, repair the sealing to keep water out of the foundation.
- Inspect foundation bolts for rust and wear.

Every three years

- Carry out a close, visual inspection of the blades, possibly using a camera or a photo drone/UAV, and a subsequent evaluation.

The inspection described above must be performed as a visual inspection of the components and items described.

The accredited or approved service company that carries out the extended service shall forward an associated checklist of the inspection to the owner and register it in the service report. The Energy Agency's Secretariat for the Danish Wind Turbine Certification Scheme provides a checklist example as given in Appendix 1.

12 Executive Order on a technical certification scheme for wind turbines No. 73, 2013

13 Ibid.

4.2. Determining the remaining life of wind turbines

The strategy for extending the useful lifetime of a wind turbine must be based on the available information about the turbine's design parameters and operational measurements. In this strategy, the level of data is classified into the four categories shown below and explained in Section 2.

Four levels of information affecting the ability to determine possible lifetime extensions
No design basis (for example, as used in type certification) or operational measurements are available.
System-level turbine parameters (used in the initial design basis) are available without any operational measurement history.
Along with the design-basis information, SCADA-based measurements are available for at least a few years.
Multiyear load measurements, wind speed, and turbulence-intensity measurements and/or condition-monitoring measurements are available along with the design basis.

Although a definite assessment can be made when the turbine's full design basis and a multiyear, load-measurement history of relevant components are available (scenario 4), only approximate indications can be given when no design details or measurements are available (scenario 1).

Wind turbine rotor nacelle assemblies (RNA) are usually designed to specific IEC classes of wind conditions, based on the standard IEC 61400-1[14]. This implies that the quality of their structural design meets a target for average annual wind speed and turbulence variation. Additionally, based on specific site conditions, the tower or support structure and foundation are designed to meet the specifications on that site.

Because the design loads are the basis on which the turbine's structural configuration was designed, the actual environmental conditions under which the turbine has operated and the duration of operation must be analysed to determine the turbine's actual remaining life.
This can require assessment of site-specific environmental variables, such as the ten-minute mean wind speed variation over time, the ten-minute mean turbulence and its variation over time, extreme wind occurrences, etc. In the absence of such information, suitable wind-climate-analysis software might also be used.

The turbine's structural design is also based on a target annual probability of failure or annual reliability level, which implies that the structure is said to fail when the design load (characteristic load multiplied by partial safety factors) reaches a limiting level as compared with design-material resistance. The design-load and material-strength levels are usually multiplied by partial safety factors, which are based on assumed uncertainties in environmental conditions, material parameters, and design models, the cumulative consequence of which may be conservative. This may allow life extension of turbine components because, in reality, the severity of the assumed uncertainties may be less than estimated.

14 IEC. International Standard IEC 61400-1: Ed. 3, Wind Turbines – Part 1: Design Guidelines, 2005

Failure in fatigue is said to occur when the cumulative damage caused by stress cycle variations with time exceeds the material limit, based on the measured S-N curve[15] for that material.

If a turbine is designed and type certified to a given IEC class (such as Class 1A), it is often installed on a site that has milder wind conditions. For example, according to the IEC 61400-1 Ed.3, Class 1A implies an average annual wind speed of 10 m/s, with mean turbulence intensity at 15 m/s of 16%. The site on which it is installed may be flat terrain (as is often the case in Denmark), with lower turbulence and a lower average annual wind speed.

The initial design also assumes a turbulence percentile of 90%, which, depending on the actual site distribution of turbulence, may also result in differences between the actual life and the design life.

If the turbine's design basis is known and the site-specific wind conditions are measured, the lower loads on the turbine – owing to more moderate design conditions – can be considered, resulting in a longer lifetime for structural components such as blades. This can be reflected in calculating the structure's updated fatigue damage, using the site's observed wind conditions as input to the turbine's original design basis and, using standard IEC conditions, comparing it with the design-fatigue life.

Another aspect required to assess the remaining life of a turbine is a risk analysis that quantifies the likelihood of a failure, its impact, and the possibility of detecting the failure before it occurs. It can be done as part of a failure mode effect analysis (FMEA) or as part of an inspection and planned maintenance of the structure. This also requires a turbine-specific inspection plan that can critically assess the integrity of its components.

Based on the inspection and risk analysis, the annual probability of component failure must be estimated, if feasible, and compared with the required target annual probability of failure. Such an analysis requires a more detailed and thorough analysis of the component-response history and a probabilistic model that reflects the inspection report in the structural integrity of each of the turbine's structures.

The evaluation of remaining life will require an assessment of the site-specific component loads, based on the turbine's operational history and measured wind conditions, along with a probabilistic analysis contingent on the current structural condition and the impact of possible material degradation on the structure's fatigue-limit state. A probabilistic model of the turbine structure can be based on wind conditions, loads, and material-degradation models and reflect the inspection report. It would be a valuable tool that accurately estimates the remaining lifetime and predicts the schedule for maintenance that can prolong the components' lifetime and prevent future failures.

Such a detailed, model-based life prediction can only be made with a dedicated measurement database that can be shared with relevant personnel. It should be a required component of future wind farms.

15 Eurocode 3: EN 1993-1-9.Design of Steel Structures - Part 1-9: Fatigue, 2005

Assessment of existing structures to extend their useful operation can be based on ISO 13822:2010[16]. The assessment consists of the following steps.

- Specification of objectives
- Identification of relevant scenarios
- Preliminary assessment, based on available documents, preliminary checks, and inspections
- Detailed assessment (if necessary) including inspections, calculations, and application of probabilistic methods
- Results and reporting

These principles have been applied in various related industries such as bridges, buildings, and offshore structures. Note that the IEC 61400 series of standards for wind turbines does not contain requirements specifically related to the assessment of existing wind turbines.

The remaining useful life (RUL) of wind turbines should be assessed in light of the following key issues.

Process for life extension
Assess safety requirements and integrity of critical components and systems whose failure may result in injury, economic consequences or loss of life in the context of continued operation beyond the design life.[17]
Failure modes
The typical mechanisms of failures as suffered by wind turbine components, along with the consequences thereof. These depend on the reliability and the degradation of turbine components, such as gearboxes, blades, bolts, and welded details, e.g. in the tower.

