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Wind Energy and Noise

1.1 Introduction

Why write this book about noise generated by wind farms? Many people believe that wind farm noise is a non-issue and that people complain about it because they are unhappy with the lack of financial compensation they receive compared to their neighbours who are hosting the turbines. Other reasons that we often see on pro-wind-farm web sites are that the anti-wind-farm lobby has suggested a range of symptoms are caused by wind farms and that this suggestion has made some people living near wind farms develop these symptoms as a result: the 'so-called' *nocebo* effect. Although the authors of this book would consider themselves neither pro- nor anti-wind-farms, they have taken a sufficient number of their own measurements and spoken to a sufficient number of residents living in the vicinity of wind farms (including wind farm hosts) to appreciate that the character and level of wind farm noise is a problem for a significant number of people, even those who reside at distances of 3 km or more from the nearest turbine.

Although one chapter in this book is concerned with the effects of wind farm noise on people, the main focus of this book is on how wind farm noise is generated and propagated, the characteristics of the noise arriving at residences in the vicinity of wind farms, and measurement procedures and instrumentation, as well as assessment criteria that are necessary for properly quantifying the noise. As many people living in the vicinity of wind farms report 'feeling' vibration when they lie down, vibration generation, propagation and measurement are also discussed in sections in Chapters 4, 5 and 6.

To lay the foundation for the remaining chapters, the rest of this chapter is concerned with a description of how the wind industry has developed in various countries, followed by a brief history of noise studies (including a summary of noise levels generated by large wind turbines), a summary of some public inquiries and wind farm noise regulations, and finally a discussion of the current consensus on wind farm noise and its effects on people.

It is not possible to usefully take part in the wind farm noise debate without having some understanding of acoustics. This is the reason for writing Chapter 2 to follow. First, basic concepts in acoustics necessary for understanding the legislation are discussed. This is followed by a discussion of the fundamentals of frequency analysis, which is an important tool for analysing wind farm noise. Chapter 2 concludes with a discussion of

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Colin H. Hansen, Con J. Doolan, Kristy L. Hansen.

some advanced concepts of frequency analysis, an understanding of which is essential for practitioners wishing to undertake more advanced analyses of wind farm noise.

Chapter 3 contains an overview of how wind turbines generate noise, while Chapter 4 is about estimating wind turbine sound power levels. Chapter 5 is concerned with using turbine sound power levels and sound propagation models to estimate noise levels in the community. Several propagation models are considered, beginning with the simplest and progressing to the more complex and supposedly more accurate models. Chapter 6 is devoted to a detailed description of procedures and instrumentation for the measurement of wind farm noise and vibration, and includes a discussion of potential errors associated with such measurements. The chapter also includes a discussion on wind tunnel measurements for testing turbine models. Chapter 7 is about the effects of wind farm noise on people, Chapter 8 contains a discussion of various options that can reduce wind turbine noise, both outside of and inside residences, and Chapter 9 contains some suggestions of where we should be heading in terms of wind farm noise research and the reduction of its effects on people.

1.2 Development of the Wind Energy Industry

1.2.1 Early Development Prior to 2000

Mankind has harvested energy from the wind for over a thousand years. The first device designed for this purpose was a vertical-axis, sail-type windmill developed in Persia between 500 and 900 AD. This design appears to have been inspired by boats that used their sails to harness the wind for propulsion. Windmills have been primarily used for water pumping and grain grinding, with the mechanical power developed in the rotating shaft used directly to drive a pump or turn a grindstone. Wind turbines differ from windmills in that they convert the mechanical power into electrical power through use of a generator. They also have a smaller number of blades, since windmills require high torque at low rotor speeds (Manwell et al. 2009); for optimal electrical power generation higher rotor speeds and thus fewer blades are desirable. This is because high rotor speeds result in increased loading and reducing the number of blades reduces stresses on the rotor (Manwell et al. 2009). Another factor to consider is that wind turbine blades are very costly and therefore it is beneficial to minimise their number.

The most common wind turbine configuration that is used today is a horizontal-axis wind turbine (HAWT) and this book will concentrate on aspects of noise associated with this particular design, with a focus on large, industrial-scale wind turbines. The major components of a HAWT are shown in Figure 1.1. The basic principle of operation is that wind causes the blades to rotate and the rotor drives a shaft that is connected, generally via a gearbox, to a generator, which converts the rotational energy into electrical energy.

The power output and rotational speed of a HAWT can be controlled either by designing the blades such that they begin to stall at a certain wind speed (stall control) or by having a mechanism and control system that is able to vary the blade pitch (pitch control, which involves rotation of the blades about the blade axis as opposed to the rotor axis). In a pitch-controlled turbine, the controller will continually adjust the blade pitch to ensure that the power output is optimised for the wind speed being experienced by the blade. A pitch controlled machine can also be easily ‘turned off’ to protect the turbine when

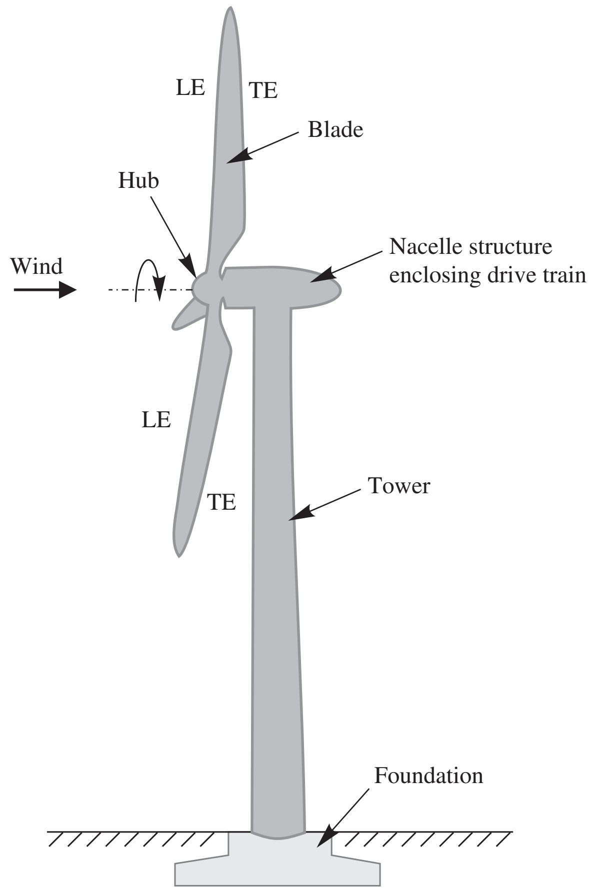

Figure 1.1 Schematic of typical wind turbine: LE, leading edge; TE, trailing edge.

the wind speed becomes too great. This is done by adjusting the pitch of the blades so that they no longer generate appreciable lift. A stall-controlled turbine blade is designed with some twist to ensure the blade stalls gradually along its length. The blade profile also has to be designed so that it stalls just as the wind speed becomes too high, thus reducing the lift force acting on the blade, which in turn limits the blade speed and power. An active stall-controlled turbine is similar to a pitch-controlled turbine in that the pitch is continually adjusted to optimise the power output. However, when the wind speed becomes too great, the stall-controlled turbine will rotate the blades so that they stall, as opposed to a pitch-controlled turbine, which rotates the blades in the opposite direction so that the lift is minimised. In some cases, turbines are also controlled using yaw control. This involves turning the rotor so the blades no longer face directly into the wind. However, this is only used on small turbines and is not relevant to the turbines that are the subject of this book.

Development of large HAWTs for incorporation into electric utilities first began in the early 1930s with the construction of the Balaklava wind turbine in Russia, which was 30 m in diameter, two-bladed and rated to a power of 100 kW. This turbine operated for around two years and generated 200 MWh (Sektorov 1934). In the late 1930s, development of the first megawatt-scale wind turbine began in the USA in a collaborative project between an engineer named Palmer C. Putnam and the Smith company, which was experienced in the construction of hydroelectric turbines and electrical power equipment. The Smith–Putnam HAWT consisted of a two-bladed rotor of diameter 53.3 m, mounted on a truss-type tower at a rotor-axis height of 33.5 m (Putnam 1948). This wind turbine was rated at 1.25 MW and included a number of technological innovations such as blade-pitch control, flapping hinges on the blades to reduce dynamic loading on the shaft, and active yaw control (Spera 2009). Several weeks of continuous operation yielded excellent power production and it was demonstrated that the wind turbine was capable of being inserted into the grid. Unfortunately, development was discontinued in 1945 when a faulty blade spar separated at the repair weld and there were insufficient funds to continue the project.

Over the next 25 years, development proceeded at a modest rate, taking place predominantly in Western Europe, where there was a temporary post-war shortage of fossil fuels that led to increased energy prices. Two HAWT designs emerged from Denmark and Germany during this time, and these would form the basis of future wind turbine development in the 1970s. The 24-m diameter, 200 kW Gedser Mill wind turbine was constructed in Denmark and was designed by Johannes Juul. The rotor consisted of three fixed-pitch blades that were connected with a support frame to improve structural integrity. This frame was removed in later years when the metal blades were replaced with fibreglass ones (Dodge 2006). The rotor was located upwind of the concrete tower and the design was notable for its simplicity, ruggedness and reliability. This wind turbine supplied AC power to the local utility from 1958 until 1967, achieving annual capacity factors of 20% in some years (Spera 2009). The annual *capacity factor* is defined as the ratio of the energy generated in one year to the amount that could be generated if the turbines operated continuously at their maximum power output. In 1967, a mechanical failure resulted in discontinued use of the wind turbine and the machine remained idle for the next 10 years (Auer 2013).

Considerable research effort, with a focus on improved rotor technology, led to the development of the Hütter–Allgaier wind turbine in Germany in the early 1960s. With a diameter of 34 m and rated at 100 kW, it was technologically advanced for its time and included an important design feature of a bearing at the rotor hub that allowed the rotor to 'teeter', in order to minimise the dynamic loading that results from the changes in gyroscopic inertia about the tower axis that arise when the blades of a two-bladed rotor move between the horizontal and vertical positions. A teetering rotor is illustrated schematically in Figure 1.2, which shows the bearing that facilitates the teetering motion. Despite its technological proficiency, the Hütter–Allgaier wind turbine encountered flutter in its long, slender blades, which slowed research progress.

Wind turbines were successfully connected to the grid in France in the period from 1958 to 1964 and the largest such turbine was called the Type Neyrpic, which was 35 m in diameter and rated at 1.1 MW. While this wind turbine demonstrated good performance, its operation was terminated abruptly when the turbine shaft broke.

In the UK, a number of unique 100 kW wind turbine designs were conceived and built in the 1950s with the intention of local grid connection. These turbines operated successfully for a few years, but technical and environmental factors led to the cessation of operations by 1963. Many projects were discontinued during this 25-year period due

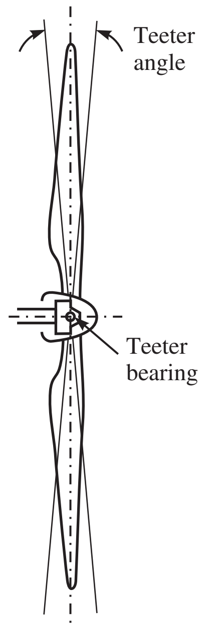

Figure 1.2 Schematic of rotor showing ability to teeter.

to technical issues and adverse weather conditions that resulted in expensive failures. These issues were not investigated further at this time due to a lack of interest in funding research into alternative energy sources, which was directly related to the availability of inexpensive fossil fuels and nuclear resources. Therefore, the Smith–Putnam wind turbine remained the largest in the world until the oil crisis of the 1970s prompted further development in the wind industry.

In the late 1970s, centres were established in Denmark, Germany and the Netherlands for testing of experimental and commercial wind turbines. These centres were also responsible for certification programs for tax or subsidy benefits to ensure that wind turbines met defined standards before entering the market. The International Energy Agency (IEA) was also established in the mid-1970s to encourage cooperation between Western countries on research, policy and development on wind energy. By the early 1990s, several countries had developed wind turbines with power ratings in the megawatt range, including Canada, Denmark, Germany, Italy, the Netherlands, Spain, Sweden, the UK and the USA (International Energy Agency 1989).

Canada pursued a different approach to most countries in the design and construction of megawatt-scale wind turbines, electing to focus on a Darrieus-type vertical-axis wind turbine. The Eolé Darrieus wind turbine was 64 m in diameter, 96 m in height, rated at 4 MW and was completed in 1987 (Richards 1987). Despite being rated at 4 MW, the power was limited to 2.5 MW to increase the lifespan of the turbine. The Eolé was connected to the Hydro-Quebec grid and it operated for over 30 000 h until 1993, generating over 12 GWh of electricity during its lifetime (Tong 2010). It was stopped due to damage to its expensive lower bearing.

Wind turbine development in Denmark proceeded at a modest rate and the size of turbines increased incrementally (Gipe 1995). Two upwind prototypes with a rated power of 630 kW, called Nibe A and B, were constructed in the early 1980s based on a similar design concept to the Gedser wind turbine. Nibe A was stall-controlled whereas Nibe B was pitch-controlled (International Energy Agency 1989), thus enabling a performance comparison to be made between these control mechanisms. The prototypes operated for 15 years, providing a wealth of information that contributed to later development of the wind industry in Denmark (Spera 2009).

The 54-m diameter, 2 MW Tvind wind turbine was a three-bladed downwind machine built by teachers and students from the Tvind school who collaborated with consultants, sub-contractors, volunteers and experts such as Professor Ulrich Hütter. Hütter's influence was evident in the choice of a downwind design (turbine blades downwind of the support tower) and the advanced blade technology. It was later discovered that the downwind configuration resulted in excessive low-frequency noise generation, as will be discussed in Section 1.3. The combination of design principles incorporated into the Gedser-type wind turbines such as the upwind, heavy, three-bladed, asynchronous generator and Hütter/Tvind advanced blade design and root assembly led to a successful combination that influenced future wind turbine development (Maegaard 2013).

In 1982, Germany embarked on an ambitious project to build the 100-m diameter Growian wind turbine, rated at 3 MW, which was the largest HAWT at the time. This wind turbine was a two-bladed downwind machine, which incorporated some of the latest technological innovations including full-span pitch control, carbon filament blades, a tubular steel tower and variable-speed operation. These features would later prove to be successful, but the overall design was over-ambitious for its time and was soon dismantled. In 1991, the 3 MW Aeolus II wind turbine, with a diameter of 80 m, was developed as a collaborative project between Germany and Sweden. In this two-bladed upwind design, advanced blade technology enabled a reduction in weight from 22 tons (existing Swedish Aeolus) to 6 tons (International Energy Agency 1989).

The two-bladed, 1.5 MW Gamma 60 upwind turbine constructed in Italy in 1991 was distinctive for its active yaw control, which provided a means of power regulation above rated speed. The 66-m diameter Gamma 60 design also incorporated a teetered hub as well as a direct current link between the synchronous generator and the step-up transformer. The innovative features of this wind turbine contributed to increased annual energy production, as well as eliminating control components on rotating parts to reduce complexity, thus decreasing manufacturing and maintenance costs (International Energy Agency 1989).

In the Netherlands, development was focussed on the 0.2–1.0 MW range and a number of demonstration projects were initiated by utility companies. The 1 MW NEWECS-45 wind turbine was developed in 1986 and consisted of a 45-m diameter rotor in an upwind configuration. The rotor design consisted of two-blades on which full-span pitch control was implemented and the tower was constructed from tubular steel.

Collaboration between Germany and Spain led to the successful development of the AWEC-60 wind turbine in 1989, which was a 1.2 MW, 60-m diameter, three-bladed upwind machine based in Spain. Whilst the design was based on the German 1.2 MW, WKA-60 wind turbine, further development was undertaken on the electrical system, glass-fibre reinforced blades and the control system in order to reduce the cost (International Energy Agency 1989).

