Chapter 16
Durability and Performance of Wind Turbines Under Climate Extremes

Rui Teixeira, Alan O'Connor, and Dimitri V. Val

Abstract This chapter discusses the impact which durability considerations and climate extremes play on the performance of wind turbine structures. An overview of the technological developments in wind energy production, both onshore and offshore, is provided. The rigorous design requirements and specifications, guidelines and codes of practice prescribed for design are discussed. The basis for computational simulations, necessary to model and assess performance is outlined. Characterization of extreme values is discussed and the impact of climate extremes on environmental loads is demonstrated. The impact of deterioration, in the context of the durability of wind turbine towers is evaluated in terms of the probability of exceedance of specified limit states. Finally, discussion is provided around optimal decision-making regarding design, operation and maintenance.

16.1 Introduction

The demand for renewable energy is unquestionable. Global climate trends have highlighted the need for renewable, low carbon-footprint technologies, and wind energy is one of the most prominent alternatives to conventional fossil fuel energy conversion. The fact that wind depends on the Sun, makes it a virtually infinite source of energy.

According to Frick et al. [17], approximately 2.5% of the total solar energy incident on the outer layer of the earth's atmosphere is transformed into wind energy. This equates to an overall wind power of approximately 4.3×10^{15} Watts or an

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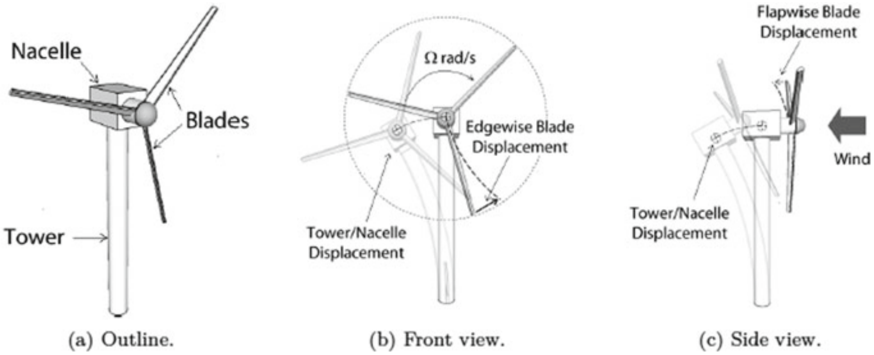
equivalent annual energy resource of 3.8×10^7 Terrawatt hours (TWh). Technically, there is more energy provided by the wind than could ever possibly be required. As a result, wind energy has experienced an exponential growth in installed power since the beginning of the current century. In particular during the last decade, the increase in the development of wind energy has been substantial. While this growing trend is expected to continue, further growth of the sector imposes more demanding, complex and accurate engineering analyses that need to enclose not only considerations of the in-service performance of turbines, but also of the impact of climate change on these.

Although various types of wind turbines have been tried and tested over the years, the wind energy industry appears to have settled on one particular design, the horizontal axis wind turbine (HAWT). This was determined as the most reliable, cost effective and straightforward solution, which currently accounts for practically every megawatt of global installed capacity. Figure 16.1a illustrates a basic outline of these machines. An electric generator, located inside the nacelle, is driven by a rotor shaft connected to a set of aerofoil blades. While some designs have been known to operate with one or two blades, the current standard is predominantly a three-blade design. The rotational kinetic energy of the rotor shaft is generated by harnessing the aerodynamic lift force as the airflow interacts with the aerofoil profile of the blades. This is the same principle which allows aircrafts to fly. In order for the blades to be positioned within the airflow the turbine must be elevated into the air by a support structure, a tower. The height of the tower is dependent on the particular turbine design (mainly, on the length of the blades), and the advantages of an increased blade length and elevation off the ground surface are well documented. In the present, blades that span longer than 100 m are being produced and towers for wind turbines with such blades are typically over 150 m. Hub heights that can surpass 250 m may be reached in some offshore wind installations.

By their nature, wind turbines are machines that exhibit particularly complex dynamic behavior. The continuous rotation of the blades within turbulent aerodynamic loading induces a variable reaction from the system. This is further accentuated by the flexibility of the blades, tower and other components. As the size of these machines increases, the magnitude of the dynamic response increases as well.

The primary dynamic effects observed in wind turbines are illustrated in Fig. 16.1b, c. In-plane bending of wind turbine blades is shown in Fig. 16.1b. This motion can be referred to as “edgewise” vibration, although some authors may use the term “lead-lag” vibration. Out-of-plane blade bending can be seen in Fig. 16.1c. This can be referred to as “flapwise” vibration, although the term “pitching” vibration is sometimes used in the literature. As blades extend to considerable lengths, the effect of blade torsion is also an important consideration in the blade design. The lateral and longitudinal vibration of the tower is also displayed in Fig. 16.1. Further dynamic effects include nacelle tilt, roll and yaw.

In recent years progressively more wind turbines have been installed offshore. As a reference, the European Union (EU) plans to reach 70 GW of installed capacity for offshore wind by 2030. In the case of offshore wind turbines (OWT), the contribution and role of engineering practices and procedures for cost reduction and reliability



(a) Outline. (b) Front view. (c) Side view.

Fig. 16.1 Outline of wind turbine components and dynamics [47]

enhancement is significant. In fact, IRENA [28] highlights that innovation in wind turbine design and operation has been a key driver for competitiveness in the wind energy sector. Iván et al. [30] identifies that research, along with a regulatory framework, are expected to be the key drivers of development for offshore wind up to 2050. In this context, while improvement of the techniques applied in the wind energy sector are in high demand, the development of innovative practices is no less important to enable the sector to become progressively more competitive.