Continued operation of a turbine is limited by safety requirements, but it also depends on a cost–benefit calculation for the expected remaining lifetime. Information from inspections, condition monitoring (CM), and structural-health monitoring (SHM) is useful to update the estimate of the turbine's reliability in its remaining lifetime, if the information can be coupled with appropriate deterioration models.

The legislation as given in part 1: section 4.1 regarding end of design lifetime for an installed wind turbine is to some degree implemented in Denmark, but there are still a lot of learnings to be made. Tools for assessing a more correct end-of-lifetime as well as assessment of remaining lifetime is needed now and in the near future.

The following section describes, for each turbine component, the importance and relevance of the two key issues listed above, as well as additional information (inspections, conditions) to be used with deterioration models to assess the remaining lifetime.

16 ISO International Standard. ISO-13822, Bases for design of structures -Assessment of existing structures, 2010

17 HSE requirements are not included in this report.

5. Component-by-component analysis

Specific requirements to determine the remaining life of wind turbine components are provided below, along with their possible failure modes and new technological focus areas to improve inspection and condition monitoring.

The analysis is divided into the subsections: rotor, nacelle, tower, offshore substructures, general issues, health & safety, economy and optimization of operation and maintenance.

5.1 Rotor

This section analyses hub, blade root and hub connection, blades and the pitch actuators where present.

5.1.1 Rotor, hub

Life-estimation process
The life-estimation process is based on the availability of a design basis. If it is available, the load models and design baseline should be revisited by the OEM or turbine owner and updated with relevant information. The updated, accurate design lifetime can then be determined using the process given in Section 2.2. The updated results will determine if inspection or monitors are required in addition to the standard service inspections performed throughout the original design life.

The rotor's operating history must also be included in the evaluation to ensure that failure modes can be monitored to prevent future failure, so that the remaining design lifetime can be realistically reached.

If the load models or design baseline do not exist, a comparable, alternative turbine type can be used as a guide, but the comparability of the two turbine types must be proven.
The component's historical performance must be included, if available, in the evaluation to ensure that failure modes are considered in future remaining life estimation.
An FMEA can be done to identify risk areas and potential failure modes by either inspection or monitoring.

Failure modes and their impact
Major failures of the rotor hub are rare, but when they occur, damage to the turbine's structural safety and remaining useful life will be considerable.

In a worst-case scenario, failure could result in damage to nearby buildings or people. Depending on the extent of the damage, the turbine might need to be decommissioned.

The major potential failure modes to be considered when planning life extension include the following.

- Broken and/or loose bolts in the interface between the hub and nacelle can cause the whole rotor and hub to fall to the ground, damaging the tower.
- Broken and/or loose bolts in the interface between the hub and blade/blade bearing can cause the blade to fall to the ground and, in some situations, the blade can be thrown far from the turbine.


Courtesy of FORCE Technology

- General fatigue of the hub structure can cause part of the hub, including the blade(s), to fall to the ground, damaging the tower.
- Failure of components related to the turbine safety system can result in a runaway turbine that can fall over.
- Loose bolts or degraded materials can cause hub covers and other parts to fall to the ground.
- Parts from components placed in the hub, such as controllers and pitch components, can fall to the ground.

Potential mitigating actions

Mitigation of the failures mentioned is feasible with inspection.

- Bolts should be inspected to ensure that they maintain defined torque levels and be analysed for fatigue damage. Replacing the bolts will probably prove to be less expensive than analysing them. Replacing the bolts is more likely than analysis if inspection determines that they are close to or above their expected lifetime.
- The hub structure should be visually inspected for cracks, corrosion, etc. To find "hidden" defects, however, other techniques such as non-destructive testing (NDT) should be used. Advanced methods should always be applied if it is suspected that the structure will be fatigued during its lifetime. Advanced load models using the design basis can also identify the risk of premature fatigue failure.
- All components of the turbine shutdown system must be inspected and tested thoroughly to minimise the risk of a runaway turbine.
- Hub cover parts must be inspected for cracks and degradation.
- Components, inside and outside the hub cover, must be inspected thoroughly to minimise the risk of parts falling.

Recommendations for further research and development

- Develop reliable, cost-effective, and easy-to-use methods to determine the condition of mounted bolts, without dismounting them.
- Develop cost-effective methods to detect fatigue failures in the hub structure. Failure-progression studies can identify actions to reduce risk.
- Develop a site-specific wind and turbulence estimation tool. For older turbines, data from meteorological masts on the turbine's entire operational period may not be available. The information can be estimated using meteorological models to create site-specific load models. Comparing the simulated loads with the design baseline can define the extent of the turbine's previous load and estimate the remaining lifetime in light of the acceptable annual probability of failure. The risk of failure can also be verified with inspections and actions. Improvements must be implemented to secure safe continued operation.

5.1.2 Blade root and hub connection

Failure modes and their impact

Blade roots and hub connections are prone to many failure modes. The blade roots have different designs that form the connection between the composite material and the steel. A bolted connection is usually present between the hub and the blade root.

Bolt failure can compromise the structural integrity of the connection between the blades and hub. Deformation of the bolt's unthreaded shank can lead to an applied locking torsion that does not ensure correct torqueing of the bolt's threaded section. Therefore, measuring the bolt's pre-stress can lead to misleading values. Corrosion and rust in the threaded section can also result in misleading pre-stress values. In both cases, incorrect torsion can result in displacement between the blade and hub and increased vibration, which can lead to fatigue-damaged bolts and crack formations in blade rings (previous cases have been registered).

In this case, bolts can fail because of both fatigue and tension. When a bolt fails, a chain reaction is likely, and the failure of several consecutive bolts results in blade and hub disconnection. Consequently, falling blades can strike other blades and the tower. If the turbine is operating, debris can be thrown more than 110 m from the turbine. This represents a substantial economic impact and a great health and safety risk to people and surrounding buildings.