Development of large-scale wind turbines was launched rapidly and successfully in Sweden in the 1980s. The WTS-75 was a two-bladed upwind turbine rated at 2 MW, which possessed some unique design features including a drive-train system with bevelled gears that eliminated the need for power slip rings and a mechanism for raising and lowering all major components. Sweden also constructed the WTS-3 downwind turbine, rated at 3 MW, which produced a relatively large amount of energy compared with other large-scale wind turbines of the 1980s. This design incorporated a teetered hub and a spring-mounted gearbox to reduce the impact of dynamic loading associated with the two-bladed, downwind configuration.

After a number of design iterations, the UK produced the 3 MW LS-1 in 1987, which was a two-bladed upwind turbine of 60 m diameter. The rotor consisted of a teetered hub mounted on elastomeric bearings and the outer 30% of the blades were mounted on rolling element bearings, which enabled variation of the blade pitch angle (Hau 2013). The drive-train design provided control of the rotor speed to within ±5% (Hau 2013).

Following the Arab oil embargo of 1973, the US government invested significant funds into a federal research plan directed towards wind energy development. The first large wind turbine that was developed as part of this program was the MOD-0 configuration in 1975. Over the next decade, this wind turbine was used extensively for testing to identify possible improvements that could be made to the design. It was 38.1 m in diameter, rated at 100 kW and was mounted atop a truss-type tower at a hub height of 30.5 m. The design was similar to the Smith–Putman and Hütter–Allgaier wind turbine designs, where the rotor was two-bladed and located downwind of the tower. Several modifications were made to the MOD-0 over its twelve-year lifetime, including replacement of the truss-type tower with a slender shell tower to reduce wake-induced fatigue loads and incorporation of a teetered hub. The extensive testing that was undertaken also resulted in a large volume of documentation, computer models and control algorithms that form the basis of modern wind turbine technology. During the early stages of the MOD-0 program, an upgraded version of this turbine, rated at 200 kW, was integrated into the grid at four separate locations and designated the MOD-0A. The locations were chosen to ensure that wind power would make up a significant proportion of the input power to the grid, enabling grid connectivity issues to be identified. The wind turbines collectively fed 3.6 GWh into their respective grids during their operating lives (Shaltens and Birchenough 1983) and achieved capacity factors as high as 0.48 (Spera 2009).

The first megawatt-scale wind turbine to be developed as part of the US federal research plan was the MOD-1 configuration in 1979. This model was designed before the problems with the MOD-0 had been identified and understood and therefore was dismantled after only two years of operation. The MOD-1 was 61 m in diameter, rated at 2 MW and resembled the MOD-0 configuration in that it had a downwind, two-bladed rotor, rigidly mounted on a truss-type tower. While this turbine was successfully integrated into the local grid, impulsive loading caused by the substantial wake deficit behind the truss tower resulted in a severe risk of early fatigue as well as environmental problems such as excessive low-frequency noise and electromagnetic interference. The next turbine in the series was the 91.4-m diameter, 2.5 MW MOD-2, which was an upwind design and represented a large technical leap from the earlier models in the US federal plan. The design employed partial-span pitch control on its two blades, which simplified the use of a teetered hub, as only the outer portion of the blades needed to rotate about the blade axis to enable control. A comprehensive testing program was carried out on the MOD-2 design, including investigation of wake-interaction effects, operation strategies and control algorithms. Successful integration into the local grid was also realised, with a group of three MOD-2 wind turbines installed at Goodnoe Hills in 1981, and contributing over 10 GWh to the local grid during 16 000 h of operational time. This group of three formed the first 'wind farm' in the world (Boeing 2015) proving conclusively that groups of wind turbines could operate in a completely automated mode.

The MOD-5B was the next wind turbine in the series to be developed under the federal wind energy program. The design was similar to the MOD-2 wind turbine, in that it consisted of a two-bladed upwind rotor, teetered hub, partial-span pitch control and a tubular steel tower. However, this wind turbine was larger, with a rotor diameter of 97.5 m and a rated power of 3.2 MW. Built in 1987, it was the first large-scale wind turbine to operate at variable speed, which led to improved efficiency and reduced structural loading (Spera 2009). From 1988, the MOD-5B wind turbine was connected to the grid on the island of Oahu in Hawaii and was fully automatic, with software changes made using the local public telephone system (Boeing 2015). The MOD-5B demonstrated excellent performance for such a large and advanced design, and during its lifetime of six years, it ran for 20 561 h and produced 26.8 GWh of electricity.

The largest wind turbine to be built before the year 2000 was the WTS-4, which was a two-bladed downwind machine, rated at 4 MW, with a hub height of 80.4 m and a diameter of 78 m. The support tower was a single 12-sided cylindrical structure of shell construction. Despite its large power rating, this wind turbine produced a relatively small amount of energy during its lifetime (Spera 2009) and it ceased operating after only four years due to a generator failure. The wind turbine was bought for a fraction of its original cost by a local engineer and wind energy enthusiast, who later watched the machine fly to pieces in a storm (Righter 1996).

1.2.2 Development since 2000

Wind power has expanded rapidly since the beginning of the 21st century to the point where there are so many different models of megawatt-rated wind turbines that further consideration of individual models is beyond the scope of this book. The rapid expansion is a result of increased awareness of global warming and eventual fossil fuel depletion, as well as rising concerns over energy security. The amount of global energy generated since the year 2000, as plotted in Figure 1.3, has consistently increased at an average annual rate of approximately 25% and was 17 times higher in 2013 than in 2000.

When describing the relative contribution of wind energy, it is common to refer to the *installed power*, which is the product of the manufacturer's power rating and the number of turbines. This is also referred to as the *installed capacity*. However, this measure does not take into account such factors as wind variability, interactions between wind turbines, lack of grid connectivity and wind turbine malfunctions. Therefore, a more conservative measure is the actual energy generated, which is measured in TWh (terawatt-hours) for large-scale turbines. The annual capacity factor is the ratio of the energy generated over one year to the amount that would be generated if the wind farm

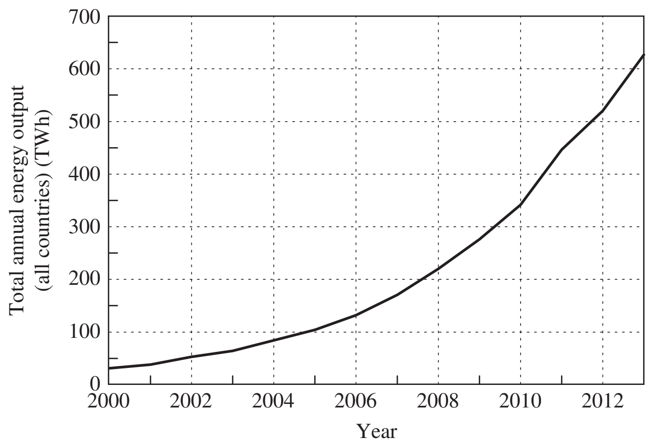

Figure 1.3 Global annual energy output (TWh).

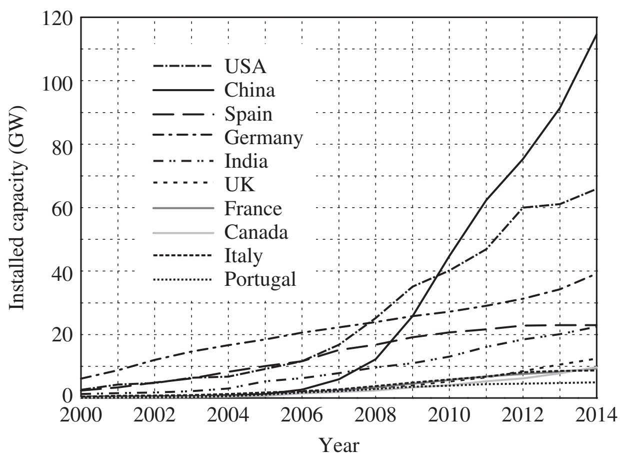

Figure 1.4 Installed capacity of wind power (2000–2014).

operated continuously at its maximum power output. This gives an indication of the overall efficiency of wind energy as a whole.

Figures 1.4–1.6 show the installed power capacity (the rated turbine power in megawatts multiplied by the number of turbines in the wind farm), generated energy (TWh) and annual capacity factor, respectively, for the top ten countries in terms of wind energy generated in 2013. The data in these figures have been compiled from information provided by the IEA, Global Wind Energy Council and the US Energy Information Administration. Germany was leading the world with installed power and generated wind energy in the year 2000 and since then has been increasing its installed power at a rate close to linear. On the other hand, the USA and China's installed power and generated wind energy has been increasing exponentially since the year 2000. As a result, these two countries have emerged as leaders in available and generated

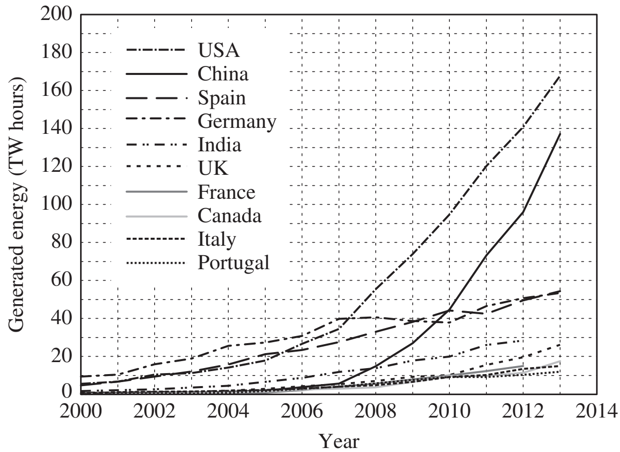

Figure 1.5 Generated wind energy (2000–2014).

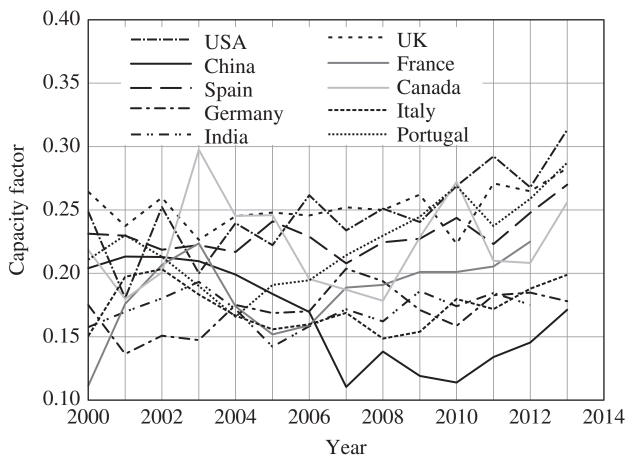

Figure 1.6 Annual capacity factor (2000–2014).

wind power as of 2013/2014. Comparison of the figures for the USA and China reveals that although China has almost double the installed power capacity of the USA, the latter still generates a larger amount of energy. It is therefore not surprising that the annual capacity factor for China is lowest for the ten countries compared in Figure 1.6. Conversely, the USA has the highest annual capacity factor, and has been the world leader for energy generation since 2007.

Technological development of wind turbines has focussed on reduction of costs, increased energy capture and greater reliability. To this end, wind turbines have become progressively larger to take advantage of the high-energy winds that occur at greater altitudes. Several advances have also been made in blade design. These include optimising the blade profile to increase efficiency in low winds, limiting aerodynamic loads in high winds and minimising blade fouling. Advanced composite materials have also been specified in blade designs in place of steel and wood, to improve the strength-to-weight ratio. Most large wind turbines today are variable-speed, pitch-regulated machines, which allows operation at near-optimum ratios between the blade-tip speed and wind speed, thus maximising output power. Modern designs are also predominantly three-bladed, as this number provides the best compromise between aerodynamic efficiency, cost, rotational mass, structural integrity, inertial stability, relatively low tip-speed ratios and aesthetics. The use of fewer blades results in increased aerodynamic efficiency since each blade disturbs the air for the following one. The cost and weight of each blade is substantial, so from this perspective fewer blades are also preferred. Also, the strength and stiffness of each blade is greater when there are fewer blades for a given rotor solidity (total blade planform area divided by swept area). On the other hand, wind turbines with less than three blades experience unbalanced loading during yaw, which can be overcome by using a teetered hub, although this is an extra complication that most manufacturers prefer to avoid. The rotational speed of a three-bladed design is lower than a one- or two-bladed design, resulting in lower tip-speed ratios and hence reduced trailing-edge noise. Many people prefer to look at turbines with three blades rather than one or two blades and since community acceptance is important for wind farm developers, this point is also taken into account.

The drive trains of wind turbines have become lighter and more reliable in recent times, which is an important development, since failure of drive-train components such as the gearbox is costly and the associated downtime is high (Ekwaro-Osire et al. 2011). In the late 1990s, direct-drive generators were introduced as an alternative to gearboxes, but despite their numerous advantages, their size and weight are issues that have prevented widespread use (Spera 2009). These days, the generator components of wind turbines are required to synchronise with electricity grids and they are therefore capable of producing AC electricity, in contrast to early wind turbines, which were developed as stand-alone units and employed DC generators. Control systems for wind turbines have become more sophisticated in recent times as well, with high-speed digital controls enabling processing of data from a number of sensors for optimised power generation. Advanced control algorithms have been developed to facilitate more efficient data processing and optimal actuator responses to sensor inputs. While a number of early wind turbine designs integrated steel truss-type or concrete monopole (single support cylinder or partial-cone) towers into their designs, modern wind turbines consist of a steel, monopole structure with a reinforced concrete foundation.

1.2.3 Support Received by the Wind Industry

Wherever wind energy has been developed successfully, it has been with the aid of government intervention in the form of financial, technical or regulatory support. The reason for this is that, at the time of writing, wind energy is more expensive than energy derived from coal or gas and the industry would be non-viable without financial incentives from governments. However, with many renewable energy targets in place around the globe, it seems that wind power is the least expensive way of achieving them. Of course, it appears that wind turbines are a very clean and environmentally friendly power source, as power is generated without producing greenhouse gases. But are they? To answer this question, one must consider the greenhouse gases that are produced during the construction of wind farms, from transportation of materials to the construction site, and during their maintenance and decommissioning. It is also important to consider the intermittency of wind power and the current lack of energy storage facilities, resulting in significant security and reliability concerns for electrical grids worldwide (Miskelly 2012). Through analysis of power output data provided by the Australian Energy Market Operator, Miskelly (2012) demonstrated that during the full calendar year of 2010, there were over 100 incidences where the entire Eastern Australian grid generated less than 2% of installed capacity. A consequence of these common-mode failures is the need for a rapid response from fossil-fuel-driven power stations, resulting in inefficient operation of these facilities and production of excessive greenhouse emissions at these times.

Recently Weißbach et al. (2013) compared wind energy with other energy generation facilities in terms of its energy return on investment (EROI) value and the number of years to achieve payback on the energy invested in construction, and his results are presented in Table 1.1. The EROI value is the ratio of the usable energy that the energy facility returns during its lifetime to all the invested energy needed to generate this energy. Weißbach further analysed the EROI value in terms of the cost of buffering needed to maintain a continuous power supply, considering the unreliability of the energy source. These values are also included, but must be considered in light of the economic threshold for the EROI value being about 7 (Weißbach et al. 2013), indicating that wind power produces considerably more energy than needed to construct and run the turbines, but that intermittency of supply makes it economically non-viable.

In Table 1.1, CSP is concentrated solar power, such as achieved by an array of mirrors directed at the apex of a tower or a large array of flat or parabolic reflectors. In the case of the more expensive but more efficient parabolic reflectors, sunlight is focussed onto a receiver tube at the focal point of the reflectors, thus heating molten salt as it flows through the tube. In all cases the heat energy generated is used to boil water to drive a steam turbine, which in turn drives a generator to produce electricity. CCGT refers to a combined-cycle gas turbine facility, in which waste heat from the gas turbine is used

Table 1.1 EROI and energy payback times for various energy generation facilities.

Energy generation type	EROI	EROI (buffered)	Energy payback time unbuffered (years)	Energy payback time buffered (years)
Solar PV (roof)	3.9	2.3	6	16
Solar PV (field)	3.8	2.3	6	16
Biomass (corn)	3.5	3.5	0.033	0.033
Wind	16	4	1	5
Solar CSP (parabolic mirror, desert)	21	9.6	1	3.5
CCGT	28	28	0.025	0.025
Coal	30	30	0.167	0.167
Hydro	50	35	2	3
Nuclear	75	75	0.167	0.167

Data from Weißbach et al. (2013).

to generate steam to power a steam turbine, with both turbines driving an electrical generator.