Figure 16.2 shows that despite the significant developments in the two last decades, the Levelized Cost of Energy (LCOE), i.e., a ratio that includes the operational lifetime costs and divides it by the benefit of energy production, for OWT installations is just now achieving the level of economic competitiveness of conventional alternatives used for electricity production (e.g., fossil fuels). Wind, nevertheless, is one of the most powerful energy resources available on earth.

In the last decade, scale-up of wind turbines has been a major driver of economic competitiveness for the sector. Larger turbines mean more installed capacity and access to a larger resource, which contributes to amortize the project development costs faster. In this context, increases in the size of blades and tower height have been a major driver to decrease the LCOE for wind turbines [28]. The fact that the technological solution to harness the wind power is well established enables the sector to improve competitiveness through scale-up. Larger turbines, however, present increased challenges in engineering design.

An area of particular focus is the need to address uncertainty in the analysis and design of wind turbines. By enhancing the characterization and understanding of uncertainties, the sector can move towards more robust and optimized designs. Uncertainty characterization unlocks a new dimension of comprehension in design. Perception of the potential deviations experienced by the design variables enables a more complete understating of the risks associated with the operation of wind turbines [52].

Taking into account uncertainty in the design process is usually facilitated by probabilistic analyses. A brief evaluation of the standards for designing wind

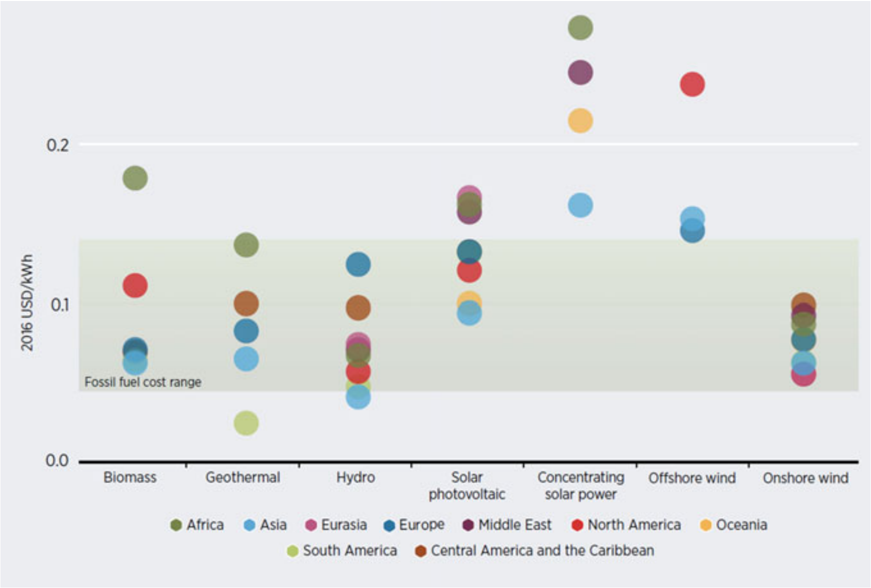


Fig. 16.2 Levelized Cost of Energy (LCOE) for different sources of renewable energy divided by region, IRENA [28]

turbines (IEC 61400 class) or other recommended guidelines, such as DNV GL guidelines [12–15], shows that assessing uncertainty is a recurrent procedure inside the design chain. Nonetheless, only limited research has been developed so far in addressing some important future sources of uncertainty, such as climate change.

With regard to the wind turbine structural performance, some components are not allowed to fail; or more exactly, in the context of the probabilistic approach, the target annual probability of failure for such components is low -10^{-4} (or 10^{-5} when failure can endanger personnel) [14]. For other components, which are less important to maintain a functioning a wind turbine (i.e., their failure does not cause the loss of the turbine or its inability to operate for a long period of time), the target probability of failure may be higher. In principle, when failure of a component does not represent danger to personnel and/or the environment, the target safety level of the component can be determined from purely economic considerations. This distinguishes two levels of relevance for the system's survivability per component—critical and non-critical.

The critical components account for most of the turbine cost breakdown. These are key structural elements of large dimensions, such as blades and tower. Failure of one of these elements usually results in either total loss of the system or prolonged disruption of its operation. The blades and tower alone account for more than 40% of the cost for a 6-MW wind turbine [5]. At the same time, according to IRENA [28], turbines comprise 64 to 84% of onshore, and 30 to 50% of offshore, wind energy projects costs. Foundations alone may account for 20% of the project total cost. Therefore, design optimization and improvement of these critical components is essential for further reduction of the LCOE for wind energy. This should be done by taking into account impacts of climate change, in particular its extremes, which may affect both durability and performance of wind turbines.

16.2 Design Requirements

Design of wind turbines is regulated by different standards and support documents, which specify a set of requirements for the design. The most widely accepted standards are those of the International Electrotechnical Commission (IEC) series 61400, which are complemented by other standards, such as Det Norske Veritas—Germanischer Lloyd (DNV GL) standards and recommendations, and the International Organization for Standardization (ISO) standards.

The IEC [26] sets the requirements for the design of onshore wind turbines, while IEC [27] does so for offshore wind turbines. There are overlaps between these standards. There are also many references in IEC [26, 27]. Furthermore, it is also common for IEC [26] to direct some of more detailed requirements regarding the design to other standards such as the ones published by the ISO. Due to the inherent complexity of the design, the terms such as appropriate, reliable, or adequate are also frequently used in the standards. This implies that different techniques may be used in the design process if these are ensured as appropriate.