Potential mitigation actions

A pre-stress check of every tenth bolt may not be sufficient. Bolts must be removed to allow visual inspection and the detection of rust and corrosion, deformation, and fatigue damage. Bolts can be greased before they are retightened in the bolt connection.

Recommendations for further research and development

NDT methods should be developed (e.g. ultrasound and X-ray) to detect pre-stress and crack formation.

5.1.3 Blades

Life-estimation process

The blades' operational history should be examined and all previous maintenance reports analysed. It should be assessed if damage observed during past inspections is critical to the blades' structural integrity. If blade damage (e.g. cracks) might worsen, the cost of preventive repairs and maintenance should be assessed.

If operational data and load models exist, the blades' remaining fatigue life can be calculated. The calculation is based on the damage history, using the process given in Section 2.2, by applying design-load calculations, acquired wind measurements, and SCADA data from past operation. An aerodynamic assessment of the blade surface must be made to quantify possible deterioration in power performance from worn surfaces, which do not affect the blades' structure but interfere with flow.

Changes in design standards, from the time the blade was designed to the present, must be considered, to substantiate the blade's survivability in any life extension.

Blade collapse after failure of the load bearing structure

Failure modes and their impact

Blades are prone to many defects and failures. Cracks and debonding along the leading edge, trailing edge, and main load-bearing laminates are among the most common damages. Blade–tower strike during operation is rare, but can occur during extreme turbulence or negative wind shear. The bolted joint connection at the blade root can also fail, leading to blade throw. Failures from lightning strikes, failure of tip brakes, and erosion are common blade faults. Erosion and dirt on blades primarily affect power production and normally do not lead to failure. Leading-edge erosion on large blades can quickly lead to energy loss and must be repaired.

Most defects and damage have economic consequences for turbine owners, but complete blade failure has health and safety implications. In some cases, a blade part can be thrown far from the turbine, with considerable health and safety consequences.

Potential mitigating actions

Today, most blade inspections are visual, and most visual inspections and repairs are done with rope access. This is expensive, may not always be accurate, and can pose health and safety risks for the technicians doing the inspection and repairs.

Blade failure is usually gradual, and the risk of failure resulting from blade-surface damage can usually be observed visually. Defects and damage not repaired in time can lead to the failure

of parts of the blade or the entire blade. Blade failure can lead to failure of the entire turbine, because blades can strike the tower, resulting in complete collapse.

Recommendations for further research and development

A crack inside the blade can cause the total failure of the blade and turbine. Research continues on improving inspection methods to detect cracks before they propagate. Drones and visual inspection can spot damage from the outside. Cracks, however, can also develop inside, and these can be detected by stiffness-degradation monitoring, if such a system is mounted.
On older turbines, thermal cameras can be used to detect heat development in cracks. The cameras can be carried by drones.

External blade inspection (visual, ultrasonic) is usually done manually, using cranes with a man basket, or with ropes.
As drone (UAV) technology improves (increasingly stable flights and flight periods exceeding 20 minutes), the duration of blade inspections could be reduced appreciably, compared with conventional inspection methods. O&M procedures would be made easier, allowing for annual and semi-annual inspections. The following is recommendations for improvement of blade inspection with drones.

- Equip drones with high-resolution cameras.
- Equip drones with NDT sensors.
- Create predefined routes over blade surfaces to cover the blades' sensitive areas and improve repeatability of the inspection measurements.
- The precision of the findings depends on the inspection method, i.e. visual, penetrant, ultrasonic, acoustic, or eddy-current inspections.

In the absence of the turbine's design basis and site-specific loading, a simpler approach is required to estimate a blade's remaining life, based on an estimated design basis and SCADA-based measurements.

If a relationship between inspection results, material properties, and turbine operation can be specified, the future inspection interval can be determined exactly.

5.2 Nacelle

Life-estimation process

For life estimation, the nacelle internals may not pose a risk to structural safety; primary and critical structural parts are covered in separate sections. Each turbine type for which components are categorised as structural parts, however, must always be evaluated individually. For example, in some turbine types, a gearbox is a wear-and-tear part, whereas in other turbine designs, it is part of the turbine's structure.

Failure modes and their impact

A gearbox/main bearing failure can result in a broken drive train. Such a failure can cause backlash on the blades, which in turn can cause the blades to rupture and fall to the ground. In a worst-case scenario, additional structural damage could occur.

Turbine safety-system failure can lead to overspeed and result in the blades' collapse or, in the worst case, a breakdown of the whole WTG. Gearboxes, brake systems, and hydraulic systems are often vital parts of the turbine's safety system, allowing it to shut down during high wind, grid dropout, and other turbine failures, e.g. blade damage, gearbox damage, etc., causing critical damage to the WTG and leading to uncontrolled situations.

Drivetrains have been known to fail, resulting in blades falling off; turbines have been known to overspeed when the safety system fails, leading to a total breakdown. In the worst case, damage to nearby people or buildings can occur. Depending on the extent of the damage, the turbine might need to be decommissioned.

Potential mitigating actions

A gearbox can be inspected using boroscope technology, but action will be based on its relation to structural integrity and safety. Condition-monitoring system (CMS) technology can be used to some extent to identify failures before they become critical. Critical components should undergo a more detailed analytical assessment to reach a greater degree of certainty regarding their performance.

Recommendations for further research and development

Gearbox/drive train inspections can be performed with a variety of remote methods, depending on the turbine/component design. For bearings and gears, CMS technology is used today; it must be further integrated with data analytics to forecast the system's health. Safety systems must be tested to verify that they are fully functional; testing procedures will depend on individual systems and turbine designs.

Inspection of broken wind turbine shaft

5.2.1 Nacelle: shaft and main bearing

Life-estimation process

The main shaft, main bearing, and gearbox should be considered together. The mounted main shaft history, with details of first mounting (repairs/renovations of the bearing seats, etc.), is essential to predicting its remaining life.

Failure modes and their impact

The main shaft is a rotating machinery element with the rotor mounted on the front end. The loads on the shaft are the result of torsion, thrust, and bending.