1.3 History of Wind Turbine Noise Studies

Here, some of the earliest reported studies concerning wind farm noise are explored. A large proportion of the work reported here was carried out in the 1980s in response to a noise issue associated with operation of the MOD-1 wind turbine. This was the first well-documented case of acoustic disturbance from a wind turbine that was significant enough to provoke complaints from neighbours. While the noise issue was exacerbated by the fact that the rotor of the MOD-1 was located downwind from the tower, it was shown that a similar mechanism was at play for an upwind rotor (Spencer 1981). The main difference between the two rotor configurations was shown to be the magnitude of the flow deficit encountered by the blades, and consequently the level of noise generated, which is much greater for the downwind configuration (Spencer 1981). Another difference, described by Kelley et al. (1985), is that the blades of a downwind rotor experience transient lift fluctuations due to the periodic vortex shedding that occurs behind the support tower, although the effect is smaller than the flow deficit effect. These differences in the blade inflow conditions cause the noise levels associated with a downwind configuration to be much higher. On the other hand, since upwind turbines also experience a flow deficit as well as inflow turbulence, many of the findings from the studies on downwind turbines are still relevant to modern upwind wind turbine designs.

As mentioned in Section 1.2.1, the MOD-1 was a downwind machine with a two-bladed rotor that was rigidly mounted on a truss-type tower. Detailed investigations carried out by Kelley and his colleagues culminated in a comprehensive report, which identified the issue as unsteady loading imparted to the rotor blades as they passed through the tower wake (Kelley et al. 1985). This phenomenon resulted in high levels of low-frequency impulsive noise that excited structural resonances and interior air volume modes of nearby houses, sometimes causing loose objects to vibrate (Kelley et al. 1985). Measurements indicated that the impulsive character of the noise was directly related to the presence of blade-pass frequency components. Noise propagation was found to be governed by a combination of atmospheric refraction and terrain reflection, which were responsible for focussing the noise towards locations occupied by residences. Due to noise complaints received from about a dozen families living within a 3-km radius of the wind turbine, MOD-1 was slowed down from 35 to 23 RPM and it was found that an 11-dB reduction in sound pressure levels could be achieved (Viterna 1981). On the other hand, there was a corresponding increase in the level of impulsive noise in the 8 and 16 Hz octave bands and while annoyance was reduced, it was not eliminated (Kelley et al. 1988). Noise issues with the MOD-1 turbine prompted a number of investigations on this specific configuration, including field measurements, modelling and wind tunnel experiments.

A predictive model for determining the amplitude of the blade-pass harmonics was developed by Viterna (1981) and implemented in computer software called WTSOUND. The approach was based on theory for aircraft propellers first developed by Gutin in 1937 (Gutin 1948). In summary, the process developed by Viterna (1981) involved the following steps:

1. Calculating the steady aerodynamic blade forces.
2. Determining the variation in these forces due to unsteady aerodynamics.
3. Carrying out a Fourier analysis of the force variation.
4. Calculating sound pressure levels in the acoustic field, by assuming the aerodynamic source to be compact with an effective radius of 75% of the blade span.

The calculated results were in good agreement with the MOD-1 data in the vicinity of two rotor diameters from the wind turbine. However, in the far field, the model underestimated the actual levels of the MOD-1 by 6 dB or more due to propagation effects related to the terrain and atmospheric conditions. Nonetheless, the model accurately recreated the $\sin(f)/f$ spectrum shape characteristic of a pulse of finite width in the time domain, where f is the frequency. For the MOD-1 wind turbine, this pulse of finite length and relatively steep edges resulted from the blade lifting surface passing through a flow deficit. Metzger and Klatte (1981) found that the spectrum envelope was very sensitive to the shape of the flow deficit and that harmonics of the blade-pass frequency in the higher frequency range could be avoided by ensuring that the shape followed a Gaussian profile. One possibility for achieving this was by modifying the tower shape in the vicinity of the rotor blades. However, this would only be effective for one wind direction unless the tower had a lightweight external shell that could rotate as the wind direction changed (Tocci and Marcus 1982).

A model of the MOD-1 wind turbine was constructed and tested in the anechoic wind tunnel at the NASA Langley Research Centre. Researchers carefully scaled the tower details to ensure that the wake would be recreated as accurately as possible (Greene 1981). Results from these experimental studies indicated that the impulsive noise associated with the MOD-1 wind turbine could be significantly reduced by using an upwind configuration. Therefore, one of the primary motives for using an upwind configuration in the MOD-2 wind turbine design was to avoid the impulsive noise issues that were associated with its predecessor (Kelley et al. 1988). The acoustic emissions of the MOD-2 wind turbine were investigated extensively by Kelley et al. (1988) and it was found that the impulsive noise was significantly reduced. Further reduction in the levels and impulsiveness of the low-frequency noise emitted by the MOD-2 machine was achieved by incorporating vortex generators and pitch schedule changes. It is worth noting that the impulsive noise was not eliminated entirely and that the degree of impulsiveness was strongly correlated with the vertical atmospheric stability, the vertical or upwash turbulence length scale and the blade loading (Kelley et al. 1988). Spencer (1981) found that the spectrum shape of a MOD-2 wind turbine with a two-bladed upwind rotor was very similar to the MOD-2 with a downwind rotor in the frequency range from 0 to 45 Hz. The main difference between these spectra was the relative amplitude of the blade-pass harmonics, since the flow deficit associated with the downwind case was much larger than the flow deficit for the upwind turbine.

Apart from impulsive noise generated by blade–tower interaction, a number of other aeroacoustic noise sources associated with wind turbine operation were identified and modelled in the late 1980s and early 1990s. The investigated sources were mainly broadband in nature and resulted from inflow turbulence and airfoil self-noise. Grosveld (1985) found good agreement between predictions of broadband noise and far-field measurements in the vicinity of the two-bladed MOD-OA, MOD-2 and WTS-4 wind turbines and the three-bladed US Windpower Inc. wind turbine. The prediction model considered contributions from inflow turbulence to the rotor, trailing-edge effects and the wake due to a blunt trailing edge and it was found that at low frequencies the dominant source was inflow turbulence noise (Grosveld 1985). Glegg et al. (1987) developed a prediction method for wind turbines that included the source mechanisms of unsteady lift noise, unsteady thickness noise, trailing-edge noise and the noise from separated flow. To determine the inflow turbulence, which is a required input for the unsteady lift and thickness calculations, a detailed model of the atmospheric boundary layer was implemented. Good agreement was obtained between the atmospheric boundary layer model and anemometer measurements, but a 10-dB discrepancy was noted between the measured and calculated acoustic results. Improved correspondence between measurements and predictions was achieved by assuming a turbulence length scale equal to the blade chord. The authors also observed that the presence of the tower on an upwind turbine caused significant acoustic scattering when the rotor blades were close to the tower and hence this effect was also incorporated into their theoretical model (Glegg et al. 1987). However, due to the short duration of this effect, it was found to have a negligible contribution to the average level. On the other hand, the authors noted that it would increase the detectability of the signal.

A review of the aeroacoustic noise generated by large wind turbines was presented by Hubbard and Shepherd (1991) and an additional mechanism of impulsive noise generation was attributed to rotor inflow velocity gradients. Various wind velocity profiles were assumed as inputs to the model developed by Viterna (1981) and the results were compared to measurements recorded up to 80 m from the two-bladed WWG-0600 upwind turbine. There was good agreement between the results, for a specific assumed atmospheric wind velocity profile resulting from the atmospheric boundary layer. On the other hand, the actual wind velocity profile was not measured and therefore it is not known if the assumed velocity profile was accurate.

Propagation of noise from the MOD-1 wind turbine was investigated in detail by Thompson (1982) through analysis of field measurements and development of a computational model. The results indicated that the primary mechanism responsible for enhanced far-field noise levels was atmospheric refraction of acoustic waves caused by vertical wind shear. The influence of ground and surface wave propagation on the enhanced noise levels was found to be negligible in comparison to this effect. Based on the collected data, conditions of adverse noise propagation were predicted to occur about 30% of the time at complex terrain sites. A similar investigation was carried out by Willshire (1985) and Willshire Jr and Zorumski (1987) on the WTS-4 wind turbine. It was shown that low-frequency sound was refracted in the downwind direction, resulting in an attenuation rate of 3 dB per doubling of distance for frequencies below 20 Hz. Predictions of both ray tracing and normal-mode theoretical models supported this observation. In the upwind direction, the absence of a shadow zone was noted for these infrasonic frequencies and the propagating signals indicated a spherical spreading characteristic, resulting in an attenuation of 6 dB/doubling of distance.

The acoustic and vibratory response of buildings to wind farm noise was explored by Stephens et al. (1982) and it was shown that in some circumstances, low-frequency wind turbine noise could be perceived more readily indoors than outdoors. A number of reasons for this phenomenon were presented, including selective attenuation of higher frequencies by the building structure, room modes, structural resonances and noise-induced vibrations. Other complicating factors mentioned included the role of stiffness and air leaks at low frequencies (Stephens et al. 1982). Enhanced perception of indoor low-frequency noise was attributed to an increase in the indoor noise level relative to the outside level at specific frequencies and large variations in sound pressure level as a function of room position (Hubbard and Shepherd 1991).

Thresholds of perception were determined by Stephens et al. (1981) by exposing subjects to a range of impulsive stimuli of the type associated with blade–tower interaction. The test stimuli were synthesised based on MOD-1 data and blade–tower interaction calculations and presented to the listening subjects in an anechoic chamber. The resulting spectra consisted of harmonics of the fundamental frequencies of 0.5 Hz and 1 Hz that were dominated by specific frequencies. The resulting perception thresholds were found to be lower than the pure-tone threshold and it was observed that the chosen fundamental frequency influenced the results. A lower fundamental frequency gave rise to a lower perception threshold. In a later publication (Stephens et al. 1981), the authors presented additional perception curves for use when various levels of background noise were present in addition to the impulsive wind turbine signal. These curves indicated that the perception threshold increased with the level of background noise but that this increase was relatively less for lower frequencies. For a background level of 35 dBA, the perception threshold was still below the pure-tone threshold at all frequencies, according to the ISO389-7 (2005). Comparison of various metrics used in the assessment of low-frequency noise was carried out by Kelley (1987). Evaluators were exposed to simulated signals characteristic of wind turbine noise emissions and they subsequently recorded their perception of the noise according to specified categories and rankings. The researchers then determined the correlation between the stimulus sequences and the evaluators' responses. It was found that people reacted to a low-frequency noise environment and that the A-weighting (see Section 2.2.11) is not an adequate measure of annoyance when low frequencies are dominant (Kelley 1987). The results also indicated that the low-frequency sound level (LSL) (Tokita et al. 1984) and C-weighting (see Section 2.2.11) metrics were the most 'efficient' descriptors of low-frequency noise annoyance.

A method to control the impulsive noise associated with the flow deficit encountered by the wind turbine blades was proposed by Tocci and Marcus (1982). The method involved reduction of the flow deficit through use of airfoil-shaped fairings for the tower, which could be rotated into the appropriate direction to minimise the wake deficit. This technique would also reduce the flow deficit in front of the tower and is therefore relevant for reducing aerodynamic noise associated with blade–tower interaction for modern upwind turbines.

1.3.1 Modern Wind Turbine Sound Power Levels

Readers unfamiliar with acoustics terminology should consult Chapter 2 prior to reading further. More detail on the estimation of turbine sound power is provided in Chapter 4.

The noise output of many modern wind turbines has been reported by Søndergaard (2013) in the form of overall A-weighted sound power levels in dB re 10^{-12} Watts. He showed that the total A-weighted sound power level of turbines with a rated power greater than 2 MW could be described by Eq. (1.1) (within ±5 dB).

$$L_{wA} = 8.8\ \log_{10}(kW) + 59.6 \qquad (\text{dB re } 10^{-12}\text{W}) \tag{1.1}$$

where kW is the turbine rated power in kilowatts.

Søndergaard (2013) also provided low-frequency data in the range 10–160 Hz and showed that the A-weighted sound power level of turbines with a rated power greater than 2 MW could be described by Eq. (1.2) (within ±5 dB).

$$L_{wA} = 10.3\ \log_{10}(kW) + 74.9 \qquad (\text{dB re } 10^{-12}\text{W}) \tag{1.2}$$

The data provided by Søndergaard (2013) were used to derive the relationships in Eqs. (1.1) and (1.2), which show that as the turbine rated power increases, so too does the noise it produces over the entire frequency spectrum, with low-frequency noise increasing by the same amount as mid- and high-frequency noise.

The relative frequency distribution of the noise for turbines with a rated power greater than 2 MW is shown in Figure 1.7, where the decibel difference between the 1/3-octave band sound power level and the total sound power level is plotted.

An interesting result from Sondergard's analysis is that modern pitch-RPM regulated turbines do not produce any more noise as the hub height wind speed increases above about 8 m/s. However, it is quite a different story for stall- and active-stall-regulated turbines. For these turbines, the noise output increases markedly as the wind speed increases above 8 m/s, by anything from 8 to 12 dBA for a wind speed increase to 12 m/s. The 8 m/s wind speed was chosen because this is the wind speed at which all turbines reach 95% of their rated power.

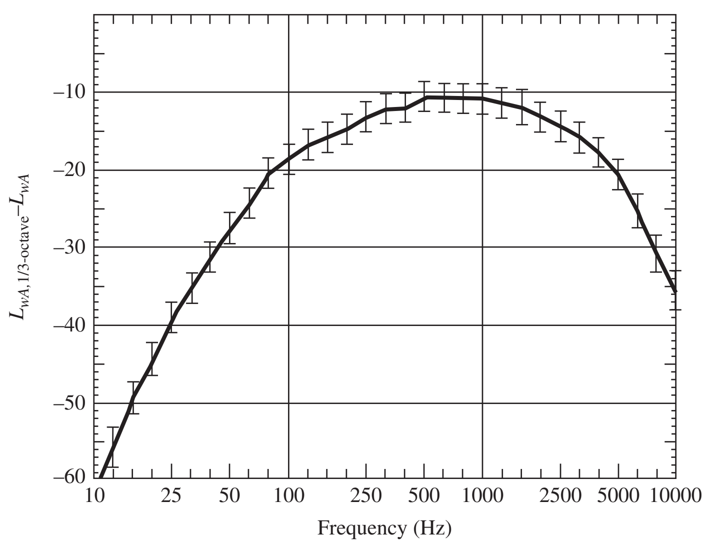

Figure 1.7 Wind turbine 1/3-octave band A-weighted sound power level (dB) normalised to the total A-weighted sound power level, for turbines with a power rating greater than 2 MW. The error bars show the 95% confidence interval around the mean. Data from Søndergaard (2013).

1.4 Current Wind Farm Noise Guidelines and Assessment Procedures

Worldwide, there is a plethora of standards, guidelines and recommended assessment procedures for wind farm noise and its allowable limits. As many as possible are reviewed here but unfortunately it is not possible to capture every single one that has been published. Here we are concerned with assessment procedures and allowable limits – standards that concern sound power measurements or sound propagation predictions are discussed in relevant sections elsewhere in this book and only the parts relevant to allowable limits and assessment guidelines are discussed here.

In the following paragraphs and later in the book, the term *wind shear* is used quite often, so it is useful to discuss its meaning here. Wind shear is a way of describing the variation of wind speed with altitude. For high wind shear conditions, the wind speed increases much more rapidly with altitude than it does under low wind shear conditions. Low wind shear generally occurs during the day, when solar radiation heats the ground and causes mixing in the atmospheric boundary layer within a few hundred metres of the ground, resulting in only a small variation of wind speed with altitude in the boundary layer. At night, in the absence of solar radiation, there is reduced mixing in the boundary layer and it is quite common for wind turbines to be generating a significant amount of power while there is little or no wind close to the ground. One method of quantifying wind shear is with the use of a shear exponent (or coefficient), ξ, which relates wind speed to altitude. The ratio of the wind speed, $U(h)$, at height, h, to the wind speed U_0 at height h_0 is given by,

$$U(h) = U_0 \left(\frac{h}{h_0} \right)^{\xi} \tag{1.3}$$

where the wind shear coefficient can vary from 0.1 to 0.6, depending on the ground surface roughness and the atmospheric stability. This is discussed in much more detail in Section 5.2.4.