Regarding the design for operational conditions, two major issues can be highlighted: the loading and the response. In the scope of the loading are included the variables which are going to induce loading on a wind turbine, including their interaction with the system. Furthermore, changes in the loading profiles as a result of factors such as climate change should be considered. All aspects of the analysis which concern the response of a wind turbine to the loading variables, including durability-related effects, are in the scope of the response.

Figure 16.3 shows a simplified representation of the loading, response, some pivotal engineering concepts, and their interaction [52]. Within the loading scope are also different environmental conditions that will interact with the system. These manifest in loading through hydrodynamics (for sea conditions—OWTs only), aerodynamics (for wind conditions), and other external environmental or non-environmental conditions which generate additional types of physical interactions (e.g., ice loading, vessel loading), and their coupled behaviour.

The response tackles the analysis, as the name indicates, of the system’s response and its dynamics. Most of the analysis addresses the response of the system and its reliability. For design purposes, structural response is usually assessed in the context of two types of ultimate limit states: ultimate strength and fatigue. The “feedback" from the structural response is what affects the electrical response, e.g., production of energy. The control and protection system overlaps both knowledge areas and their interactions.

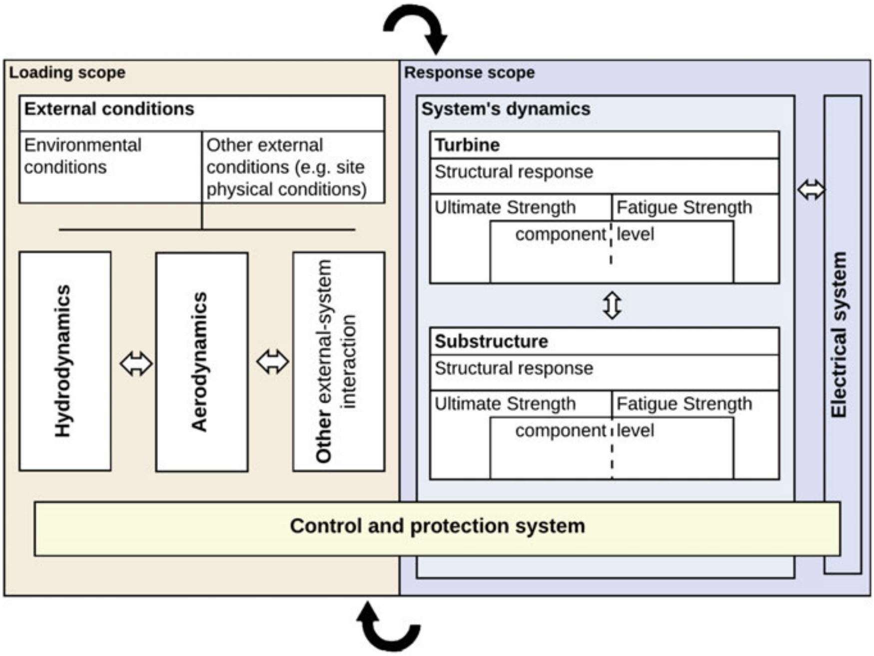


Fig. 16.3 Design interaction of the loading and response for OWT operation regimes [52]

IEC [26, 27] recommends to base the structural analysis of wind turbines on ISO [29], indeed, many wind turbine design standards are built upon relevant ISO standards. DNV [14] presents an organized structure of assumptions for the design of OWTs, but also with many references to the ISO standards. DNV GL also offers a range of guidelines such as DNV [13, 15] for the design of offshore structures, which are of relevance to OWTs.

In order to produce robust designs, the IEC 61400 defines a set of Design Load Cases (DLCs), which represent various operational scenarios for the purpose of design. Each DLC is a set of operational conditions, which may occur during the lifetime of a wind turbine.

Among the DLC events, which must be analyzed, are environmental conditions represented by Normal Wind Profile (NWP), Normal Turbulence Model (NTM), Extreme Wind Model (EWM), Extreme Turbulence Model (ETM), Extreme Coherent Gust With Direction Change (ECD), Extreme Wind Shear (EWS), Extreme Operating Gust (EOG), and Extreme Direction Change (EDC). The DLCs are configured to simulate a variety of situations including normal power production, power production with a fault occurrence, a startup event, normal shut down, emergency shut down, parked conditions, parked with a fault, and transportation. Some of the faults, which are common to wind turbines, include a control system failure, electrical faults, and the loss of the electrical network connection. Within the load cases, both ultimate and fatigue loads are included. Furthermore, it is clear that climate change may affect the probabilities and, thereby, return periods associated with environmental loads.

While a wind turbine must be capable of resisting the most extreme wind conditions for the ultimate limit-state (ULS), it is often the fatigue loading of the turbine which dictates the design. Hau [22] states that wind turbines are the perfect fatigue machines, owing to the considerable variability of the wind loads and the necessity for a highly elastic structure due to their size. Pedersen et al. [42] notes that turbulence in the inflow has the primary influence on fatigue damage accumulation in upwind turbines. Thomsen and Sørensen [55] investigated the fatigue effects on a wind turbine operating in wakes. Since wind turbines are generally located in clusters or wind farms, this is an important consideration in the design. It was shown that the increase in the fatigue loading in a wind farm could vary between 5 and 15% compared to free flow conditions, depending on the wind farm layout. It was also found that the increase of fatigue loads caused by wake effects was the same for both offshore and onshore sites. Wind turbine interaction within a wind farm has become one of the most relevant topics in the research of wind energy. It is noted that despite always being a recurrent concern in the design, just recently, the paradigm of the sector has started to move from individual machine analysis to coupled interaction assessment in windfarms.