There are three types of drivetrain setup:

1. The main shaft with two bearings and an overhanging gearbox.
2. The main shaft with one main bearing and a bearing in the gearbox as the second main bearing (three-point suspension).
3. No main shaft at all.

In particular, the section of the main shaft between the rotor hub and the main bearing is heavy loaded. A crack initiation at this position can be catastrophic, leading to the loss of the rotor. When refurbishing the main shaft, the inner ring on the main bearing is cut through with an angle grinder, the shaft is ground, and the grinding is filled by welding. The welding can introduce residual stresses in some areas, from which a crack can propagate, resulting in the main shaft breaking. Welding on a main shaft is not allowed. Fretting corrosion may occur on the shaft at the main bearing inner-ring fit. When changing the main bearing, the main shaft's condition should be evaluated, to determine if the shaft can be used as it is. The shaft can be renovated by metal spraying and grinding at the bearing fit, if the fretting corrosion is not too severe.

Potential mitigating actions

The area in front of the main bearing (front-end main bearing) shall be absolutely free of any stress riser that may have a notch effect to initiate a crack. Normally, a main shaft is painted or rust protected in another way. This part of the main shaft should be visually inspected at each

service inspection. If corrosion or deep scratches or cuts are observed by any tool, the shaft must be repaired. Repair is done by polishing the area until the surface is clean and smooth with large rounding. After this, paint or rust protection should be applied. It should be remembered that a visual inspection may not detect all cracks, for example, inside the bearing housing.

Recommendations for further research and development

When the main shaft is already installed, ultrasound testing is not easy, but it can be beneficial. The focus area will be the section of the shaft inside the main bearing. Suitable ultrasound equipment for testing the main shaft from the front-end surface or from the shaft close to the bearing could be developed. Material properties for fatigue resistance should be tested and verified.

5.2.2 Nacelle: frame

Life-estimation process

The mainframe is a casted/welded unit between the nacelle and the yaw bearing. The frame shall withstand dynamic loads, vibration in the nacelle, and interaction with other parts of the turbine structure.

Life prediction of the mainframe requires an understanding of fatigue failures from cyclic loading, which occur in distinct phases – the crack-initiation phase, followed by the crack-growth phase and rupture.

The crack-initiation phase is the period up to the formation of a surface crack under fatigue loading. The crack-propagation phase covers the remaining life until the crack reaches critical length. The second phase belongs to the science of fracture mechanics, where material properties and microstructure (grain size, imperfections, etc.) play a major role.

Frame failures are a significant problem for turbines. Examples of failure are fatigue cracks in welded or bolted joints in the mainframe.

Failure modes and their impact

Fatigue cracks can occur with a moderately high probability when the turbine reaches its design lifetime. Generally, the consequences of a large fatigue crack will be catastrophic, resulting in the nacelle's total failure. Fatigue failure may be a combination of a large crack and unstable crack growth caused by extreme loading.

Failure of the nacelle frame owing to fatigue failure results in the loss of the nacelle – and thus substantial economic loss – and the risk of loss of human life if the turbine is placed close to roads, buildings, etc.

Potential mitigating actions

Both inspections and data analyses are possible. If information is available about the wind climate and the turbine's operation during its lifetime, an estimate of the expected fatigue damage can be obtained and compared with the requirements in the standards and design codes.

Inspections can be performed to update the information about the remaining fatigue life. Note that there is no direct correlation between the observations made in an inspection (e.g. no crack detected or a crack of a certain length or depth detected) and the modelled fatigue damage, based on Miner's rule (used in the design standards). It should also be noted that the value of information depends strongly on the inspection method applied; for example, visual inspection

will require much shorter inspection intervals than e.g. eddy current or Magnetic Particle Inspection (MPI). Experience from other relevant industries can be applied.

Recommendations for further research and development

Multiyear data must be made available about each fatigue-critical component in the frame, along with information about wind climate, condition monitoring, SCADA data, etc., resulting in an updated estimate of the (design) fatigue lifetime, according to the design standard used (e.g. EN 1993-1-9 combined with IEC 61400-1). The inspection planning should evaluate the reliability of the inspection method used, intervals between inspections, component criticality, and planned actions if cracks are detected.

5.2.3 Nacelle: electrical components, including controller

Life-estimation process

The life-estimation process in section 2 is not directly applicable to the electrical units, because they must be individually inspected so that their functionality and associated protection systems remain intact without degradation. Life estimation is therefore based on the probability of maintaining electrical contacts for safe power generation under the stated environmental conditions for the required duration.

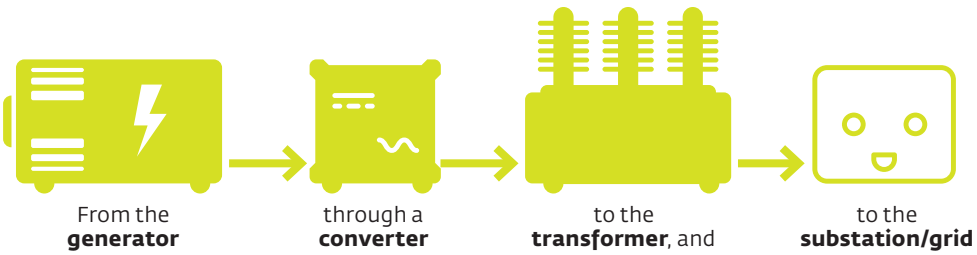

Figure 8
The energy flow during electricity production in the WTG.

Each of these segments represents a separate risk during a WTG's lifetime.

A high-level risk is that an uncontrolled combination of resistance and current flow will generate heat, which can lead to fire, and even result in an explosion.

The generator system can be described as either a synchronous generator system with permanent magnets or an asynchronous generator system that, typically, is double fed. The double-fed asynchronous generator currently represents approximately 70% of the market, but numbers will decrease.

Neither the synchronous nor the asynchronous generator represents a risk in itself. It is the attached electronic equipment (converters) that poses a risk.