1.4.1 ETSU-R-97 (used mainly in the UK and Ireland)

ETSU-R-97, a detailed report published in 1996 (ETSU 1996), was perhaps the first government-sponsored work written with the specific purpose of providing detailed planning guidance for the assessment and rating of noise from wind farms. It was prepared by a working group sponsored by the UK Department of Transport and Industry. It follows on from a UK Department of Planning Policy Guidance note (PPG22) published in 1993, which was written at a time when not much was known about wind farm noise and its effects on people, although there was a considerable body of work available from NASA on noise emissions and health effects from the much noisier downwind turbines. ETSU-R-97 is important in that many existing local guidelines for wind farm noise, both in the UK and other countries, have been based on it. However, much more has been discovered about wind farm noise, its characteristics and its effects on people in the past two decades, so the guidance in ETSU-R-97 has become outdated and inappropriate in many areas. The main problems with the recommendations in ETSU-R-97 are listed below.

1. The recommended use of the $L_{A90,\,10\mathrm{min}}$ metric for measurement of wind farm noise, which is the sound pressure level exceeded 90% of the time in a 10-min period, is based on the assumption that wind farms produce a steady noise at residences, in other words, one that does not vary very much in level over a 10-min period. Many more recent studies, including those of the authors of this book, have shown this to not be the case and although many current guidelines use the more acceptable $L_{Aeq,\,10\mathrm{min}}$ metric, there are still a number that continue to use the $L_{A90,\,10\mathrm{min}}$ metric. The $L_{Aeq,\,10\mathrm{min}}$ metric represents a noise energy average and generally produces wind farm noise levels in the range 1.5 to 3 dB above those obtained using the $L_{A90,\,10\mathrm{min}}$ metric. However, the $L_{A90,\,10\mathrm{min}}$ metric is generally considered appropriate for measurement of background noise prior to construction of the wind farm, to minimise contributions from transient noise sources that are not representative of actual background noise levels occurring for the majority of the time. Both of these metrics are defined in Section 2.2.12.
2. ETSU-R-97 recommends that the acceptable nighttime limit for noise should be 43 dBA, based on the outdated WHO guideline that 35 dBA indoors is an acceptable level for people trying to sleep. The WHO has since updated their acceptable indoor noise level for sleep to 30 dBA (with windows open), but most guidelines based on ETSU-R-97 do not account for this change. It is strange that the recommended limit for nighttime is greater than the 35 to 40 dBA limit for daytime and this has received the appropriate criticism in the literature (Cox et al. 2012).
3. Allowable levels (day and night) can be increased to 45 dBA for residents receiving financial benefit as a result of the wind farm.
4. The noise-level limits described above do not account for the low-frequency nature of wind farm noise by the time it reaches the bedrooms in residences more than 1–1.5 km from the nearest turbine.
5. ETSU-R-97 states that noise from a wind farm should be limited to 5 dBA above background noise levels. However, it is stated that this limit should not apply in environments where the daytime background noise levels are less than the limits mentioned in items 2 and 3 above. It was assumed that audible noise above background is not disturbing to people living in low-noise environments, which is why this aspect of ETSU-R-97 has drawn considerable criticism. However, it is clear that an industrial noise source of 35 or 40 dBA superimposed on a typical rural environment of 20 dBA or less would be intrusive to most people.
6. The allowance of 5 dBA above background is based on use of the $L_{A90,\,10\mathrm{min}}$ metric for measurement of wind farm noise, rather than the usual $L_{Aeq,\,10\mathrm{min}}$ metric, which means that when comparing with other standards, the allowed increase of $L_{Aeq,\,10\mathrm{min}}$ over background $L_{A90,\,10\mathrm{min}}$ is actually at least 7 dBA, and could be more, depending on the difference between $L_{A90,\,10\mathrm{min}}$ and $L_{Aeq,\,10\mathrm{min}}$ for wind farm noise. This then exceeds the limit beyond which complaints may be expected.
7. There is no consideration of the common nighttime situation where wind shear is high and there is no (or very little) wind at a residence, while at the same time there is sufficient wind to drive the turbines. This negates the assumption that as the hub height wind speed increases, background noise due to the wind will increase at a greater rate than wind turbine noise.
8. There is no specific adjustment for amplitude modulation (see Section 2.2.7) or maximum allowed modulation depth (see Eq. (2.26)), nor is there any allowance

for random amplitude variation, which is caused by sound from different turbines combining destructively or constructively at any receiver.

9. A curve-fit procedure is used for establishing background $L_{A90,\,10\text{min}}$ noise levels as a function of measured or estimated wind speed at a height of 10 m above the ground. The curve-fit procedure involves collecting over 2000 data points of noise levels as a function of hub-height wind speed (converted to a standardised 10 m height). At least 500 data points must be for the condition of the wind blowing towards the receiver (±45° from directly downwind). Each data point represents a 10-min average and there is no requirement to separate out nighttime from daytime data. The data points are plotted on a graph of $L_{A90,\,10\text{min}}$ vs hub-height wind speed and a line of best fit (regression line) is drawn through the data points. Generally, the line is a second- or third-order polynomial (see item 10). Using the line of best fit to establish background noise levels prior to construction of the wind farm means that half the data represent noise levels that are less than the established levels. In establishing background noise levels for the purpose of assessing the intrusiveness of wind farm noise, it would be more reasonable to use levels that are at least one standard deviation (if not two standard deviations) below the average line of best fit. Using one standard deviation would still result in 16% of the data points being less than the specified level, whereas two standard deviations would result in 2.5% of the data being less than the specified level.
10. In the procedure for establishing background noise levels, there is no mention of the electronic noise floor problem of instrumentation, which currently varies between 16 and 18 dBA for most monitoring systems. This means that all measured levels below 26–28 dBA (depending on the actual noise floor) must be corrected to obtain the true noise level. The amount to be subtracted from the measured level can range from 0.5 dB for a measured level 10 dBA above the instrument electronic noise floor to 7 dBA for a measurement 1 dBA above the noise floor. This has a large effect on the order of the curve fit used, which generally should be a straight line or a second-order polynomial rather than the third-order polynomial suggested in the Institute of Acoustics (IOA) good practice guide (IOA 2013) for implementation of ETSU-R-97. In fact, the order of polynomial chosen has a large influence on the resulting ‘average’ background noise levels at both low and high wind speeds.
11. ETSU-R-97 states that noise levels should be measured using a microphone on a tripod 1.2–1.5 m above the ground in 10-m wind speeds of up to 12 m/s. It is now well known that wind speeds at 10 m of 12 m/s will often result in excessive wind noise on a microphone at a height of 1.2 m, particularly if only a 90-mm diameter primary wind screen is used, with no large secondary wind screen. It is far more practical to measure background noise, as well as wind farm noise, using a microphone mounted on the ground and with a large secondary wind screen in addition to the standard 90-mm wind screen commonly used. This minimises the effect of wind noise on the microphone that results in erroneous measurements at higher wind speeds. Unfortunately, it is difficult to accurately relate the ground-level measurement to what would be measured at a height of 1.5 m, as the relationship between the two measurements is frequency- and ground-type-dependent and is also dependent on interaction between all the contributing noise sources (see Section 6.2.4).

Institute of Acoustics *Good Practice Guidelines*

In 2013, the (British) Institute of Acoustics released a *Good Practice Guide* to the use of ESTU-R-97, in response to a number of instances where it had been applied incorrectly. The *Good Practice Guide* contains a total of 21 recommendations directed at ensuring consistent application of ETSU-R-97 when calculating noise levels in the community that might be expected from a proposed wind farm. The more important recommendations are summarised below.

1. Engage all relevant parties as soon as possible.
2. Background noise surveys should include all areas where the L_{A90} levels due to the wind farm are expected to exceed 35 dBA.
3. Exclude noise levels from existing wind farms in the background noise assessment.
4. Although background noise measurements can be carried out at any time of the year, seasonal effects leading to raised levels should be excluded.
5. Enhanced microphone wind screens should be used. However, these are not defined.
6. Measurement locations for background noise should be 3.5–20 m from a dwelling and noise from local sources should be excluded as much as possible by choice of measurement position. Remaining noise from local sources should be removed from the data. The morning chorus of bird calls should also be removed. If rush-hour traffic at night does not occur regularly, then data including these events should also be removed.
7. Noise measurements should be correlated with wind speed values corresponding to the standardised 10-m height. They should be calculated from from hub-height wind speed, which can either be measured directly or calculated from measurements made at two heights, with the higher of the two being no lower than 60% of hub height. The hub-height wind speed, U_H, is determined from wind speed measurements, U_1 and U_2, at two heights, h_1 and h_2, respectively, (where h_2 is the upper height) using the following two equations.

$$U_H = U_2 \left(\frac{h_H}{h_2} \right)^{\xi} \tag{1.4}$$

where h_H is the hub height and the shear coefficient ξ is calculated using

$$\xi = \frac{\log_{10}(U_2/U_1)}{\log_{10}(h_2/h_1)} \tag{1.5}$$

For cases where $U_1 > U_2$, the hub-height wind speed is set equal to U_2.
The standardised wind speed at a height of 10 m is derived from the hub-height wind speed using Eq. (1.6).

$$U_{10\mathrm{m}} = U_H \left[\frac{\log_{\mathrm{e}} \left(\frac{10}{z_0} \right)}{\log_{\mathrm{e}} \left(\frac{h_H}{z_0} \right)} \right] \tag{1.6}$$

where $z_0 = 0.05$ m is the standard ground roughness length used for all ground surfaces, $U_{10\mathrm{m}}$ is the standardised wind speed at 10 m and U_H is the wind speed determined at hub height, either by direct measurement or by use of Eqs. (1.4) and (1.5). Because Eq. (1.6) is only valid for a neutral atmosphere, the standardised wind speed at 10 m will rarely be the same as the actual wind speed measured at 10 m. Also, to be strictly correct, Eq. (1.6) should have a '1+' in the numerator and denominator as shown in Eq. (5.17).

8. Rain-affected data must be excluded from background noise measurements.
9. For background noise measurements, no fewer than 200 valid data points should be recorded in each of the amenity hours (defined below) and nighttime periods, with no fewer than 5 valid data points in any 1-m/s wind-speed bin.
10. Amenity hours are defined as 18:00 to 23:00 every day plus 13:00 to 18:00 Saturday and 07:00 to 18:00 Sunday. Night hours are from 23:00 to 07:00 every night.
11. Directional background noise measurements may be necessary in cases where an existing noise source such as a busy road is on the opposite side of the residence to the proposed wind farm, which would mean that the residence would be in the upwind direction from the road (least background noise) while it would be in the downwind direction from the turbine (most background noise).
12. The noise propagation model described in ISO9613-2 is appropriate for calculating wind farm noise levels at residences and other sensitive receivers, provided that the following considerations are taken into account.
    a) Predictions should be based on octave band analysis.
    b) Topographic screening effects of the terrain should be limited to a reduction of no more than 2 dB, and then only if there is no direct line of sight between the highest point on the turbine rotor and the receiver location.
    c) A ground factor, G, of 0.5 should be used for propagation over any ground except water, paved surfaces or concrete. A soft ground factor of 1.0 should never be used, even if the ground is soft and a ground factor of 0.0 will tend to over-predict noise levels when the ground is soft, although it is appropriate when the ground is hard.
    d) Atmospheric conditions of 10°C and 70% humidity are recommended to represent a reasonably low level of air absorption.
    e) A receiver height of 4 m should be used to reduce the sensitivity of the results to the receiver region ground factor.
    f) A correction of +3 dB (or +1.5 dB if using $G = 0.0$) should be added to the calculated overall A-weighted noise level (see Section 2.2.11) for propagation 'across a valley', if 1.5 times the average of the source and receiver heights is less than the mean height above the ground of the line, R, joining the source and receiver. That is, if $0.75(h_S + h_R) < h_{mean}$. The reason for the increase is the reduced ground absorption effect and the possible presence of more than one reflected path from the turbine to the receiver (see Figure 1.8, which shows two possible reflection paths in a valley (R_1 and R_2).
    g) A measurement uncertainty of 2 dB should be added to measured turbine sound power levels before using them to calculate community noise levels.
    h) In converting L_{A90} noise levels to L_{Aeq} levels, 2 dB should be added to the L_{A90} levels for comparison with the L_{Aeq} predicted levels.

To further expand on the IOA good practice guide, a number of supplementary guidance notes were issued in 2014. The first (IOA 2014a) provides guidance on the following aspects of data collection.

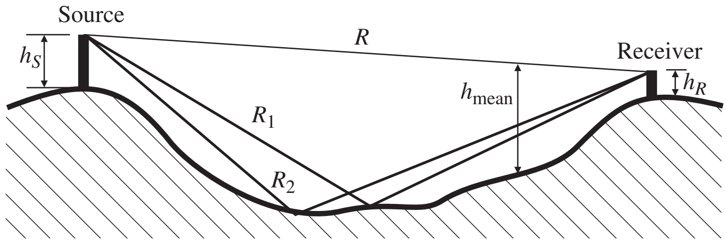

Figure 1.8 Valley between source and receiver

- Secondary wind screens should be used to reduce wind-induced noise on the microphones.
- Background noise measurements should be taken at least 3.5 m from a reflective surface.
- Measurement equipment should not be sited where noise levels are influenced by local noise sources specific to the measurement location.
- Care should be taken in the interpretation of wind speed data obtained using SODAR or LIDAR equipment, which measure wind speed as a function of altitude from a ground-based sonar or laser system, respectively (see Section 6.4.1).

The second note (IOA 2014b) provides guidance on the derivation of curves used to define existing background noise levels. Details are provided on how to analyse the data, including how to account for wind direction effects.

The third guidance note (IOA 2014c) provides more details on how to interpret sound power level data supplied by manufacturers, and how to include uncertainty in the sound power data.

The fourth guidance note (IOA 2014d) explains how to calculate the wind speed at hub height from measurement data at other heights, such as those obtained from an anemometer on a mast or SODAR data. The guidance note also explains how to adjust the wind turbine sound power output in cases where the measured wind speed at 10 m height is used instead of the standardised wind speed calculated as discussed in the previous section. The adjustment used is based on the plotted curve of turbine sound power output vs actual wind speed at a height of 10 m. In this case, the *Good Practice Guidelines* recommend a conservative correction based on shifting the turbine sound power level prediction curve to the 'left' along the wind speed axis (i.e. moving the curve to lower wind speeds) to account for the effects of wind shear. The recommended shift is 1 m/s for turbine hub heights of up to 30 m, 2 m/s for hub heights of up to 60 m and 3 m/s for hub heights of more than 60 m. However, the fourth guidance note provides a more accurate method that can be used if wind shear data are available. This involves either:

- shifting the turbine sound power level prediction curve to the 'left' along the wind speed axis as described above, but using a shift amount based on the measured wind shear rather than a fixed amount;
- correcting the background noise data regression curve (based on measured wind shear values) by shifting the background noise data to the 'right' along the wind speed axis (increased wind speeds for a given background level).

The fifth guidance note (IOA 2014e) is concerned with compliance measurement, mentioning the need for tonal analysis as well as recommending that background noise measurements be repeated with the wind farm shut down. A series of measurements are then taken in downwind conditions, with the turbines operating and shut down, and two sets of data corresponding to the two conditions are then plotted as a function of the standardised 10-m height wind speed. Curves of best fit are then derived for each data set and the turbine noise contribution is then determined by subtracting the level with the turbines off from the level with the turbines on, as described in Section 2.2.9, for each integer wind speed using the noise levels corresponding to the curves of best fit to the measured data.