As noted previously, OWTs are subjected to additional loading conditions which must be considered in the design, i.e., hydrodynamic loading. These additional marine induced effects such as, loads due to waves, sea and tidal currents, tidal fluctuation of the water level, sea ice, marine growth, seabed movement and scour, must be considered in the design. Given the random nature of waves, it has been suggested that their state is the best described by stochastic models. Considerable research has been conducted on the topic of stochastic wave modelling for OWTs [2, 8, 32, 35, 36]. BS EN 61400-3-1 [4] and DNV-OS-J101 [12] recommend to use spectral models for the simulation of wave states. One of such models, the Pierson-Moskowitz spectrum, is applicable to a fully developed sea state, while the JONSWAP spectrum is more suitable for a developing sea state, e.g., events such as storms. The correlation between wind and wave conditions must be also addressed [11]. As these conditions are affected by local site factors such as fetch, water depth and bathymetry, the determination of the parameters of the stochastic wave models must be made from suitable long-term measurements and allow for consideration of the effects of climate change, which may require the use of non-stationary stochastic models.

As a result of all the complexities that merge in the analysis of OWTs, the design standards for these need to be treated as dynamic documents, which build upon cumulated knowledge in the field. Often, new contributions to the standard improvement come from research. A representative example of that can be found in Cheng [9], where the author investigated extreme loads and concluded that the most significant operational loads for a pitch-controlled wind turbine occurred at mean wind speed values, slightly larger than the turbine's rated wind speed. To address this problem a methodology for robust design of such turbines accounting for extreme loading was introduced.

16.3 Computational Simulations

In wind turbines there is continuous movement of one main component of the system (the rotor) relative to the rest of its structure. The required flexibility of the turbine's blade and tower components coupled with strongly variable loading conditions (i.e., wind) makes dynamic analysis of such systems a complex problem, which still needs to be further investigated. Accurate dynamic analysis is essential for the design of wind turbines since it provides information about the interaction between the environmental loads and the structure and resulting internal dynamic forces within the structure. This information is obviously needed to design the structure, ensuring that it will be capable to withstand variable dynamic loads and operate effectively for the duration of its design life.

The behavior of wind turbine structures as they respond to the aerodynamic loads is termed aeroelasticity. This implies that the aerodynamic loads applied to the structure induce deflections, which in turn cause a change in the aerodynamic loads acting on the structure creating an iterative loop of varying loads and deflections. Since wind turbines generally have low structural damping they can suffer from aeroelastic instabilities under certain conditions. Aeroelastic phenomena such as, stall and flutter in wind turbines, are well documented [6, 18, 20, 21, 31].

The computational codes that analyze wind turbines are commonly referred to as aero-hydro-servo-elastic codes. The demand for these to be accurate is to some extent related to the fact that they show the potential to be significant enablers of further developments in the sector of wind energy. Major efforts to develop accurate aero-hydro-servo-elastic codes have been made since the establishment of the wind energy sector and resulted in the emergence of different codes to satisfy the necessity for simulation models. Current reference computational codes in the field of wind turbine simulation are FAST, HAWC2, GH Bladed, ADAMS and FLEX5. A brief overview of one these codes, FAST, developed by the National Renewable Energy Laboratory (NREL), is shown in Fig. 16.4.

One of the identified trends in the numerical simulation of wind turbines is the application of more complex computational fluid dynamics (CFD) and Finite Element (FE) techniques to the analysis the turbine's dynamic behavior. The application of both is expected to further increase the computational cost of the analysis of wind turbines, which is already rather high. Furthermore, the increasing size of wind turbines may also introduce significant non-linearities in the structural response due to larger deflections, which in turn may increase the demand for more complex modelling techniques such as the ones mentioned above. Furthermore, variation of the structural performance with time due to durability-related issues will add further complexity to the analysis.

Several publications have addressed the issue of the continuous drive to increase the complexity and, subsequently, computational demand associated with dynamic analysis of wind turbines [37, 41, 51, 53]. Keeping the computational efforts within reasonable bounds for the purpose of the wind turbine's design is important not only

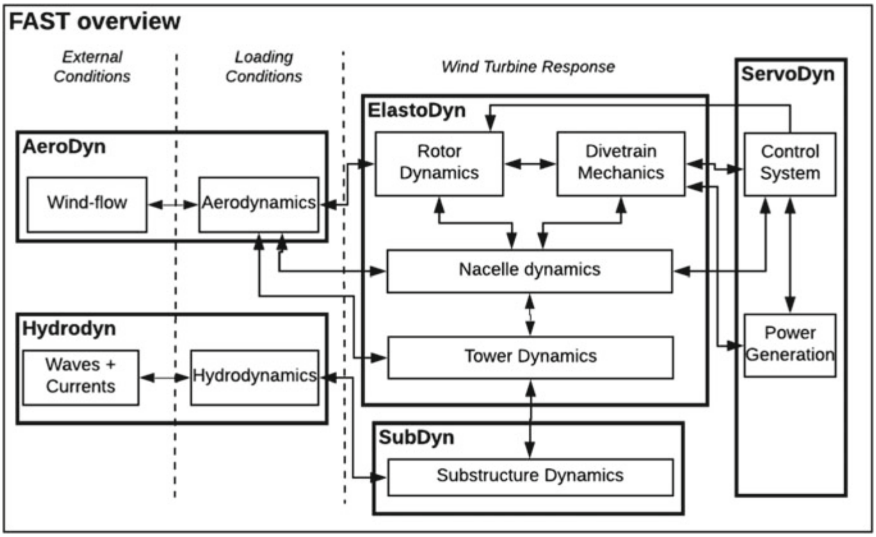


Fig. 16.4 NREL's FAST (v8) software overview [33]

for foreseeable future but at present as well. The design process often requires repetitive analyses of a wind turbine for the same operational conditions. For example, Moriarty et al. [40] performed 2 × 4725 computational simulations to achieve an accurate assessment of the response for two wind turbine configurations—stall and pitched controlled (i.e., 4725 simulations for each configuration)—in order to analyse extreme and fatigue loading in the context of a probabilistic approach. Despite the high number of total simulations, only 9 simulations were performed per wind condition, which was defined by the mean wind speed (between 5–25 in 1 m/s increments) and turbulence level (between 0.2–5 in 0.2 increments). Further refinement of the considered wind conditions may increase the number of simulations to be performed exponentially.