Both types of generators need converters for feeding the grid. The synchronous generator needs a full AC–AC back-to-back converter. The double-fed asynchronous generator needs an AC–DC back-to-back converter to feed the stator. The power from the stator is fed directly to the grid. Therefore, the converters for doubly-fed asynchronous generators only need to be sized for a fraction of the generator's power. Furthermore, filters and rectifiers (IGBT or GTO) are required to handle the reactive power and magnetisation of the stator.

These converters and filters represent a considerable risk and will be discussed further. Breakers in the relevant switchgears represent a considerable risk too and should be studied when considering life extension.

Power from the generator and output from the converters are typically produced at 690 V and must be stepped up to 10 KV or higher.

If the transformer for this is situated in the nacelle, it represents a major risk, which should be studied when considering life extension.

Failure modes and their impacts

a. Electrical protection system inclusive of converter (filters, converters, and breakers): consequences and damage

Electrical faults cause major material damage and have economic consequences, such as total loss of the WTG resulting from fire. In addition to the WTG's total loss, environmental damage resulting from oil spills is typical. As for health and safety, there have been several incidents involving service personnel who have suffered major injuries from electrical arcing when working on a power panel in the nacelle.

Electrical faults in filters, converters, and circuit breakers after the first ten years are more likely than natural aging from wear and tear. A known problem is a capacitor fire, whose prevention and detection is important to mitigate major risks, especially in older systems depending on that type of capacitor. Several root-cause analyses have demonstrated that the most likely origin of a fire is an old or aging capacitor.

Circuit breakers suffer from wear and tear after years of operation. Depending on the system's internal design, the number of switching varies considerably and must be considered when evaluating the grade of aging. In other words, circuit breakers, which are activated at each start/stop, will suffer wear and tear considerably more than circuit breakers designed for protection only.

b. Transformers installed in the nacelle

Many transformers installed in the nacelle are the dry type and are situated in a separate, high-voltage section. Internally, the windings in the coils can be connected, but care should be taken to avoid arcing to ground. The high- and low-voltage terminals can also initiate arcing to ground.

Potential mitigating actions

a. Electrical protection system inclusive of converter (filters, converters, and breakers)

High-risk capacitors do not visually age, and inspection to determine potential damage is not possible. Circuit breakers can be inspected to measure wear and tear.

b. Transformers

It is crucial to inspect for partial discharge, dust in the cooling channels, bent connection rods between the taps, and connections.

Failed electrical systems can be seriously damaging to the turbine, especially in the case of safety systems, such as a short circuit in the generator, converter burnout, etc., which can lead to nacelle fires. The likelihood of an electrical failure must be quantified before taking any life-extension decision.

Recommendations for further research and development

a. Filters, converters, and breakers

The renewal of capacitors and circuit breakers after a predetermined time should be considered. The number of years before replacement in undertaken should be decided on a case-to-case basis, depending on the electrical system's design and the type of capacitors. Furthermore, installation of an arc-detection system is recommended. The arc-detection system monitors a developing arc, and the control system immediately switches off the power supply. Note that a few important circumstances must be considered, including security for safe functionality and power after first activation, and security for the breaker's functionality, in case of an electrical fault.

b. Transformers

Arc detection is necessary to protect the transformer and the entire WTG. The same concerns about functionality, as mentioned above, should be considered.

5.2.4 Nacelle: yaw systems

Life-estimation process

Turbine yaw systems consist of several active components and interfacing areas between the nacelle (mainframe) and the tower. Active components include (i) the yaw drives and (ii) the yaw brake. Interfacing areas include (i) the yaw mesh, i.e. the meshing between the yaw-drive pinion and the yaw-gear rim, (ii) the yaw bearing, connecting the mainframe to the tower head, and (iii) the yaw-brake disc and yaw brake.

The yaw bearing and bearing bolts, as well as interfacing areas and yaw drives, are designed for the normal operational lifetime of a turbine, i.e. 20–25 years, and life-extension planning must consider their functionality and wear and tear. The yaw-brake system, including the yaw-brake disc and yaw brake with brake calipers, needs refurbishment following replacement schedules during the turbine's lifetime and any life extension. The yaw system's main purpose is to align the nacelle to the main wind direction identified by the turbine-control system and – if the nacelle is aligned to the wind direction – to maintain this orientation by activating the yaw brakes. Yaw control algorithms are normally designed so that fatigue loading of its components is kept low, and power capture by the turbine is optimised.

Failure modes and their impact

Yaw systems consist of structurally relevant parts (yaw bearing and bearing bolts), interfacing areas (yaw mesh and yaw drives), and wear-and-tear parts (yaw brakes and brake discs). Static yaw misalignment (the deviation between wind direction and turbine orientation) should be low, whereas dynamic yaw misalignment (the scatter of yaw misalignment) could be high, depending on the level of yaw-fatigue loading.

Yaw-system failure represents a significant problem for turbines. Examples of yaw-system failure are cracked yaw-drive shafts, fractured gear teeth, pitted yaw-bearing races, and failed bearing mounting bolts.

Yaw drives and yaw-brake systems (brakes and brake discs) are not relevant to structural safety, because they are not in the load path (rotor–nacelle–tower). Therefore, failure of these components has only an economic impact. Except for wear of yaw-brake discs and damaged yaw-gear rims, in most cases, the yaw drive and yaw-brake components can be exchanged quite easily. Nevertheless, this can cause excessive downtime, if the spare parts are not available.

The yaw's main bearing and bolt connection to the mainframe and tower head are relevant to structural safety. Broken bolt connections can, in the worst case, lead to the loss of the turbine, if the nacelle or rotor collapses.

Potential mitigating actions
The same inspection and analysis can be applied to the yaw bearing's bolt connection and to the other bolt connections in the load path.

Generally, the impact of a defective yaw system is not catastrophic, except in cases where the bolt connection breaks. In worst case, this can cause the complete nacelle, including the rotor, to fall off. If it strikes the tower, the turbine may be totally lost.

Recommendations for further research and development
To eliminate the risk of worn-out bolts caused by fatigue loading, they should be replaced regularly, unless calculations or data are available confirming that inspections alone will be sufficient.