The sixth guidance note (IOA 2014f) provides guidance for the calculation of noise propagation over water. The guidance note recommends that the ISO9613-2 noise propagation model be used with the hard ground correction, $G = 0$, provided that propagation over water is 50% or more of the total distance from the wind farm to the receiver. Where the body of water is at least 700 m in extent or the turbines are offshore, the expression in Eq. (1.7) should be used to calculate the noise level L_p at a receiver located at a distance r from the turbine rotor. If none of these conditions are met, the ISO9613-2 propagation model should be used.

$$L_p = L_w - 20\log_{10}(r) - 11 + 3 - A_{\text{atm}} + 10\log_{10}\left(\frac{r}{700}\right) \tag{1.7}$$

where L_w is the sound power level of the turbine and A_{atm} is the attenuation due to atmospheric absorption (see Section 5.2.2). Propagation modelling is discussed in more detail in Chapter 5.

Problems with the British Institute of Acoustics *Good Practice Guidelines*

Some of the problems associated with implementing ETSU-R-97 according to approach in the IOA *Good Practice Guidelines* and its six accompanying supplements are listed below.

1. There is no mention of accounting for the electronic noise floor of the instrumentation as described on page 20.
2. The simple wind speed measure at 10 m height recommended by ETSU-R-97 is now replaced by an *estimated* wind speed at 10 m height, where the least preferred method of obtaining the 10 m wind speed is to actually measure it at 10 m height, and even then the actual measurement should be adjusted. This is because the 10-m wind speed to be used is a reference wind speed based on the wind speed measured at hub height, h_H. That is, the standardised 10-m wind speed, $U_{10\text{m}}$, is obtained from the turbine hub-height wind speed, U_H, by correcting it to 10-m height, $h_{10\text{m}}$, using a ground roughness factor of $z_0 = 0.05$, without taking into account any atmospheric effects, using the following equation.

$$U_{10\text{m}} = U_H \frac{\log_e(h_{10\text{m}}/z_0)}{\log_e(h_H/z_0)} \tag{1.8}$$

Clearly, this will produce large errors in the 10-m wind speed in conditions of high wind shear. This explains the large scatter in data obtained when background noise levels are plotted as a function of the hub-height wind speed referenced to 10 m.

3. There is no requirement for turbine manufacturer data to include or exclude an allowance for uncertainty in the sound power measurement.
4. The step change in the ground effect of 3 dB that can occur when there is concave ground between the turbine and receiver (see item 12f above) can result in a 3-dB variation in noise predictions at the margin when the ground just satisfies the concave criterion, as it could depend on the accuracy of the height assumed for the receiver location and the methodology used to calculate the mean propagation height.
5. The allowable noise limits (especially at night) seem too high when compared to WHO recommendations and other jurisdictions. The anomaly of higher allowed noise levels at night than during the day needs to be addressed.

More recent standards such as IEC 61400-11 Ed. 3.0 (IEC 61400-11 2012) use the wind speed at hub height rather than at the 10-m reference height and this is reflected in more recent regulations as well. In this case, the wind speed is what is actually measured at hub height, or derived from the turbine power output, using the power curve supplied by the manufacturer for the particular turbine. This is discussed in more detail in Section 1.5.2.

1.4.2 National Planning Policy Framework for England

This policy framework sets out the UK government's planning policies for England and how these are expected to be applied. It was published in 2012 and updated in 2014 (UK Government 2015). The reason for introducing this guidance note here is that it is a contemporary view of what is acceptable and what is unacceptable in terms of community disturbance from noise. Although the policy provides clear guidelines regarding what action needs to be taken if noise affects a community, it does not provide any guidance regarding what percentage of people or number of people in a community have to be affected before action is taken. The guidance provided by the English National Planning Policy Framework, regarding the types of action that should be taken for various effect levels, is summarised in Table 1.2.

1.4.3 World Health Organisation Guidelines

Although not specifically targeted at wind farm noise, the World Health Organisation (WHO) has issued guidelines for acceptable environmental noise limits for Europe in 1999 (Berglund et al. 1999) and 2009 (Hurtley 2009), which in summary recommend an allowable nighttime indoors noise level of 30 dBA and an allowable outside level of 45 dBA, based on the assumption that the residential structure will result in 15 dBA noise reduction when the windows are open for ventilation. However, this is based on the annoying noise having a spectral distribution similar to traffic noise, which is dominated by mid-frequencies. The allowed levels were derived from surveys in urban and suburban environments where background noise levels are much higher than in rural environments. This results in an industrial noise source introduced into a rural environment being much more annoying than if it were introduced into an urban environment, so this alone is justification for requiring lower outside noise levels than recommended by the WHO documents.

Unlike traffic noise, wind farm noise is dominated by low frequencies at large distances (over 1.0–1.5 km) from the nearest turbine in a wind farm, and as was written in the 1999 WHO document:

Table 1.2 Action to be taken for different levels of noise.

Perception	Outcomes	Effect level	Action
Not noticeable	None	No observed effect	No measures required
Noticeable and not intrusive	Noise can be heard but doesn't cause any change in behaviour or attitude. Can slightly affect the acoustic character of the area but not such that there is a perceived change in the quality of life.	No observed adverse effect	No measures required
Noticeable and intrusive	Noise can be heard and causes small changes in behaviour and/or attitude, e.g. turning up volume of television; speaking more loudly; where there is no alternative ventilation, having to close windows for some of the time because of the noise. Potential for some reported sleep disturbance. Affects the acoustic character of the area such that there is a perceived change in the quality of life.	Observed adverse effect	Mitigate and reduce to a minimum, taking account of the economic and social benefits being derived from the activity causing the noise
Noticeable and disruptive	The noise causes a material change in behaviour and/or attitude, e.g. avoiding certain activities during periods of intrusion; where there is no alternative ventilation, having to keep windows closed most of the time because of the noise. Potential for sleep disturbance resulting in difficulty in getting to sleep, premature awakening and difficulty in getting back to sleep. Quality of life diminished due to change in acoustic character of the area.	Significant observed adverse effect	Avoid, as it is undesirable for such exposure to be caused
Noticeable and very disruptive	Extensive and regular changes in behaviour and/or an inability to mitigate effect of noise leading to psychological stress or physiological effects, e.g. regular sleep deprivation/awakening; loss of appetite, significant, medically definable harm, e.g. auditory and non-auditory.	Unacceptable adverse effect	Prevent. The impacts on health and quality of life are such that regardless of the benefits of the activity causing the noise, this situation should be prevented from occurring.

Source: English National Planning Framework, Planning Practice Guidance for Noise recommendations, 2014.

> …if the noise includes a large proportion of low-frequency components, values even lower than the guideline values will be needed, because low-frequency components in noise may increase the adverse effects considerably.

The WHO document also states that when prominent low-frequency components are present, as indicated when the difference between the C-weighted and A-weighted noise levels (see Section 2.2.11) exceeds 10 dB, then measures based on A-weighting are inappropriate. In addition, the residential-structure noise reduction assumed for European houses is much greater than measured in rural properties in more temperate climates such as in Australia. Also, the reduction for noise (such as wind farm noise) that is dominated by low frequencies is much less than for noise characterised by the spectrum typical of traffic noise, which is dominated by mid-range frequencies. It seems that most guidelines written specifically to assess and control the impact of wind farm noise have conveniently omitted the requirements listed below, which follow directly from the WHO guidelines:

- consideration of poorer noise-reducing characteristics of housing structures for low-frequency noise, which may result in higher than 30 dBA noise levels indoors when the noise is dominated by low frequencies such as wind farm noise;
- the greater potential for noise dominated by low frequencies to be more annoying than a more balanced noise spectrum;
- the fact that the WHO document applies to European houses, which are better noise insulators than houses in more temperate environments, such as rural Australia.
- the suggestion of a need for an alternative to the dBA metric for assessment when the noise spectrum is dominated by low frequencies.
- any recognition that background noise levels in rural environments is much less than background noise levels in suburban and urban environments in Europe, on which the WHO guidelines are based.

1.4.4 DEFRA Guidelines

In 2005, the University of Salford prepared guidelines for the assessment of low-frequency noise disturbance (Moorhouse et al. 2005). These guidelines have been applied to wind farm noise due to its dominance by low frequencies at distances exceeding approximately 1.0–1.5 km from the nearest turbine. After a very extensive literature review, the authors proposed that the noise will be annoying if the unweighted L_{eq} exceeds the DEFRA limit values in Table 1.3 in any 1/3-octave band.

Table 1.3 1/3-octave band unweighted noise limits (L_{eq}) recommended by DEFRA to avoid annoyance.

	1/3-octave band centre frequency (Hz)												
	10	**12.5**	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
DEFRA limit	92	87	83	74	64	56	49	43	42	40	38	36	34
Pure-tone annoyance threshold (night)	92	88	84	75	62	55	46	39	33	33	32	30	26

If the noise is steady, the limits in the table are increased by 5 dB. A steady noise is one that satisfies either of the following conditions, where the parameters are evaluated for each 1/3-octave band for which the criteria are exceeded:

- $L_{10} - L_{90} < 5$ dB
- The rate of change of sound pressure level ('fast' time weighting) is less than 10 dB/sec. This can be determined using a sound level meter capable of storing short time (<0.1 s) values of L_{eq}.

The DEFRA guidelines may be too high, as they are above the annoyance limits for pure-tone sound derived from the median threshold levels listed in the ISO standard, (ISO1996-1 2003) and the amount of exceedance of the threshold levels for the noise to be annoying Gottlob (1998). Of course, there will be 50% of the population who will be more annoyed than the levels based on median thresholds and to account for more than 97.5% of the population the threshold should be reduced by two standard deviations or 6 dB (see Section 7.3.4). However, if the noise is not tonal, it is likely to be less annoying, especially at the higher frequencies.

1.4.5 Noise Perception Index

Hunt and Hannah (2009) suggest that regulations should be based on the noise perception index (NPI), as first introduced by Hessler (2008) for general environmental noise. The NPI is calculated as follows.

$$\mathrm{NPI} = \frac{1}{N}\sum_{i=1}^{N}\left\{10\log_{10}\left[10^{L_{Aeq}/10} + 10^{(L_{A90})_i/10}\right] - (L_{A90})_i\right\} \tag{1.9}$$

where L_{Aeq} is the calculated noise level at the residence due to the wind farm, L_{A90} is the measured background noise level at the residence prior to construction of the wind farm and N is the number of 10-min periods of ambient noise measurement.

The expected community reaction is listed in Table 1.4 and some examples of NPI values that may be expected for wind farms (as determined by Hunt and Hannah (2009)) are listed in Table 1.5.

Although the NPI is rather over-simplified for wind farm noise, it could be used as a regulatory tool in addition to the other tools discussed in Section 1.6.

Table 1.4 NPI values for a range of receiver sites.

Calculated wind farm L_{Aeq}	Ambient sound level measured prior to wind farm, L_{A90}		
	High	Medium	Low
Low	NPI < 5	5 < NPI < 6	6 < NPI < 8
Medium	5 < NPI < 6	6 < NPI < 8	8 < NPI < 9
High	6 < NPI < 8	8 < NPI < 9	NPI > 9

After Hunt and Hannah (2009)

Table 1.5 Community perception of noise and community response as a function of the NPI value of the noise.

NPI (dBA)	Perception	Predicted community response
≤ 3	Generally imperceptible	No response
3–5	Barely perceptible to perceptible	No response to potentially adverse response
5–10	Perceptible to noticeable	Potentially adverse response to adverse response
> 10	Readily noticeable	Adverse response

1.5 Wind Farm Noise Standards

Environmental noise standards are not very widespread and those that exist generally, with a few exceptions, do not provide adequate guidance regarding acceptable environmental noise levels. In the following subsections, general environmental noise standards are discussed first, followed by a detailed discussion of three standards that are specifically directed at wind farm noise.

1.5.1 General Environmental Noise Standards

The five most well known general standards are discussed below.

ANSI S12.9-4 (2005)

This standard does not specify recommended maximum allowable A-weighted (see Section 2.2.11) levels but does state that the maximum allowable level specified in regulations should be reduced by 5 dB if the noise is impulsive and by a further 5 dB if the noise contains identifiable tones. The sound is considered to be dominated by low frequencies if the C-weighted level exceeds the A-weighted level by more than 10 dB. In that case, to minimise annoyance, the levels in the 16-, 31.5- and 63-Hz octave bands must all be less than 65 dB. There are also adjustments for sounds that increase rapidly in level at a rate greater than 15 dB/s.

ISO 1996

Although the 1971 version of this standard recommends maximum acceptable outdoor noise levels as listed in Table 1.6, the most recent version of the standard, published in 2007, does not recommend any maximum levels.

Other General Environmental Noise Standards

Other environmental noise standards such as BS7445-3 (1991), AS1055.2 (1997) and ASTM E1686-10 (2010) do not recommend acceptable noise limits and provide only vague guidance.

1.5.2 IEC 61400-11

This international standard does not provide advice on acceptable community noise levels, but is focussed on a description of procedures and instrumentation to be used for

Table 1.6 Recommendations for community noise limits according to ISO1996-1971.

District type	Day 7am–7pm (dBA)	Evening 7pm–11pm (dBA)	Night 11pm–7am (dBA)
Rural	35	30	25
Suburban	40	35	30
Urban residential	45	40	35
Urban mixed	50	45	40

the measurement and analysis of acoustic emissions from wind turbines. It includes a description of appropriate measurement positions for a microphone on the ground to measure the sound power of a wind turbine (see Section 4.6), determination of average sound pressure levels and corresponding wind speeds. Of particular interest is the procedure for calculating the uncertainty in the sound pressure level corresponding to a particular wind speed 'bin'. A wind-speed bin is 0.5 m/s wide and centred around integer and half-integer wind speeds. The uncertainty analysis for both sound pressure level and wind speed measurements is discussed in Section 4.6.

The standard uses hub height as the height of the reference wind speed. The wind speed is determined from the electric power output of the turbine for each wind-speed bin. The 'allowed range' of the power curve is defined as the parts of the power output vs wind speed curve for which the following relationship is satisfied:

$$(P_{k+1} - P_{\text{tol}}) - (P_k + P_{\text{tol}}) > 0 \tag{1.10}$$

where k is the wind speed bin number, P_k is the turbine electrical power output corresponding to wind speed bin, k, and P_{tol} is the tolerance on the power reading, which is the same for all bins, at typically 1% to 5% of the maximum value.

For the 'allowed range' of the power curve, the normalised hub-height wind speed, U_H is equal to the wind speed, U_P, corresponding to the turbine electric power curve. For all wind-speed bin numbers not included in the 'allowed range' of the power curve above, the hub-height wind speed, U_H, must be determined from the nacelle anemometer output, U_{nac}, as follows:

$$U_H = \kappa_{\text{nac}} U_{\text{nac}} \tag{1.11}$$

where the coefficient, κ_{nac}, is the value of U_P/U_{nac}, averaged over all wind speed bins included in the 'allowed range' of the power curve.

In cases where background noise levels are to be determined prior to construction of the wind farm, the corresponding wind speeds, U_z, must be measured at a height of at least 10 m above the ground at a typical turbine location, and these measurements are then used to derive corresponding hub-height wind speeds. The hub-height wind speed, U_H for the background noise measurements is then calculated as

$$U_H = \kappa_b U_z \tag{1.12}$$

where the coefficient, κ_b, is the value of U_P/U_z, averaged over all wind speed bins included in the 'allowed range' of the power curve.

The IEC standard also provides a procedure for determining whether or not audible tones are present. This is discussed in more detail in Section 6.2.12.

1.5.3 NZS6808

This standard is the only recent environmental noise standard that suggests acceptable community noise levels. In addition it outlines suitable methods for the prediction and measurement of wind farm noise. Although the standard specifies a generally acceptable noise level of 40 dBA (L_{A90}), the recommended allowed level is 35 dBA in areas of high amenity where existing background noise levels are very low, especially at night, and the average difference between wind farm predicted noise levels and ambient L_{A90} noise levels exceeds 8 dBA. The standard also allows for adjustment of the measured noise level if the noise contains special characteristics such as tonality, impulsiveness, amplitude modulation (see Section 2.2.7) or beating (see Section 2.2.6). The maximum adjustment allowed to account for the more annoying nature of the special characteristic is a 6-dBA increase to the measured noise level.