16.4 Climate Change Consideration for Environmental Variables

Consideration of environmental loads plays a major role in the design of wind turbines. It is well known that our environment is changing and along with it the frequency and severity of environmental loads to which wind turbines are subjected. In this context, two aspects of environmental loading, namely, wind fields and hydrodynamic loading are considered.

An important component of dynamic modelling is accurate representation of the turbulent wind field. This is a topic which had been addressed in publications long before wind turbines became prominent with applications for bridges and building structures [24, 50, 59]. The emergence of wind turbines and the direct influence of accurate wind modelling on structural, aerodynamic and power production calculations have inspired further research on the topic.

The wind inflow, V_0, may be represented by a stochastic wind model with a fluctuating component, $V'(t)$, and a mean component, $\overline{V}$, which includes the effects of wind shear, i.e., $V_0 = \overline{V} + V'(t)$. The effect of wind shear is accounted for in this case by the log law:

$$\overline{V}(Z) = \frac{1}{k} v_* ln \frac{z_s}{z_0}$$

where z_s is the height above the ground surface, $\overline{V}(z_s)$ is the mean wind velocity at height z_s, v_* is the friction velocity, k is the Von-Karman constant, and z_0 is the roughness length.

The fluctuating, or turbulent, wind velocity time-histories, $V'(t)$, can be generated using the Discrete Fourier Transform (DFT) method. Fourier coefficients are established from a specific Power Spectral Density Function (PSDF) as normally distributed random numbers with zero mean and standard deviation σ_i, where σ_i is equal to the area under the PSDF between the frequency limits f_i and $f_i + df$. The Kaimal spectrum as specified in Annex of IEC or BS EN 61400-1 [3] is used to generate a wind velocity time-history with a prescribed mean value of zero and standard deviation of 2.29 m/s (Fig. 16.5). This is a typical value for mean wind speeds of 18 m/s with low turbulence characteristics [3]. It is obvious that climate change will influence the statistical parameters associated with wind field modeling and that these should be considered in design, while the currently used values of the parameters are shown in Table 16.1 [47]. However, at present, there is still not enough

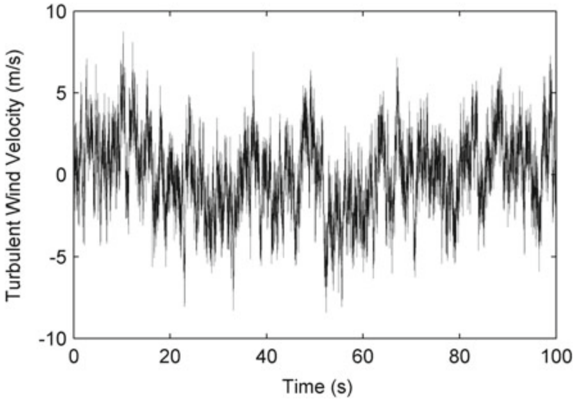


Fig. 16.5 Wind turbulence time history [33]

Table 16.1 Turbulence standard deviation at mean hub height wind speeds [47]

	Mean hub height wind speed, V (m/s)					
σ_1(m/s)	16	18	20	22	24	25
Low turbulence	2.11	2.29	2.47	2.65	2.83	2.92
Medium turbulence	2.46	2.67	2.88	3.09	3.30	3.41
High turbulence	2.82	3.06	3.30	3.54	3.78	3.90

evidence to properly predict the impact of a changing climate on wind characteristics in different regions of the world [57]. Prediction of climate change influence on wind speeds is a recurrent research topic and, due to the large uncertainty that is inherent to climate change, has generated significant discussion in the literature [19, 25, 34, 45]. A common trend that has been identified is for changes in the annual mean wind speed to be less pronounced, while inter annual variability is expected to increase. Effects of climate change are also expected to be highly local and provisions for such local dependence are needed for future wind turbine analysis and design considerations. Regardless, at the present, there is still not enough evidence to properly predict the impact of a changing climate on wind characteristics in different world regions [57].

Nonetheless, several studies sought to characterize the explicit evaluation of potential impacts of climate change on wind energy and wind turbines before. Pryor and Barthelmie [44] predicted that it would have limited influence in the sector, however, they did not explicitly discuss the sector-specific technical considerations related to the turbines. Recent research efforts have been directed to address this issue in more detail. Hdidouan and Staffell [23] highlighted the need for conducting further research related to climate change effects on the wind energy sector when they evaluated the LCOE for windfarms. Wilke and Galasso [58] also tackled this issue by studying structural components of wind turbines. They concluded that the effects of climate change were expected to be small for the structural components because these are highly reliable, i.e., having very low probability of failure. Moreover, being the long-term operation costs of wind turbines mostly driven by non-structural elements. Nonetheless, the authors showed that environmental parameters influenced the loading on wind turbines. In this regard, only a limited number of studies have been found that tried to infer explicitly on how climate change scenarios may impact wind turbines at the system and component levels (in the response side as described previously), such as the influence on the Design Load Cases (DLCs), or other structural considerations. There is some agreement in the literature that regarding the environmental parameters, climate change will mainly affect the intensity and frequency of the extremes. Thus, further research may be required to investigate the extent of the climate change influence on the wind turbine durability and performance. This is particularly relevant for structural components that are highly influenced by extreme loading. An example of such can be identified in extreme loading and its large influence in the fatigue of composite material structural components [51, 53].