A reduction in yaw-drive fatigue loading could be achieved by using hydraulic components in the yaw-system design. This would soften the stiff and undamped yaw systems commonly driven by electrical-induction motors in combination with reduction gears.

5.3 Tower

This section analyses weldings & flanges in the tower and doors.

5.3.1 Tower: weldings and flanges

Life-estimation process
RUL can be estimated using a deterministic, semi-probabilistic approach or method. In both cases, the accuracy of the estimate of RUL depends strongly on the information available about the fatigue load and fatigue strength. The deterministic approach will provide a characteristic estimate of RUL, based on characteristic values of the fatigue load and fatigue strength through S-N curves. Inspection results may be difficult to include in a deterministic assessment. In a probabilistic method, more detailed information can be modelled, and an estimate of both the expected value and the RUL's standard deviation can be obtained. Moreover, inspection results and previous repairs and maintenance can be included in the assessment.

Failure modes and their impact
Fatigue cracks may occur with low probability when the turbine reaches its design lifetime. Generally, the consequences of a large fatigue crack in the circumferential weldings will be catastrophic, resulting in the tower's total failure. Criticality will be increased if the welding is exposed to corrosion. Fatigue failure can be a combination of a large crack and unstable crack growth caused by varying loads, as modelled by FAD diagrams in e.g. BS 7910.

Tower failure caused by fatigue failure in the circumferential weld results in the loss of the nacelle and thus substantial economic losses, as well as the risk of loss of human life if the turbine is placed close to roads, buildings, etc., or if technicians are working on the turbine. However, because failure can be expected to occur when the turbine is operating, this is unlikely because turbines are stopped during maintenance and service.

Potential mitigating actions
Based on inspections and analyses, along with wind-climate data and the turbine's lifetime op-


Courtesy of FORCE Technology

erational history, an estimate of the expected fatigue damage can be obtained and compared with the requirements in the standards and design codes.

Inspections can be performed to update the information about the remaining fatigue life. The value of information depends strongly on the inspection method applied. Experience from other industries, such as bridges and offshore oil and gas platforms, can be applied, as necessary.

If a probabilistic approach is used, a risk assessment can be performed accounting for the individual consequences of failure.

Recommendations for further research and development
First, update the information about each critical fatigue in the tower with information from wind climate, condition monitoring, SCADA data, etc., resulting in an updated estimate of the (design) fatigue lifetime, according to the design standard used (e.g. EN 1993-1-9 combined with IEC 61400-1). Second, perform the inspections. The inspection planning should evaluate the reliability of the inspection method used, the intervals between inspections, and the planned actions if cracks are detected. A reliability level for an existing turbine tower – lower than for a new tower – may then be considered.

5.3.2 Tower: doors

The general issues and descriptions in sections 5.1.1 and 5.3.1 also apply to this subsection.

Failure modes and their impact
As for tower fatigue, cracks in the door–tower connection may, with low probability, occur when the turbine reaches the design lifetime. Generally, the consequence of a large fatigue crack developing into the circumferential welding will be catastrophic, resulting in the tower's total failure. Other cracks are usually less critical.

For flange connections, fatigue, especially, and incorrectly executed or maintained bolted connections may result in the tower's total failure.

Potential mitigating actions
Both inspections and analyses are possible; see Sections 5.1.1 and 5.3.1.

5.4 Offshore substructures

Commercial offshore wind turbines are supported on fixed base substructures such as monopiles, gravity foundations, tripods and jackets. Amongst these, monopiles make-up the overwhelming majority.

Life-estimation process

An offshore substructure is loaded by gravity, wind-driven loads, and hydrodynamic loads, and is affected by corrosion, marine growth, etc. Accessories mounted on the substructure, such as boat landings, are also affected by impact loading from boats and vessels.

RUL can be estimated using a deterministic, semi-probabilistic approach or method. In all cases, the accuracy of the estimate of RUL depends strongly on the information available relevant to quantifying the fatigue damage and the structure's fatigue strength. The deterministic approach will provide a characteristic estimate of RUL, based on characteristic values of the fatigue load and fatigue strength through S-N curves. Inspection results are difficult to include in the assessment. In a probabilistic method, more detailed information about the uncertainties affecting fatigue can be accounted for, and an estimate of both the expected value and the RUL's standard deviation can be obtained. Further, inspection results and previous repairs and maintenance can be included in the assessment.

Failure modes and their impact

The result of a foundation failure can be total failure of the complete turbine, including the foundation.

The foundation can be protected from corrosion by active cathodic protection, passive cathodic protection, and paint systems.

For monopile-type substructures, the grouted joint between the monopile and the transition piece is a critical joint that must be inspected every few years to ensure its integrity. The dynamic loads affect the fatigue life of the steel parts and the wear of the grouting material between the steel shells. Moreover, corrosion reduces the static and fatigue strength of the structure's steel, including bolts.

Another common failure mode arises from the removal of the soil around the foundation by the water currents, commonly referred to as scour, thus reducing the bearing capacity of foundation support. Scour protection is used to prevent removal of the seabed, but monitoring for the onset of scour is required to allow preventive action that does not result in undue vibration of the support structure.

Potential mitigating actions

Desktop analysis of critical stress hotspots and possible structural degradation with time should be made along with an inspection of the structure's exterior and interior to detect corrosion in painted and, especially, unprotected areas.

Visual inspection for defects of the platform, boat landings, and J-tubes can be done with drones and unmanned underwater vehicles.

Compare the real lifetime loads with the design loads, where load measurements are possible. Both periods of idling and operational time must be accounted for in the comparisons, along with measurement of the soil/foundation's actual stiffness.

Inspection of the cathodic system, scour, and grouting shall be done during normal service work.

Recommendations for further research and development
Today, partial safety factors and stress concentration factors used in substructure design can be less conservative, owing to research and real-time measurements. This can lower costs and be further assessed at the end of the design life to evaluate further powering or decommissioning.