NZS 6808 (2010) also specifies two methods for calculating community noise levels; one based on ISO9613-2 (see Section 5.6) and the second based on a simplified version of ISO9613-2 (1996).

The standard covers the measurement of background noise levels as a function of wind speed at hub height prior to construction of the wind farm and compliance assessment measurements after construction. One interesting compliance checking technique suggested in the standard is to measure noise levels with and without turbines operating to obtain the contribution due to the turbines. However, the standard states that it is not necessary to turn off turbines that do not contribute significantly to noise levels at the measurement location. These turbines are those that collectively are calculated to contribute 10 dB less than the highest contribution from a single turbine.

Details of recommendations for compliance testing according to this standard are outlined in Section 6.2.14.

1.5.4 AS4959

AS4959 provides advice on choosing analytical models to use for estimating community noise levels using the turbine sound power levels as a basis. Advice is also provided on how to measure $L_{A90,10\text{min}}$ background noise levels and how to find the average as a function of wind speed at turbine hub height by regression analysis. For compliance testing, this standard suggests that $L_{A90,10\text{min}}$ be measured with the wind farm operational, thus representing a background plus wind farm $L_{A90,10\text{min}}$ measurement. The standard suggests that this would be a good approximation to the L_{Aeq} level produced by the wind farm only and thus should be used as a measurement to compare with L_{Aeq} criteria. The justification for this is that for wind farm noise in the absence of background noise, the $L_{A90,10\text{min}}$ measurements are lower than the $L_{Aeq,10\text{min}}$ measurements by between 1.5 and 2.5 dBA and this is the amount by which background noise may be expected to increase the $L_{A90,10\text{min}}$ measurement. This may be a reasonably accurate assumption in some situations, but one would not expect it to apply in all or even the majority of situations, especially at night when rural noise levels are very much lower than implied by the above equivalence. In this case, the L_{Aeq} level would be underestimated by 1.5 to 2 dBA, or possibly more.

An alternative compliance testing method is also provided and involves measuring $L_{Aeq,10\text{min}}$ levels directly with the turbines operational and also with them shut down. The turbine contribution is then found by subtracting the $L_{Aeq,10\text{min}}$ level without the turbines operating from the $L_{Aeq,10\text{min}}$ level with the turbines operating, as described in Section 2.2.9. No advice is provided regarding what community noise levels would be acceptable.

Details of recommendations for compliance testing according to AS 4959 (2010) are outlined in Section 6.2.14.

1.6 Regulations

Most regulations and governmental (or county) ordinances are based on standards and guidelines available at the time the ordinance was drafted. Many state government and local regulations are generated within the framework of a more general act of Parliament, with names such as The Noise Abatement Act, the Environmental Protection Act and the Control of Pollution Act. Under these acts it is unlawful to create a private or public nuisance, with the remedy being an abatement notice served by a local authority such as a council, or a magistrates' court order. Private nuisance is a civil wrong and recognises the right of someone to use their land without unreasonable disturbances from neighbouring property. In practice, the bar is usually set fairly high so that minor problems such as annoyance are not considered to be a nuisance in law.

Statutory nuisances are nuisances that have been declared as such in an Act of Parliament. For example, the 1990 Environmental Protection Act in the UK provides that 'noise emitted from premises and being prejudicial to health or a nuisance' shall constitute a statutory nuisance. However, whether a noise is a nuisance or not is not defined by its character, level or duration, but by the subjective assessment of a court, which makes it very difficult to obtain a ruling against such a huge operation as a wind farm, especially if the court believes that wind farms are of benefit to society as a whole. Thus it is prudent for local government to rely on their own regulations to specify allowable noise levels and any penalties to compensate for the annoying character of the noise.

1.6.1 What Should be Included in a Wind Farm Noise Regulation?

Suggestions for a general wind farm regulation may be found in a paper by the AWED (2016). However, based on our experience with wind farm noise data collection and analysis and residents, we believe that to minimise the impact of wind farm noise on local communities, a local wind farm noise regulation should also include the features outlined in the following subsections.

Minimum Setback Distance to Residences

The setback distance is the distance from the nearest turbine in a wind farm to a residence, provided that the resident is not a turbine host. Shepherd et al. (2011) recommend that the setback distance should be more than 2 km in hilly terrain. However, noise measurements by the authors of this book indicate that for modern wind farms with turbine powers of 3 MW and greater, the setback distance should be much larger than 2 km if intrusive noise at noise-sensitive locations is to be at acceptable levels at night when people are trying to sleep. In addition there should be a minimum setback distance of 4 to 5 times the total turbine height (nacelle height plus blade length) to the nearest neighbour's property line.

Maximum Allowed Calculated External Noise Levels

Maximum allowed calculated external noise levels 30 m from the residential structure should be as listed in Table 1.7 at the exterior of homes of any residents not hosting turbines. These levels are those recommended by the international standard, ISO 1996 (1971).

However, as wind turbines are mostly in rural areas, a level of 25 dBA is very difficult to achieve, which is why the most stringent regulations currently in force recommend a limit of 35 dBA in sensitive noise areas. However, this limit is too high for many residents so 30 dBA may be a reasonable compromise for the maximum allowed noise at the exterior of rural residences.

Kamperman and James (2008) have studied a number of wind farms and their effects on residences and have made the following recommendations.

- An allowed A-weighted (see Section 2.2.11) nighttime limit of 35 dBA or L_{A90}+5 dBA, whichever is *lower*, where L_{A90} is determined using several 10-min measurements during the quiet night hours between 10pm and 4am when the wind is blowing slightly (<2 m/s at 1.5 m above the ground) from the wind farm to the residence and the wind farm is not operating. Daytime levels can be 5 dBA higher.
- A maximum C-weighted noise level of 50 dBC for properties more than 1.6 km from a major highway and 55 dBC for properties less than 1.6 km from a major highway.
- A maximum allowed difference of 20 dB between the measured L_{A90} prior to construction of the wind farm and the C-weighted L_{Ceq} with the wind farm operating.
- A maximum allowable difference in the A-weighted noise level with and without turbines operating. That is, $L_{Aeq} \leq L_{A90} + 5$, where L_{Aeq} is the A-weighted equivalent noise level with the turbines operating and L_{A90} is the A-weighted level exceeded 90% of the time when the turbines are not operating. As turbine L_{Aeq} levels are between 1.5 and 3 dB above turbine L_{A90}, an increase of 5 dBA in the L_{A90} background noise approximately represents a turbine noise source generating the same noise level as the existing background noise, thus raising the background noise level by 3 dBA (see Section 2.2.8).

Table 1.7 ISO1996-1971 recommendations for allowable community L_{Aeq} noise limits.

District type	Day (7am–7pm) (dBA)	Evening (7pm–11pm) (dBA)	Night (11pm–7am) (dBA)
Rural	35	30	25
Suburban	40	35	30
Urban residential	45	40	35
Urban mixed	50	45	40

- To minimise the influence of wind noise on background noise measurements, L_{A90} results are valid when L_{A10} results are no more than 10 dBA above L_{A90} for the same time period.
- A 5 dB penalty is to be applied if any tones are audible.

Adjustment for Uncertainties

Any noise level calculated using a generally accepted propagation model with downwind conditions included, should have 4 dBA added to the calculated level to account for uncertainties in turbine sound powers and uncertainties in the propagation model parameters. A fine example of the under-prediction of wind farm noise levels is presented in Stigwood et al. (2015, Fig. 1). This figure clearly shows that the ISO9613-2 predictions are consistently 2–4 dB above the average of the measured data over the entire range of standardised wind speeds at 10 m. The difference between the predictions and the level exceeded 10% of the time is approximately twice that.

Maximum Allowed Calculated Low-frequency Noise Level

Maximum allowed calculated low-frequency noise level in the range 10–160 Hz should be less than 25 dBA at the exterior of homes of any residents not hosting turbines, with a 4 dBA allowance for calculation uncertainty, so the calculated level is actually less than 21 dBA. The reason for using an A-weighted level is that it is comparable to the existing Danish low-frequency noise requirement for calculating interior noise levels. The DEFRA criteria for external low-frequency noise in Table 1.3 should also be satisfied and perhaps revisited to ensure that the recommended levels are sufficiently low.

Maximum Allowed Amplitude Modulation

A maximum allowed amplitude modulation (AM) amount should be defined and the means by which this should be measured is discussed in Section 6.2.10. However, the metric to be used and the recommended allowable level is still under discussion (AMWG 2015). Alternatively, a penalty should be added to the L_{Aeq} or L_{90} measurements to account for amplitude modulation. Renewable UK (2013) recommend the following:

> …for AM with a peak to trough level of less than 3 dB there should be no AM penalty; for AM with a peak to trough level of 3–10 dB there is a sliding scale of penalties ranging from 3–5 dB; and for AM with a peak to trough level of $\geq$ 10 dB there is 5 dB penalty.

However, the alternative of only a penalty on the allowed total A-weighted level has not been generally accepted and is not preferred by many researchers AM is a cause of annoyance even for low-level A-weighted noise, as excessive AM is mainly a low-frequency noise problem (Renewable Energy Foundation 2014). Amplitude modulation is defined and discussed in Section 2.2.7.

Compliance measurements typically require the accumulation of a large number of data points of L_{Aeq} or L_{90} vs standardised wind speed at 10 m or wind speed at hub height. A regression line is then drawn through the data and this is defined as the turbine noise level (after background noise has been accounted for). However, the following points need to be taken into account when deciding how to include a penalty for amplitude modulation.

- Amplitude modulation is most apparent when the L_{Aeq} or L_{90} levels are at their lower end (Stigwood et al. 2015).
- As a result, if the penalty is applied to the individual measurements during which AM was detected, the effect of the penalty on the regression line will be negligible in almost all cases.
- Thus it is recommended that if amplitude modulation exceeds the allowable level for a greater percentage of 10-minute measurements than is considered acceptable, then the AM penalty should be applied to the average data for each wind speed at which AM was detected.

Minimum Turbine Spacings

Allowed minimum turbine spacings should be at least 10 blade lengths (5 rotor diameters) for turbines that are downwind of any others. This applies to all turbine spacings for wind farms where there is no dominant prevailing wind. When turbines are not downwind of any others, the spacing should be at least 7 blade lengths (3.5 rotor diameters). This could apply to turbines arranged along a ridge in a line normal to the prevailing wind direction. If these spacings (or alternative spacings recommended by the turbine manufacturer) are not maintained, turbine sound power levels that are higher than those specified by the manufacturer will result, due to inflow turbulence as a result of wakes from upstream turbines.

Allowance for Increased Noise in Hilly Terrain

An allowance should be made for increased turbine sound power levels for turbines located in hilly terrain where the in flow will be more turbulent and off-axis.

Penalty for Tonal or Impulsive Noise

There should be a 5 dBA penalty applied to the allowable limit if tonal noise is present or if the noise is impulsive. If both are present the penalty should be 8 dBA.

Accounting for Multiple Wind Farms

There should be a requirement that takes into account the development of more than one wind farm in the same general area. The existing ambient sound level should be the one that existed prior to construction of the first wind farm.

Determination of a Compliance Testing Method

A compliance testing method should be defined. Some suggestions regarding how this may be done, based on what has been published in the literature as well as the authors' own experience, are outlined below.

- Noise levels should be measured between the hours of 11pm and 5am when there is high wind shear so that the turbines are rotating and producing more than 70% of their rated power, while the wind speed at the residence where compliance testing is being performed is less than 2 m/s.
- Adequate wind screening of the microphones should be specified for all noise measurements. This means that secondary wind screens should be used and microphones should be mounted on the ground to minimise the wind speed over the microphone.
- As wind farm noise levels are generally quite low, it is difficult to accurately measure L_{Aeq} levels due to the influence of extraneous noise. It is therefore preferable to measure L_{A90} levels and add 2 dB to obtain the approximate L_{Aeq} level. The L_{Aeq} level due to

the turbines is the level that should be compared with the measured background L_{A90} level when determining how many decibells the turbine noise is above background noise levels.

- Measurements should be done with and without the wind farm operating for the same weather conditions. The determination of the wind-farm-only contribution to the noise levels when the wind farm is operating may be determined using one or both of the following methods, although the second one may be a little complex to include in a regulation.
  1. The measured data should be divided into nighttime (11pm to 5am) and the remainder (5am to 11pm). Of particular importance are the nighttime levels. The data should be further divided into turbine OFF and turbine ON levels and only downwind conditions should be considered (with a ±45° angle allowed from direct downwind). Data containing local noise source events should be discarded, as should data recorded when it is raining. In addition, data that includes the early morning bird chorus should be discarded. The remaining A-weighted (see Section 2.2.11) noise-level data should be plotted as a function of wind speed at hub height and a curve of best fit plotted through the data points for the nighttime data and then separately for the remaining (daytime and evening) data. To obtain the wind farm contribution, the level with the turbines OFF should be subtracted logarithmically from the level with the turbines ON, as described in Section 2.2.9, for each integer wind speed, using the noise levels corresponding to the curves of best fit to the measured data. It is well known that turbine noise is most annoying at night at times of high wind shear. This situation often corresponds to there being low or no wind at the residence but significant wind at turbine height, an occurrence that is relatively common in some regions. This results in lower background noise levels at times of high wind shear, so it is suggested that nighttime data should be further divided into low and high wind shear conditions. Long-term measurements by Bigot et al. (2015) showed that month-long average noise levels for an average wind shear exponent of 0.42 (high wind shear) were between 3 and 8 dB higher (depending on the hub-height wind speed) than they were for a shear exponent of 0.25 (low wind shear). This is discussed in more detail in Section 5.2.4.
  2. Alternatively, the data in each grouping just described can be presented as a probability density function plot, as described by Ashtiani (2013, 2015). This method calculates the probability of the existence of a particular dBA level that is due only to the turbine operation. Clearly, the probability of the existence of a particular dBA level will depend on the chosen dBA level and there will be some dBA levels with a much higher probability of occurrence than others, although implementation of the method is quite complex. Its advantage for compliance checking is that it allows regulations to be set along the lines of 'wind farm noise levels should not exceed x dBA for more than 10% of the time'. It also allows the percentage of time that a wind farm is non-compliant to be determined. This method is discussed in more detail in Section 6.2.14.
- In the non-operating condition, all cooling fans and power supplies in the turbine nacelles must be switched off.

- Data recorded prior to construction of the wind farm should also be considered, as even a non-operating wind farm can contribute to background noise levels as a result of wind blowing over the support tower and stationary blades.
- The level of amplitude modulation should be measured using one of the methods described in Section 6.2.10. Perhaps the simplest method is that used by Tachibana (2014), which is described in Section 6.2.10.
- Wind farm operators must be required to make nacelle and mast wind data and turbine output data publicly available in an accessible format to enable compliance checking by any party.
- Compliance management procedures should be required as part of any development approval and should include continuous real-time measurement of noise over the frequency range from 0.5 Hz to 2000 Hz and include quantification of undesirable characteristics such as modulation and tonality.

Instrument Specifications

Desirable instrumentation specifications for background noise and compliance measurements include:

- an electronic noise floor at less than 10 dBA (to allow accurate background noise level measurements down to 20 dBA or corrected background noise measurements to 13 dBA)
- the ability to measure linearly down to 0.5 Hz or linearly down to 10 Hz and then down to 0.5 Hz with a calibrated 'roll-off'.
- secondary wind screens in addition to primary wind screens to protect measurement microphones from wind-induced noise, as discussed in Section 6.2.3.

No Change to Turbine Model

The wind farm developer should not be permitted to change the turbine model after development approval has been given without undertaking another noise prediction study with the new turbines. If the resulting sound levels at any residence are higher than originally calculated, an amendment to the development approval should be sought.

Acoustic Study Funding

The government body responsible for compliance assessment should be funded by the wind farm developer to choose and hire an acoustic consultant to do the testing independent of any influence from the developer.