For the case of wave height, the need to characterize extreme waves using field data dates back to the 1960s, where a “design wave” was characterized using full records of data. Since then, the topic of extreme wave or “design waves” has been under discussion and possibly will remain so for decades to come. In the present it is common to use only exceedance data for this.

Currently, several standards and practices are found to guide the design of offshore structures. While some of them present generic considerations related to the definition of the significant wave height (H_s) occurrences, e.g. emphasizing the need for reliable and robust estimations, other standards/guidelines provide specific recommendations about the techniques for modeling H_s. DNV GL recommended practice on environmental conditions and loads, DNV [15], accepts the use of different approaches.

If H_s is a random variable with maxima m_{H_s}, then for all $u < m_{H_s}$, the function

$$F_{x_{Hs},u}\left(x_{H_s}\right) = Pr\left[(H_s - u) \leq x_{H_s} \middle| H_s > u\right], x_{H_s} > 0$$

can be used to model exceedances of H_s, x_{H_s}, over a certain threshold u. This function represents the cumulative function over values exceeding the threshold u, which can also be defined as:

$$F_{x_{Hs},u}\left(x_{H_s}\right) = \begin{cases} \frac{F\left(x_{H_s}+u\right)-F(u)}{1-F(u)}, if x_{H_s+u} > u \\ 0, if x_{H_s} \leq u \end{cases}$$

a normalised representation of $F_{x_{H_s},u}\left(x_{H_s}\right)$. Analysis of x_{H_s} comprises the definition of a subset of $H_s > u$. Pickands III [43] showed that the limit probability distribution of this subset approached a Generalized Pareto (GP) distribution [52], and an application of this approach to modelling of exceedance of wave data and characterization of extremes is now discussed.

It considers wave data recorded by Met Éireann at four different buoy locations around the Irish Coast, Fig. 16.6. The records started in 2000 and ended in the year 2015. These are then used to extrapolate data using only exceedances. Usage of exceedances allows to increase the accuracy of the extrapolation in the region of interest (the tail region, where extremes are located) and definition of a cumulative density function to define extreme waves.

Different values of H_s with return period level T_r depending on u (=5.0 m) are shown in Table 16.2. The appropriateness of the threshold value as well as the return period estimation of H_s in the context of expected sea states considering the effects of climate change should be reflected upon in assessing appropriate design values for OWTs. The interested reader is directed to the referred work where further discussion and insight on approximation of extreme using exceedance data and other extreme value analysis is provided.

In design is important to emphasize the large uncertainties associated with extreme predictions. For future climate change prediction, as well as for present extrapolation

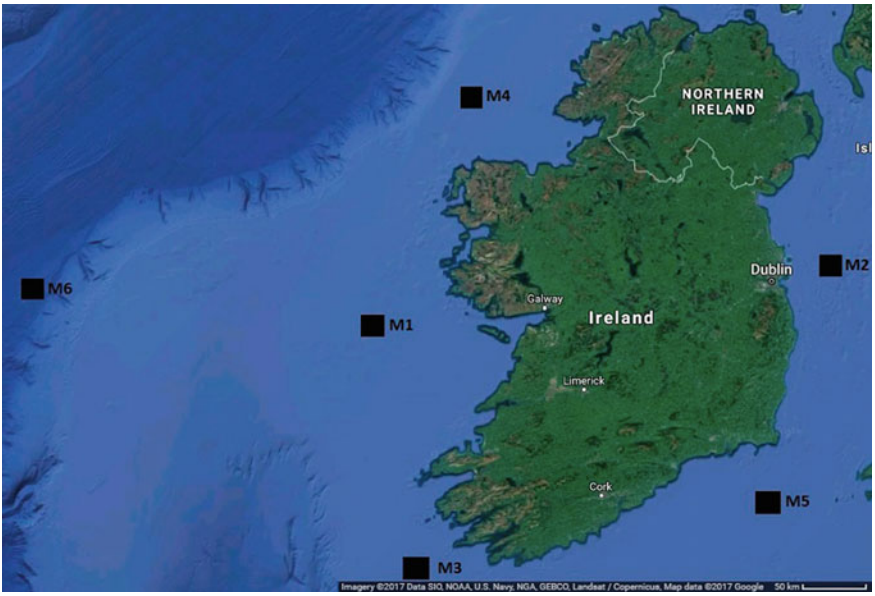


Fig. 16.6 Map with Approximate Location of Met Éireann Oceanographic Buoys [54]

Table 16.2 20-year and 50-year return levels of H_s [54]

Buoy reference	H_s	
	T_{r_20}	T_{r_50}
M1	15.58	16.73
M4	19.65	22.22
M5	12.42	13.75
M6	20.25	22.63

of climate variables, the designer should be aware that complex modelling techniques do not suffice for lower uncertainty in the estimations, and hence, any extreme value prediction should be accompanied by an appropriate uncertainty assessment.