5.5 General issues

The below subsections address the general connectors and issues that are not particular to any single major component of the turbine, but are nevertheless critical to the structural integrity of the turbine.

5.5.1 General: bolts

Life-estimation process
Bolts can be found many places in a turbine holding critical components together. Towers are often fastened at flange connections by bolts, and these must be inspected, because bolt failure can result in failure of the entire turbine. Blades are also bolted to the turbine's hub, and their failure can lead to either throwing a blade or failure of the entire turbine. Different bolt connections in the turbine have different accessibility, and so a blade bolt joint can be much more difficult to inspect, control, and repair than e.g. a tower flange connection. Their life estimation must be based on inspection in conjunction with the component that is bolted.

The photo shows a fracture surface with the characteristics of fatigue. Fatigue occurs when a material is subjected to cyclic loading and visually resulting in the characteristic beachlines and final rupture

Failure modes and their impact

Typical failures include
- Fatigue damage
- Overload fracture
- Hydrogen embrittlement (with corrosion or manufacturing processes as the source of hydrogen)

These failure modes must be addressed through the proper selection of corrosion protection and the right type of bolt and tightening torque to hold the load.

Material inclusions, such as particles, can initiate cracks sooner under varying loads. This represents the common failure mode and one of the most critical causes for fatigue-crack propagation.

The presence of pre-cracks in the galvanized layer or inside the surface layer is also a cause of bolt-fatigue damage. The concentrated stresses are in the boundary layer between the galvanized layer and the bolt's Fe (Ferrous) surface. For an increasing number of cycles, the pre-crack develops into the material and provokes structural damage.

The bolt's deformation initiates fatigue cracks, as do corrosion, rust effects, removal of the painted thick layer, etc., which can affect the pre-stress condition and increase dynamic loads. The pre-stress condition (under-stress, over-stress) is a determining factor in fatigue damage to bolts.

Crack propagation leads to bolt-fatigue failure, which can lead to a chain reaction on other bolts and seriously risk the complete bolted connection. If cracks are identified in time, bolt replacement is inexpensive.

A pre-torqueing check may not be sufficient. Bolts must be removed for visual inspection and detection of rust, corrosion, deformation, and fatigue damage. Bolts can be greased before refitting in the bolt connection.

Potential mitigating actions

At the end of the turbine's design life, an assessment of the bolts' remaining lifetime may include the following points.
- The bolts' remaining fatigue life.
- The bolts' corrosion protection may be failing or degrading.
- Localised corrosion may act as stress raisers for crack initiation.
- Incidents may lead to suspicion of the bolts' inferior performance, e.g. insufficient corrosion protection followed by repair work at an early stage.

Recommendations for further research and development

Investigate the coating of bolts that ensures high fatigue and corrosion strengths.
Use condition-monitoring methods for the pre-stress condition and loads on bolts (e.g. load cells, strain gauges).

Corrosion inside a wind turbine

5.5.2 General: weldings

Generally, the same procedures described in section 5.3.1 can be applied.

5.5.3 General: corrosion

Life-estimation process

The degradation of paint systems on steel will lead to corrosion, if dehumidifiers or other means such as cathodic protection are not used.
Submerged structures, such as foundations, are more prone to corrosion than others are; therefore, the externals and internals of substructures like monopiles and jackets must be inspected to quantify the degree of material degradation caused by corrosion and its impact on lifetime. Other elements, such as bearings, are also affected by corrosion; movement in bearing seats leads to fretting corrosion. This depends on the extent of the movement, the surface structure, and material type of the bearing seat.

Failure modes and their impact

Corrosion will reduce the thickness of steel and introduce notch factors. This will lead to less static and fatigue strength of metallic structures, such as offshore substructures, the transition piece connecting the tower, etc.

On surfaces such as blade bearings, corrosion can lead to considerable wear on seals. Fretting corrosion at bearing seats can create high notch factors in the main shaft. It can also cause extensive play in bearing seats, at main bearings, and in gearbox bearings. Generally, the corrosion of metallic structures can lead to higher maintenance costs.

Potential mitigating actions

Visual inspection can be done on structural steel and aluminium. Based on the inspection, impact analysis on the strength can be performed.

Bolts must be disassembled to check for possible corrosion. A sample check is sufficient. Fretting corrosion cannot be checked. A database for the turbine's disassembled components is required. If cracks occur as a result of fretting corrosion, they can be found by axial ultrasonic check into the main shaft.

Recommendations for further research and development

The foundation's corrosion protection relies on the performance of the cathodic protection system and the coating condition. This should be evaluated using cost-effective surveys and/or a close review of historical data from inspections or monitoring devices to assess the possibility of life extension.

5.6 Health and safety

5.6.1 Non-destructive testing

Old turbines will need to be inspected, maintained, and repaired as inexpensively as possible while continuing to prioritise health and safety. Because the spot price of electricity may be low, turbine owners may not find it economically viable to implement expensive inspection techniques. Nevertheless, NDT is a common practice encompassing all measuring and inspection techniques that do not require the test specimens to be destroyed. Several cost-effective inspection techniques, such as ultrasonic and eddy current, are some of the best inspection methods for in-service turbine inspection.

For example, ultrasonic inspection can be used to inspect bolt cracks, delamination in the blade, and cracks in mainframes.

Ultrasonic methods, can be combined with advances such as phased array, and automatic inspection for data acquisition and storage. Eddy current is a good method for weld and HAZ inspection of cracks without the necessity of removing the surface coating. Other methods include acoustic emissions and infrared scanning.

5.6.2 Risk assessment

Risk assessment concerns the risk posed to people, buildings, industrial complexes, etc., by a turbine failure. Developing a proper risk assessment tool will require methods for calculating the probability of complete or partial structural failure, the consequences, and acceptance criteria, along with the likelihood of an impact from the throw of debris from the failed turbine.

5.6.3 Repair

Turbines will fail, and repair will be required throughout the turbine's lifetime. It is important that decision rules are applied so that damage can be detected early, preventive maintenance can be performed, and reliability requirements can be satisfied. This will indicate which repairs and maintenance are needed and how the repair must be performed.