Decommissioning Costs

Although not related to noise, it is important that any regulation specifies a required upfront payment for decommissioning (of the order of $350 000 per turbine in 2011 US dollars, put into a long-term investment account or bonds), as it is likely that the company installing the wind farm will not be around when its design life expires (usually 25 years).

Property Value Assessment

Another item not related to noise but important nevertheless, is that the value of properties within 5 km of a wind farm should be assessed by an independent commercial property assessor appointed by the local council prior to construction, and the difference between that valuation and any sale price achieved within one year post construction should be paid to the resident by the wind farm operator at the time of sale. Alternatively, if the property cannot be sold for a reasonable price, the wind farm operator should be required to purchase the property at the market value prior to construction of the wind farm.

1.6.2 Existing Noise Ordinances and Regulations

There are a multitude of noise ordinances and regulations in existence, so only a summary of some of these are listed in Tables 1.8–1.10 below (see Fowler et al. (2013) and Batasch (2005)). In the tables, allowed evening levels are similar to daytime levels except where indicated.

It is abundantly clear from Tables 1.8, 1.9 and 1.10 that there is very little commonality between different jurisdictions, both in terms of the allowed noise levels and the metric used to quantify them. Notes that should be read in conjunction with Tables 1.8–1.10 are listed below. The notes that are relevant to the various jurisdictions in the tables are indicated by superscript numbers adjacent to the name of the applicable country, state or county.

1. The quantities $L_{A90,10\mathrm{min}}$, L_{Aeq}, L_{dn} and L_{den} are defined in Section 2.2.12.
2. In many jurisdictions, a 5-dB penalty is applied if the turbine noise has readily identifiable tonal components. In Germany the penalty is 3 dB or 6 dB, depending on the distinctiveness of the tones. However, there is a relatively stringent definition of what constitutes a tone and this is discussed in more detail in Section 6.2.12,
3. In Norway, France, the Netherlands and many places in the USA, no tonal penalty is applied.
4. Daytime usually refers to the hours between 7am and 7pm, evening between 7pm and 10pm and nighttime is between 10pm and 7am. Exceptions are:
   - the UK, where 10pm is replaced with 11pm and evening is defined as between 6pm and 11pm
   - Arapahoe County in Colorado, where the 11pm is replaced with 7pm
   - the Netherlands, where 10pm is replaced with 11pm and evening is defined as between 7pm and 11pm
   - Italy, where daytime is 7am to 9pm, evening is 9pm to 11pm and nighttime is 11pm to 7am.
5. In Italy, there is an additional requirement that a noise source cannot exceed existing L_{A90} background noise levels in residential areas by more than 3 dBA at night and 5 dBA during the day, except for industrial areas and residences near major roads.
6. In some of the cases listed in the tables, the levels are not legislated but are merely guidelines or standards. However, local authorities usually follow the guidelines in terms of setting allowable levels for each development.
7. In some of the cases listed in the tables, different allowable levels are specified for locations where the background noise is low. These are the values that are listed in the tables, as almost all wind farms are located away from densely populated areas so that background noise levels around typical wind farm developments are almost always low.
8. In Flanders, Belgium, the evening limits (between 7pm and 10pm) are the same as the nighttime limits.

Table 1.8 Noise metrics and threshold limits for Western USA.

State or county	Setback distance	Noise metric	Rural		Residential		Residential, near industry	
			Day	Night	Day	Night	Day	Night
California (Alameda)	N/A	L_{50}	–	45	–	45	–	45
California (Contra Costa)	N/A	L_{dn}	60	60	60	60	60	60
California (Fairfield)	N/A	L_{Aeq}	–	45	–	45	–	45
California (Fresno)	N/A	L_{50}	–	45	–	45	–	45
California (Kern)	N/A	L_{dn}	50	50	50	50	50	50
California (Kern)	N/A	$L_{A8.3}$	45	45	45	45	45	45
California (Monterey)	N/A	L_{den}	45–55	45–55	45–55	45–55	45–55	45–55
California (Morro Bay)	N/A	L_{Aeq}	–	45	–	45	–	45
California (Riverside)	2–3000 ft	L_{Aeq}	60	60	60	60	60	60
California (Sacramento)	N/A	L_{50}	–	50	–	50	–	50
California (San Bernadino)	N/A	L_{Aeq}	–	45	–	45	–	45
California (San Francisco)	N/A	L_{Aeq}	55	50	55	50	55	50
California (San Joaquin)	N/A	L_{Aeq}	–	45	–	45	–	45
California (Santa Cruz)	N/A	L_{Aeq}	–	40	–	45	–	45
California (Solano)	2000 ft	L_{Aeq}	44	44	44	44	44	44
California (Solano)	2000 ft	L_{den}	50	50	50	50	50	50
Colorado	N/A	L_{Aeq}	50	50	50	50	50	50
Colorado (Arapahoe)[3]	$H + B$	L_{Aeq}	55	50	55	50	55	50
Nevada (Lyon)[3]	$2(H + B)$	L_{Aeq}	55	55	55	55	55	55
New Mexico (San Miguel)[3]	0.5 miles	L_{Aeq}	<bk	<bk	<bk	<bk	<bk	<bk
Oregon[3,13,15]	N/A	L_{A50}	36	36	36	36	36	36
Washington	N/A	L_{Aeq}	60	50	60	50	70	70
Washington	N/A	L_{A25}	65	55	65	55	75	75
Washington	N/A	$L_{A16.7}$	70	60	70	60	80	80
Washington	N/A	$L_{A2.5}$	75	65	75	65	85	85
Wyoming (Laramie)[3]	$5.5H$	L_{Aeq}	50	50	50	50	50	50
Wyoming (Plympton)[3,12]	N/A	$L_{Ceq} - L_{Aeq}$	15	15	15	15	15	15

Background noise is usually measured using the $L_{A90,\,10\text{min}}$ metric. However, the wind farm noise is measured using the metric indicated in column 3 of the table. The term <bk, means that introduced wind farm noise must be less than existing background noise levels, which implies that the introduced noise can increase existing noise levels by a maximum of 3 dB; H is the hub height of the turbine; B is blade length.

Table 1.9 Noise metrics and threshold limits for Eastern USA.

State or county	Setback distance	Noise metric	Rural		Residential		Residential, near industry	
			Day	Night	Day	Night	Day	Night
Georgia[3]	Various	L_{Aeq}	55	55	55	55	55	55
Illinois[3,13]	N/A	L_{eq}	Table 1.11					
Indiana (Tipton)[3,13]	N/A	L_{eq}	Table 1.11					
Maine (Freedom)[21]	13H	L_{Aeq}	40	35	40	35	40	35
Michigan[3,10]	N/A	L_{Aeq}	55	55	55	55	55	55
Michigan (Huron)[2,10]	N/A	L_{A90}	55	55	55	55	55	55
Minnesota[3]	N/A	L_{Aeq}	50	50	50	50	50	50
Minnesota (Lincoln)[3]	750 ft	L_{Aeq}	50	50	50	50	50	50
New York (Jefferson)[2,10]	1000 ft / 5 H	L_{A10}	50	50	50	50	50	50
North Carolina[3]	$2.5(H + B)$	L_{Aeq}	55	55	55	55	55	55
North Carolina (Carteret)[16]	$2.5(H + B)$	L_{Aeq}	35	35	35	35	35	35
Pennsylvania (Potter)[3]	1750 ft / $5(H + B)$	L_{Aeq}	bk+5	bk+5	bk+5	bk+5	bk+5	bk+5
Wisconsin	N/A	L_{Aeq}	50	45	50	45	50	45
Wisconsin (Shawano)[2,14]	1250 ft / $3.1(H + B)$	L_{Aeq} Table 1.12	bk+5	bk+5	bk+5	bk+5	bk+5	bk+5

Background noise is usually measured using the $L_{A90,\,10\text{min}}$ metric. However, the wind farm noise is measured using the metric indicated in column 3 of the table. The term, bk+5, means that introduced wind farm noise must be less than 5 dBA above the existing background noise levels; H is the hub height of the turbine; B is the blade length.

9. The South Australian guidelines distinguish between rural living and rural industry, with the latter defined as any farming residence on a farm producing any rural produce for sale. This means that farmers can be subjected to 5 dBA more noise than non-farming residents, irrespective of how noisy their farming operation may be and irrespective of whether it produces noise at night.
10. In the UK, Michigan in the USA, Jefferson County in New York USA, New Zealand and all states of Australia, the allowed level is the greater of the level specified in the table and existing background noise plus 5 dB, where the background noise levels are determined from 10-min $L_{A90,\,10\text{min}}$ data points (that is, the level exceeded 90% of the time during the 10-min period), plotted as a function of wind speed at hub height, which can be measured at hub height or calculated from a measurement at a lower height. Daytime background noise level data are combined with nighttime noise level data and plotted as a function of 10-min averaged hub-height wind speed, where the 10-min wind speed average is the same period as the 10-min noise level. A total of 2000 data points are needed, with at least 500 representing the condition

Table 1.10 Noise metrics and threshold limits for countries outside the USA. *H* is the total height of the turbine (hub height plus blade length) and *B* is the blade length. Wind speeds are at 10 m height.

State or county	Setback distance	Noise metric	Rural		Residential		Residential, near industry	
			Day	Night	Day	Night	Day	Night
Australia (SA)[2,9,10]	1000 m	$L_{A90,\,10\text{min}}$	40	40	40	40	40	40
Australia (VIC)[2,10]	2000 m	$L_{A90,\,10\text{min}}$	40	40	40	40	40	40
Australia (QLD)[2,10,20]	1500 m	L_{Aeq}	37	35	37	35	37	35
Australia (NSW)[2,10]	2000 m	L_{Aeq}	35	35	35	35	40	40
Australia (WA)[2,10]	2000 m	L_{Aeq}	35	35	35	35	40	40
Belgium (Flanders)[3,8]	6*B*	L_{Aeq}	48	43	44	39	44	39
Belgium (Wallonia)[3]	3*H*	L_{Aeq}	45	45	45	45	45	45
Canada (Alberta)[3,18]	N/A	L_{Aeq}	–	40	–	43–46	–	43–46
Canada (British Columbia)[3]	N/A	L_{Aeq}	40	40	40	40	40	40
Canada (Manitoba)[3,19]	N/A	L_{Aeq}	40	40	40	40	40	40
Canada (New Brunswick)[3,19]	N/A	L_{Aeq}	40	40	40	40	40	40
Canada (Ontario)[3,19]	N/A	L_{Aeq}	40	40	45	45	45	45
Canada (Prince Edward Is.)[3]	3*H*	–	–	–	–	–	–	–
Denmark[2,17]	4*H*	L_{Aeq}	42–44	42–44	37–39	37–39	37–39	37–39
Denmark[2,17]	4*H*	$L_{Aeq,LF}$	25(in)	20(in)	25(in)	20(in)	25(in)	20(in)
France[3,11]	N/A	L_{Aeq}	35	35	35	35	35	35
Germany[2,11]	N/A	L_{Aeq}	50	35	50	35	55	40
Ireland	N/A	L_{Aeq}	40	40	40	40	40	40
Italy[4,5]	N/A	L_{Aeq}	50	40	55	45	60	50
New Zealand[2,10]	N/A	$L_{A90,\,10\text{min}}$	40	35	40	40	40	40
Norway[3]	N/A	L_{den}	45	45	45	45	45	45
Sweden[2]	N/A	L_{Aeq} at 8 m/s	35	35	40	40	40	40
Switzerland	N/A	L_{Aeq}	50	40	50	40	50	40
The Netherlands[3,4]	N/A	L_{den}	47	47	47	47	47	47
The Netherlands[3,4]	N/A	L_{night}	41	41	41	41	41	41
United Kingdom[2,4,10]	N/A	$L_{A90,\,10\text{min}}$	35–40	43	35–40	43	35–40	43

The label, (in) means indoor noise level.

where the wind is blowing from the wind farm to the measurement location (±45° from the direct downwind direction).

11. For France and Germany the allowed level is the greater of the level specified in the table and existing background noise plus 5 dB during the day, and plus 3 dB at night. In France, an adjustment is allowed so that allowable noise limits can be raised by 1, 2 or 3 dBA when the exceedance occurs for periods of 4–8 h, 2–4 h or 20–120 min, respectively.
12. The town of Plympton in Wyoming, USA has focussed its regulations entirely on the low-frequency and infrasonic part of the noise spectrum. No tones, in the frequency range 0–20 Hz and with a sound pressure level exceeding 50 dB

when energy-averaged over several minutes, are allowed inside of a residence if the peaks exceed the RMS sound pressure level by more than 10 dB. In addition, the maximum allowed difference between the unweighted sound pressure level in the range 0.1 Hz and above and the A-weighted level (see Section 2.2.11) cannot exceed 20 dB.

13. Tipton County in Indiana and Oregon specify allowable octave band limits in the frequency range from 63 Hz to 8 kHz (see Table 1.11).

Table 1.11 Octave band noise limits in Illinois (L_{eq}) and Oregon (L_{50}).

	Octave band centre frequency (Hz)								
	31.5	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Illinois, day	75	74	69	64	58	52	47	43	40
Illinois, night	69	67	62	54	47	41	36	32	32
Tipton County (IN)	–	75	70	65	59	53	48	44	41
Oregon, day	68	65	61	55	52	49	46	43	40
Oregon, night	65	62	56	50	46	43	40	37	34

14. Shawano County in Wisconsin, USA specifies the allowable 1/3-octave band noise limits (L_{eq}) listed in Table 1.12.

Table 1.12 1/3-octave band noise limits in Shawano County (WI) (L_{eq}). The 70 dB in bands 2–12.5 Hz is for each band in that range.

1/3-octave band centre frequency (Hz)																
2–12.5	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**
70	68	68	67	65	62	60	57	55	52	50	47	45	42	40	37	35

15. In Oregon USA, the allowed increase of any noise source above the existing ambient is 10 dBA (L_{A50}) and the minimum allowed ambient noise level for this consideration is 26 dBA, so that the maximum allowed noise level is never less than 36 dBA, even in very quiet environments.
16. In Carteret County, North Carolina, the allowed level can be exceeded any number of times for a maximum of 5 consecutive minutes at any property line.
17. In Denmark, the lower limits apply to a wind speed of 6 m/s and the upper limits apply to a wind speed of 8 m/s. Also the low-frequency limit ($L_{Aeq,LF}$) is a calculated indoor level as described in Section 5.4.
18. In Alberta, Canada, the levels are for residences that are more than 500 m from a heavily travelled road or railway and which are not subjected to frequent aircraft overflights. For residences between 30 and 500 m from a heavily travelled road or railway, 5 dB is added to the levels in the table and for residences less than 30 m

from a heavily travelled road or railway or which are subjected to frequent aircraft overflights, 5 dB is added to the levels in the table.

19. In Manitoba, New Brunswick and Ontario, Canada the allowable levels in rural and residential areas vary as a function of wind speed at 10 m height, as shown in Table 1.13.

Table 1.13 Allowed wind farm L_{Aeq} noise levels in three Canadian provinces

10-m height wind speed (m/s)	4	5	6	7	8	9	10	11
Allowed everywhere, Manitoba	40	40	40	43	45	49	51	53
Allowed everywhere, New Brunswick	40	40	40	43	45	49	51	53
Allowed rural, Ontario	40	40	40	43	45	49	51	
Allowed residential, Ontario	45	45	45	45	45	49	51	

20. In Queensland, Australia, nighttime (10pm to 6am) background noise levels are separated from daytime levels when determining how much greater wind farm noise is than background noise levels. In addition, maximum allowed C-weighted (L_{Ceq}) levels of 60 dBA at night and 65 dBA during the day are specified.
21. The limits in the town of Freedom, Maine, USA are 'not to exceed' limits and in addition there are C-weighted limits that are not to be exceeded. The post-construction C-weighted measurement cannot be more than 20 dBC above the pre-construction measured A-weighted ambient noise level. In addition, 50 dBC is not to be exceeded at any time.