16.5 Modelling Impact of Durability on Performance

As a means of considering the impact of durability on the performance of wind turbines it is proposed that fragility curves to be employed, relating wind hazard intensity to a considered limit-state, as a method for comparing the relative structural performance of the turbines. A displacement-based fragility curve generation procedure may be utilized, based upon performance metrics related, e.g., to nacelle (tower tip) displacement. The choice of the displacement limit-state reflects the stability of the tower structure and its ability to resist the prescribed loading conditions. Mean hub-height wind speed can be chosen as the fragility hazard parameter as it is quite straightforward and it dictates the underlying turbulent parameters of the wind speed.

The fragility term employed in the analysis may be represented as:

$$Pr\left[d_{tip} > LS \middle| \overline{V}_{hub} = \overline{V}\right]$$

where d_{tip} is the maximum nacelle displacement, LS is the tower limit-state, and $\overline{V}_{hub}$ is the mean wind speed at the hub height.

The proposed methodology has been employed to consider the performance of turbine structures manufactured from steel and pre-stressed concrete. The specific parameters of the modeled towers may be found in Quilligan et al. [46]. This methodology can also be applied to present the effect of the soil stiffness degradation around the pile foundations of wind turbines, which occur due cyclic lateral loading. This is relevant for both offshore and onshore wind turbines (e.g., [1, 60]). This phenomenon may have a major influence on the dynamic response of the turbines and also lead to an increase in their tilt and, subsequently, the maximum nacelle displacement.

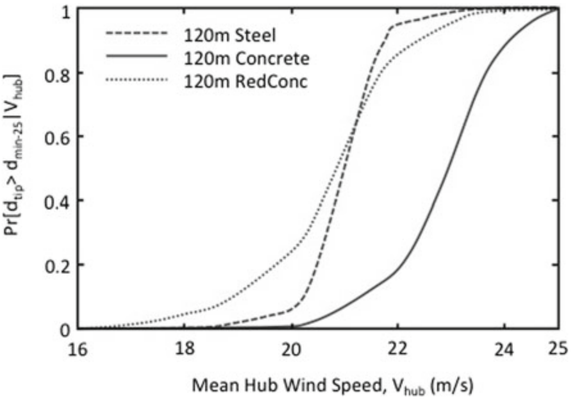
One of the main factors affecting the durability of wind turbines, especially of those located offshore, is corrosion. Corrosion may have a detrimental effect on both steel and reinforced/pre-stressed concrete, i.e., the materials used for the turbines' towers. Corrosion of steelwork is relatively easily detected and protection against it is well developed (e.g., Bayliss and Deacon [7]). While it can be controlled it is still has high impact on the costs of the structure maintenance. The same extends to the corrosion of reinforcing steel in concrete. The latter can be caused either by carbonation, which is a slow process that poses a very low risk to wind turbine concrete structures due to their relatively short design life (typically, 20–25 years), or chloride ingress. Since sea-water contains salt, chloride-induced corrosion is a major danger to the durability of concrete structures of OWTs. A large amount of research has been done on modeling the chloride-induced corrosion and risk associated with it (e.g., [56]). In the context of climate change, both corrosion initiation and propagation depend on ambient temperature and humidity. The effect of a change in the ambient temperature on the rate of chloride ingress and corrosion propagation is usually taken into account by introducing a correction factor, k_T, which value is estimated based on the Arrhenius equation:

$$k_T = \exp\left[b_T\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right)\right]$$

where b_T is a regression parameter, T_{ref} the reference temperature (293 K), and T the ambient temperature.

Any pre-stressed concrete towers of wind turbines would be also subjected to a number of effects, which can affect their performance and, subsequently, durability over time. Creep and shrinkage are two processes which must be considered in the long-term design of pre-stressed concrete structures and, therefore, of pre-stressed

Fig. 16.7 Fragility curves for 120 m steel and concrete towers [46]



concrete wind turbine towers. Both of these processes have the ability to induce tensile stresses, which may lead to cracking of the concrete and a reduction in the overall strength of the structure. Numerous efforts have been made by researchers, e.g., Cluley and Shepherd [10] and Mazloom [39], to quantify the effects of creep and shrinkage on the strength of pre-stressed concrete structures. Taking the approach outlined by Mayfield [38] and utilizing the formula:

$$J(t,t') = \frac{1+\phi(t,t')}{E(t')}$$

where $J(t,t')$ is the creep function, $\phi(t,t')$ is the creep coefficient, and $E(t')$ is the modulus of elasticity at age t', it is possible to get an estimate of the reduced modulus of elasticity of the concrete after loading for time t. Considering that $J(t,t')$ is the strain at time t due to a unit constant stress that has been acting since time t', it can be shown that $1/J(t,t')$ is an approximation of the modulus of elasticity at time t.

Figure 16.7 presents the computed fragility curves for 120 m high wind turbine towers constructed from steel (120 m Steel) and pre-stressed concrete (120 m Conc) [46]. The figure also shows the revised fragility curve for the pre-stressed concrete tower, which indicates a reduction in the strength due to long term effects associated with creep and shrinkage (120 m RedConc). Generally, the results indicate a higher probability of the limit state exceedance when the durability aspects and the impact for long-term performance are considered. Similar conclusions regarding the performance of steel towers as a function of variation in durability characteristics can be drawn.

Furthermore, the impact of durability on the fatigue performance of turbines may need to be considered, since in many cases fatigue is the controlling limit state.

16.6 Decision Making Regarding Design, Operation and Maintenance

As should be clear from above, reductions in the LCOE of wind energy can be achieved through innovations, more efficient, reliable and durable design solutions, and optimal planning of operation and maintenance (O&M). To implement this in practice, rational and consistent procedures for decision making regarding the design, installation and O&M of wind turbines are required. These procedures should take into account currently available information, data which can be collected during the operational life of wind turbines, and also uncertainties associated with this data. Bayesian statistical decision theory provides a solid theoretical basis for such procedures [48].