5.7 Economy

Deterioration models for different components, including uncertainty modelling, are essential to both risk assessment and economic-impact estimation. Models for damage accumulation with time must be developed as a decision tool for repair and maintenance. Specific models to represent the fatigue damage of different materials and their types of deterioration are important for setting up requirements for inspection intervals. Experience from bridges and the oil and gas industry can be used.

Information from CM and SHM can be used with turbine surveillance. Reliability assessment should recognise that some information must be considered as indicators with uncertainty.

The conditions affecting wind-farm sites change over time. Changes may include additional wind turbines or changing obstacles, such as trees and buildings. Therefore, original assumptions made during the site-evaluation process might no longer be valid. For example, the load level might have been under- or overestimated. A measurement that uses undisturbed wind quantity measurement for each turbine could be used to allow an environmental condition, based on the turbine's operation. For example, based on a combination of wind speed and turbulence intensity measured sectorwise, a strategy could be established to avoid curtailment strategies or the load level to increase the turbine's lifetime.

Another step would be to use an undisturbed wind speed and turbulence intensity sampled during the last quarter of the turbine's lifetime. Having this information and comparing it with previous SCADA wind statistics could make it possible to estimate with some confidence the


Courtesy of Siemens Wind Power

Safe climbing exercises

previous stress level and to estimate the residual turbine/component lifetime. The longer the measurement period, the higher the confidence level for the estimation of the residual lifetime.

Integrate CMS information of different systems (blade, drive train, converter) with SCADA turbine control data. The same approach used for wind speed can be used.
For example, based on a combination of wind speed, turbulence intensity, and CMS indicators, a strategy could be established to avoid curtailment strategies or the load level to increase the turbine's lifetime.

5.8 Optimisation of O&M

Operational and maintenance can be based on condition monitoring data acquired from the wind turbines whereby needed maintenance to different components can be planned well before failure of the component and taking into consideration weather windows and revenue from electricity production. Such a framework of optimizing the maintenance activities is very much needed to lower operational costs.

Condition monitoring

Condition monitoring (CM) could be installed for systematic data collection and evaluation to identify changes in the turbine's structural parts, so that remedial action could be planned to maintain reliability in a cost-effective manner. Many failure modes have measurable responses and develop over time. These are the ideal applications for condition-based maintenance (CBM). CM can provide early warning of potential failure, if the measurement parameters are correctly chosen and measured with accurate sensors. Analysis of valuable information from CM can be used to plan maintenance, and variations can be managed as needed.

When used to drive reliability improvement, CM offers diagnostics, information, and data for root-cause analysis and equipment redesign, along with verification of defects or design correction. CM applied proactively embraces world-class reliability maintenance concepts when using CBM.

Structural life cycle asset integrity management

An effective and integrated integrity-management approach for optimum asset return through a turbine's various life cycles would be crucial to success. It would be a key enabler to visualising the connectivity between system and component reliability and translate it into:

- ongoing updates to operating risks;
- ongoing updates to the expected remaining life, based on measured information;
- ongoing updates to changes in the inspection/condition monitoring/maintenance programme;
- ongoing updates to/need for operational changes;
- ongoing updates to new experiences across asset life cycles and performance standards;
- ongoing updates to the level of compliance with the governing technical requirements and legislation;
- technical connectivity and visibility between the design and installation premises and the operating condition.
- It would serve the operator with the application of the best-practice design and sound operational performance standards.

Reliability-based optimisation of operation and maintenance

A database could be installed for the systematic utilisation of failure data from different turbine components to better identify commonalties of dominant degradation characters, and so allow reliability-based planning of inspection and monitoring activities. Such a database could serve as key enabler for the optimisation of Life Cycle Cost to Life Cycle Time.

As the typical failure mechanisms have identifiable and measurable characteristics that develop over time, it serves as a key enabler for the CBM and inspections already proposed in this document. For example, the proposed CBM programme provides early warning of potential failure. Complementing that, the reliability database provides an understanding of potential systemic failures and helps account for that, either in the design process or in necessary planned repairs.

Thanet Wind farm, Courtesy of Vattenfall

Appendix

Danish Wind Turbine Certification Scheme

Turbine		**Inspection date**	
Manufacturer		**Installation date**	
Type		**Type of inspection**	
ID No.		**Fitter ID**	
GSNR No.			

1. Blade	PLEASE TICK
Personnel basket	
Suspended platforms/hoists	
Abseiling	
Telephotos	
Blade bearings	

Manufacturer, type	
All observations are documented with photos.	
Blade No.	Observation

2. Machine frame	PLEASE TICK
Welded	
Integrated	
Assembled with bolts	

All load-bearing welds inspected visually	
All observations are documented with photos.	

3. Main shaft	PLEASE TICK
1 main bearing	
2 main bearings	

Surface protection must be intact. No rust! All observations are documented with photos.	

4. The yaw bearing ring	PLEASE TICK
Ball bearing	
Sliding bearing	
Passive yaw brake	
Active yaw brake	

Backlash in the bearing controlled Yaw brake function checked All observations are documented with photos.	

5. Tower	PLEASE TICK
Tubular tower	
Lattice mast	
Number of segments	

All welds in tower inspected visually. All observations are documented with photos.	

6. Bolts assembly	All observations are documented with photos.
Shall be 10% of the bolts in each assembly. If there is pitting on nuts and bolts, then all bolts must be checked and defective bolts replaced.	
1. Tower Assembly	
2. Tower Assembly	
3. Tower Assembly	
4. Tower Assembly	
Top-flange/nacelle	
Blade/hub	
Blade/blade bearing	
Blade bearing/hub	
Blade/blade extension	
Blade extension/hub	
Hub/main shaft	
Main bearing/machine frame	
Machine frame/generator console	
Machine frame/yaw bearing	
Yaw bearing/top-flange	

7. Foundation	Please tick
Embedment	
Foundations bolts	
Concrete slab	

All observations are documented with photos.	
Cracks in concrete	
During casting	
Sealing	

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