Based on this theory, a comprehensive decision procedure can be represented by a decision tree shown in Fig. 16.8. Possible design decisions/solutions are represented by the set $\mathbf{Z} = \{z_1, z_2, \ldots\}$ which, in order not to overcomplicate the decision tree, encompasses all decisions related to the initial design and installation. In principle, the design solutions can be optimized to eventually maximize an expected 'utility' $u\,(\mathrm{z}, e, s, a, \theta)$ associated with the operational life a wind turbine or, more generally, wind farm. The utilities are usually expressed in monetary terms as the difference between the total benefits and costs and depend on other factors, as should be clear from Fig. 16.8, which will be considered later. In practice, the design solutions are usually controlled by standards, e.g., IEC 61400, available resources and technologies. This emphasises the importance of continuous review and updating of the design standards, in particular, in light of climate change, since the optimality of the design solutions of wind turbines, to a large extent, depends on these documents. By the same reason, the search for optimal design solutions is often not included in the optimization process, which concentrates on optimizing the O&M strategies.

During their operational life, components of wind turbines deteriorate due to environmental loads and effects; possible deterioration processes include fatigue, corrosion, wear and erosion. In addition to uncertainties in load- and resistance-related parameters, there are large uncertainties associated with these deterioration processes. This means that possible states/conditions of wind turbines represented in the decision tree by the set $\boldsymbol{\theta}$, which include states of the turbine failure, are random

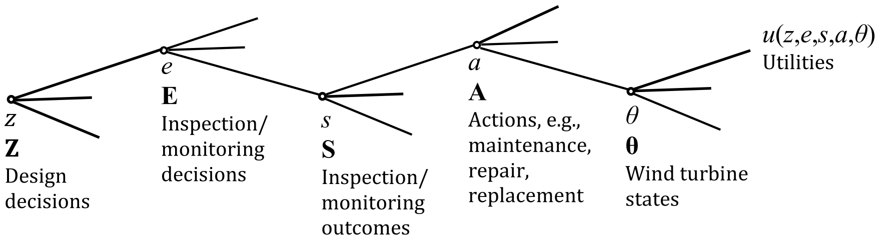


Fig. 16.8 Decision tree for optimal design and O&M of wind farms

in their nature. In order to reduce the probability of turbine failure, certain actions **A** (e.g., preventive maintenance, repair, component replacement) may be required. Such actions may be planned using only previously available information, which is employed to predict the effects of deterioration processes on the condition of wind turbine components. The probabilities assigned to the possible states in $\boldsymbol{\theta}$ are then called prior probabilities; $P'\left[\theta_j\right]$ is the prior probability of the j-th state. After setting utilities of all possible action-state combinations, u (z, a_i, θ_j), the expected utilities corresponding to different actions can be calculated as $E[u(z, a_i, \theta)] = \sum_j u\left(z, a_i, \theta_j\right) P'\left[\theta_j\right]$. The action, which results in the maximum expected utility, can then be identified. In Bayesian decision theory, this is referred to as prior analysis.

The prior analysis is not efficient, especially over a relatively long time horizon (e.g., over 5 years), since the prediction of the state probabilities becomes very inaccurate. To reduce this uncertainty, inspections of wind turbines should periodically be conducted. The outcome of an inspection, s, i.e., new information about the condition of the turbine components, is then employed to update the prior probabilities assigned to the turbine states based on Bayes' theorem. The updated probabilities, $P''\left[\theta_j | s\right]$, are called posterior probabilities. The decision making process is similar to that described above in the context of prior analysis except that the expected utilities are calculated using the posterior probabilities and the utilities also depend on the inspection outcome s. This is referred to as posterior analysis. It is important to note that in this case a decision whether or not to conduct the inspection is not included in the decision procedure.

The most advanced type of analysis that enables optimal planning of inspection/monitoring activities, which are represented in the decision tree by the set **E**, is the so-called pre-posterior analysis. This analysis involves simulation of the inspection/monitoring outcomes and then updating the prior probabilities of the wind turbine states based on these outcomes. The utilities are then also depend on possible combinations of (e, s). A framework for optimal planning of O&M activities for OWTs using pre-posterior analysis was proposed by Sorensen [49] and then extended by Florian and Sorensen [16] for offshore wind farms.

16.7 Conclusions

In this chapter, potential impacts of a changing climate on the performance, durability and, subsequently, analysis and design of wind turbines have been considered. It has been demonstrated that these impacts may be substantial and, therefore, need to be properly addressed. It is believed that this mainly should be done via updating relevant design standards and guidelines, in particular that concerns environmental loads (e.g., wind, waves) and conditions (e.g., temperature, humidity), as sufficiently reliable information on the impacts of climate change on these parameters become available. Since the design life of wind turbines is relatively short, usually 20–25 years, it is also believed that stochastic models of environmental loads and other climate-related variables (i.e., wind, waves, temperature, etc.) employed for their analysis and design can be treated as stationary. This means that relevant parameters of the models should be adjusted in accordance to expected effects of climate change averaged over the intended period of the turbine's design life, but to be considered as time-invariant in the analysis/design. Such a simplification seems well justified, since based on available evidence changes in climate-related variables over 20–25 years are usually not significant. The importance of consideration of aspects related to durability and deterioration in the context of assessing the probability of limit state exceedance has been demonstrated. Finally a basis for determining optimal decisions regarding design, operation and maintenance is provided. It is clear from the chapter that such a basis would be incomplete without adequate consideration of durability and the influence of climate extremes.

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