1.7 Inquiries and Government Investigations

There have been numerous court cases in which residents have opposed planned wind farm developments as well as existing developments, and these are too numerous to list here. There are very few examples of successful litigation by residents, although in some cases wind farm operations have been limited to daytime and evening hours.

There have been a number of government-related inquiries, investigations and action plans directed at wind farms in a number of countries. Many of these include wind farm noise as a priority issue. Those mentioned below are those for which information is publicly accessible.[1]

1.7.1 Australia 2010–2014

In Australia, there have been four inquiries into the effects of wind farms on health: two by the National Health and Medical Research Council (NHMRC) and two by the Australian Senate.

1 The conclusions of the various reports are mostly reproduced verbatim, but with occasional minor edits.

NHMRC 2010, 'Rapid Review of the Literature on the Effects of Wind Farms on Human Health'

This study, undertaken by the NHMRC, was a 'rapid review' of the literature and concluded the following:

- There are no direct pathological effects from wind farms and any potential impact on humans can be minimised by following existing planning guidelines.
- There is currently no published scientific evidence to positively link wind turbines with adverse health effects.
- Noise levels from wind turbines have been assessed as negligible; that is, they appear to be no different to levels found in other everyday situations.
- A survey of all known published results of infrasound from wind turbines found that wind turbines of contemporary design, where rotor blades are in front of the tower, produce very low levels of infrasound.

This study attracted considerable criticism as it ignored much evidence that acoustical and medical experts considered should have been included. It has now been rescinded in light of the more recent study described below and reported in February 2015.

NHMRC 2013/14/15, 'Comprehensive Review of the Effects of Wind Farms on Human Health'

The NHMRC undertook a comprehensive review of the literature in 2013 and 2014 to determine whether or not wind farms produced any adverse health effects. All of the reviewed studies were considered irrelevant or of poor quality and thus were not able to be used to arrive at a conclusion. The review then used parallel studies of the effects of other noise sources with similar A-weighted noise levels (see Section 2.2.11). In addition, no studies were identified that specifically looked at possible effects on human health of infrasound. The findings published by the NHMRC are listed below and these are followed by a detailed critique of the entire approach:

- There is currently no consistent evidence that wind farms cause adverse health effects in humans.
- There is no direct evidence that exposure to wind farm noise affects physical or mental health. There are unlikely to be any significant effects on physical or mental health at distances greater than 1500 m from wind farms.
- There is consistent but poor-quality direct evidence that wind farm noise is associated with annoyance. Bias of different kinds and confounding factors are possible explanations for the associations observed.
- There is less consistent poor-quality direct evidence of an association between sleep disturbance and wind farm noise. However, sleep disturbance was not objectively measured in the studies and bias of different kinds and confounding factors are possible explanations for the associations observed. While chronic sleep disturbance is known to affect health, the parallel evidence suggests that wind farm noise is unlikely to disturb sleep at distances of more than 1500 m.
- There is no direct evidence that considered possible effects on health of infrasound or low-frequency noise from wind farms.
- Background evidence indicates that wind farm noise is generally in the range of 30–45 A-weighted decibels (dBA) (see Section 2.2.11) at a distance of 500–1500 m from a

wind farm and below 30–35 dBA beyond 1500 m. Although individuals may perceive aspects of wind farm noise at greater distances, it is unlikely that it will be disturbing at distances of more than 1500 m.

In summary, the NHMRC has labelled all evidence as poor, bringing them to the first conclusion stated above. Of course, there is ample evidence in the literature that does not support this conclusion, nor the conclusion that wind farms have no effect on sleep for residents at distances greater than 1500 m. The study seems to be biased towards the wind farm industry, as the first statement could equally have been written as 'There is currently no consistent evidence that wind farms do *not* cause adverse health effects in humans', which would have resulted in an entirely different perception by the community. The emphasis in the report on 'confounding factors' and the many statements that findings of health effects or sleep problems could be due to causes other than wind farms also negates the findings of many worthwhile studies published in peer-reviewed journals.

As one may expect, the NHMRC review findings have attracted a substantial amount of criticism. As stated by Hanning (2015),

> …in considering the evidence, NHMRC adopted inappropriately strict evidential criteria. This is the reactionary approach to public health risks and is clearly not in the public interest. Action in defence of the public health does not require certainty. In addition, they have turned the burden of proof on its head. It is the wind industry's duty to prove the safety of its activities not that of the public.

However, the review does recommend that more research should be done.

South Australian Parliamentary Committee on Wind Farm Developments in South Australia

This committee was formed in 2012, received over 150 submissions and produced no publicly available report or recommendations.

Australian Senate, Community Affairs References Committee, 2011

The Australian Senate Community Affairs References Committee investigated the social and economic impact of rural wind farms in 2011 and published a report with the following recommendations related to wind farm noise.

- Noise standards adopted by the states and territories for the planning and operation of rural wind farms should include appropriate measures to calculate the impact of low-frequency noise and vibrations indoors at impacted dwellings.
- Further consideration should be given to the development of policy on separation criteria between residences and wind farm facilities.
- The Commonwealth Government should initiate as a matter of priority thorough, adequately resourced epidemiological and laboratory studies of the possible effects of wind farms on human health. This research must engage across industry and the community, and include an advisory process representing the range of interests and concerns.
- The National Acoustics Laboratories should conduct a study and assessment of noise impacts of wind farms, including the impacts of infrasound.

- The draft National Wind Farm Development Guidelines should be redrafted to include discussion of any adverse health effects and comments made by NHMRC regarding the revision of its 2010 public statement.

None of these recommendations have been implemented by 2015, four years after their publication.

Australian Senate, Select Committee on Wind Turbines, 2015

The Select Committee on Wind Turbines was established in 2014 with the following terms of reference relevant to wind turbine noise:

- the role and capacity of the National Health and Medical Research Council in providing guidance to state and territory authorities;
- implementation of planning processes in relation to wind farms, including the level of information available to prospective wind farm hosts;
- adequacy of monitoring and compliance governance of wind farms;
- application and integrity of national wind farm guidelines.

In August, 2015, the committee produced a final report containing the following recommendations related to wind farm noise:

1. An Independent Expert Scientific Committee on Industrial Sound (IESC) should be established, with funding from a levy on wind turbine operators accredited to receive renewable energy certificates, for the purpose of:
    - conducting independent, multidisciplinary research into the adverse impacts and risks to individual and community health and wellbeing associated with wind turbine projects and any other industrial projects which emit sound and vibration energy;
    - establishing a formal channel to communicate its advice and research priorities and findings to the Environmental Health Standing Committee;
    - developing a single national acoustic standard on audible noise from wind turbines that is cognisant of the existing standards, Australian conditions and the signature of new turbine technologies;
    - developing a national acoustic standard on infrasound, low-frequency sound and vibration from industrial projects;
    - developing a national standard on minimum buffer zones;
    - developing a template for State Environment Protection Agencies to adopt a fee-for-service licensing system (see recommendation 9, below);
    - developing a guidance note proposing that State Environment Protection Authorities be responsible for monitoring and compliance of wind turbines and suggesting an appropriate process to conduct these tasks;
    - providing scientific and technical advice to State Environment Protection Authorities, the Clean Energy Regulator and the Federal Health Minister to assist in assessing whether a proposed or existing wind farm project poses risks to individual and community health;
    - publishing information relating to its research findings and providing the Federal Health Minister with research priorities and research projects to improve scientific understanding of the impacts of wind turbines on the health and quality of life of affected individuals and communities;

- providing guidance, advice and oversight for research projects commissioned by agencies such as the National Health and Medical Research Council and the Commonwealth Scientific and Industrial Research Organisation relating to sound emissions from industrial projects.

This committee was established in October, 2015.

2. The National Environment Protection Council should establish a National Environment Protection (Wind Turbine Infrasound and Low Frequency Noise) Measure (NEPM), developed from the findings of the IESC.
3. If the Regulator of the Renewable Energy (Electricity) Act 2000 receives an application from a wind power station that is properly made under section 13, the Regulator must:
   - seek the advice of the IESC on whether the proposed project, over its lifetime, poses risks to individual and community health;
   - confer with the Federal Minister for Health and the Commonwealth Chief Medical Officer to ascertain the level of risk that the proposed project poses to individual and community health; and
   - not accredit the power station until such time as the Federal Minister for Health is satisfied that these risks have been mitigated.
4. Provision should be made in the Renewable Energy (Electricity) Act 2000, that compliance with the National Environment Protection (Wind Turbine Infrasound and Low-Frequency Noise) Measure (NEPM) is a pre-requisite for wind energy generators to receive Renewable Energy Certificates and that wind energy generators operating in states that do not require compliance with the NEPM are ineligible to receive Renewable Energy Certificates. Existing and approved wind farms should be given a period of no more than five years in which to comply.
5. The Commonwealth Government should introduce National Wind Farm Guidelines which each Australian State and Territory Government should reflect in their relevant planning and environmental statutes.
6. The Renewable Energy (Electricity) Act 2000 should be amended to enable partial suspension and point in time suspension of renewable energy certificates for wind farm operators that are found to have breached the conditions of their planning approval.
7. A National Wind Farm Ombudsman should be established, with funding from a levy on wind turbine operators accredited to receive renewable energy certificates, to handle complaints from concerned community residents about the operations of wind turbine facilities. This position was filled in October, 2015.
8. Data collected by wind turbine operators relating to wind speed, basic operation statistics including operating hours and noise monitoring should be made freely and publicly available on a regular basis.
9. All State Governments consider shifting responsibility for monitoring wind farms in their jurisdiction from local councils to the State Environment Protection Authority.
10. The Federal Department of the Environment prepare a quarterly report collating the wind farm monitoring and compliance activities of the State Environment Protection Authorities.
11. The National Health and Medical Research Council (NHMRC) continue to monitor and publicise Australian and international research relating to wind farms and

health. The NHMRC should fund and commission primary research that the IESC identifies as necessary.

12. A national regulatory body be established under Commonwealth legislation for the purpose of monitoring and enforcing wind farm operations.

1.7.2 Canada

In Canada, there have been two enquiries into the adverse health effects of wind farms, one by Health Canada begun in 2012 and reported on in 2014 and one by The Council of Canadian Academies, reported on in 2015, which was sponsored but not influenced by Health Canada. This latter study was undertaken by an expert panel that included medical experts and acoustics experts.

Health Canada, 2014

In 2014, Health Canada reported the results of a wind farm noise study that had the following objectives:

- Investigation of the prevalence of health effects or health indicators among a sample of Canadians exposed to WTN (wind turbine noise) using both self-reported and objectively measured health outcomes.
- Application of statistical modelling in order to derive exposure response relationships between WTN levels and self-reported and objectively measured health outcomes.
- Investigation of LFN and infrasound from wind turbines as potential contributing factors towards adverse community reaction.

The conclusions of the study, which have been criticised by a number of medical professionals (for example, Krogh and McMurtry (2014)), are listed below.

- Self-reports of diagnosis of a number of health conditions were not found to be associated with exposure to WTN levels.
- Self-reported stress, as measured by scores on the Perceived Stress Scale, was not found to be related to exposure to WTN levels.
- Exposure to WTN was not found to be associated with any significant changes in reported quality of life for any of the four domains, nor with overall quality of life and satisfaction with health.
- Annoyance towards noise, shadow flicker, blinking lights, vibrations, and visual impacts were found to be statistically associated with increasing levels of WTN. The relationship between noise and community annoyance is stronger than any other self-reported measure, including sleep disturbance. Additional findings related to WTN are listed below.
    - A statistically significant increase in annoyance was found when WTN levels exterior to residences exceeded 35 dBA.
    - Reported WTN annoyance was statistically higher in the summer, outdoors and during evening and nighttime.
    - WTN annoyance significantly dropped in areas where calculated nighttime background noise exceeded WTN by 10dB or more.
    - Annoyance was significantly lower among the participants who received personal benefit.

  - WTN annoyance was found to be statistically related to several self-reported health effects including, but not limited to, blood pressure, migraines, tinnitus, dizziness and perceived stress.
  - WTN annoyance was found to be statistically related to measured hair cortisol, systolic and diastolic blood pressure.
  - The findings support a potential link between long term high annoyance and health.
  - Health and well-being effects may be partially related to activities that influence community annoyance, over and above exposure to wind turbines.
  - Self-reported and measured health effects were not dependent on the particular levels of noise, or particular distances from the turbines, and were also observed in many cases for road traffic noise annoyance.
- Calculated outdoor WTN levels near the participants' homes were not found to be associated with sleep efficiency, the rate of awakenings, duration of awakenings, total sleep time, or how long it took to fall asleep.

The most significant shortcoming of the above study was that there was an assumption that increasing wind turbine noise levels should be correlated to increasing numbers of people suffering symptoms. Perhaps a more reasonable assumption would be that a fixed percentage of people are susceptible to wind farm noise and that the range of wind farm noise levels that can produce a reaction or symptom in all of the sensitive people is quite large.

Another shortcoming is that the noise levels used to correlate health effects were based on calculated average levels. There was no consideration of the spectrum shape of noise arriving at different residences, how it varied with time, nor whether pulsating or rumbling noise was present. Thus any attempt to just correlate A-weighted average predicted noise levels (see Section 2.2.11) using a relatively simple noise propagation model cannot yield reliable results.

The results of the Health Canada study were reported in detail in a number of publications in 2016 (Michaud et al. 2016a,b,c).

Council of Canadian Academies, 2015

The Council of Canadian Academies is an independent not-for-profit organisation that supports independent, science-based, authoritative expert assessments to inform public policy development in Canada. The Minister of Health (responsible for Health Canada) asked the Council to find an answer to the question, 'Is there evidence to support a causal association between exposure to wind turbine noise and the development of adverse health effects?' The following sub-questions were also included in the request.

- Are there knowledge gaps in the scientific and technological areas that need to be addressed in order to fully assess possible health impacts from wind turbine noise?
- Is the potential risk to human health sufficiently plausible to justify further research into the association between wind turbine noise exposure and the development of adverse health effects?
- How does Canada compare internationally with respect to the prevalence and nature of reported adverse health effects among populations living in the vicinity of commercial wind turbine establishments?

- Are there engineering technologies and/or other best practices in other jurisdictions that might be contemplated in Canada as measures that may minimise adverse community response towards wind turbine noise?

The expert panel identified about 30 symptoms and adverse health outcomes that have been attributed to exposure to wind turbine noise, based on a broad survey of the internet and peer-reviewed literature. Empirical evidence related to any associations between these health outcomes and exposure to wind turbine noise was then collected, resulting in an examination of approximately 300 publications, of which 38 were found to be relevant to the health effects of wind turbine noise. The study concluded the following (see the full report, CCA (2015)):

1. Standard methods of measuring sound may not properly identify nor quantify low-frequency noise nor the amplitude modulation of that noise.
2. The evidence is sufficient to establish a causal relationship between exposure to wind turbine noise and annoyance.
3. There is limited evidence to establish a causal relationship between exposure to wind turbine noise and sleep disturbance.
4. The evidence suggests a lack of causality between exposure to wind turbine noise and hearing loss.
5. There is inadequate evidence of a direct causal relationship between exposure to wind turbine noise and stress, although stress has been linked to other sources of community noise.
6. For all other health effects considered (fatigue, tinnitus, vertigo, nausea, dizziness, cardiovascular diseases, diabetes, and so on), the evidence was inadequate to come to any conclusion about the presence or absence of a causal relationship with exposure to wind turbine noise.
7. Knowledge gaps prevent a full assessment of public health effects of wind turbine noise.
8. Research on long-term exposure to wind turbine noise would provide a better understanding of the causal associations between wind turbine noise exposure and certain adverse health effects.
9. Technological development is unlikely to resolve, in the short term, the current issues related to perceived adverse health effects of wind turbine noise.
10. Impact assessments and community engagement provide communities with greater knowledge and control over wind energy projects and therefore help limit annoyance.

1.7.3 Denmark 2013

The Danish Ministry for Health and Prevention has commissioned a study into the health effects of wind turbines, which was announced by the Minister for Health and Prevention on 2 July 2013. The announcement stated:

> In the absence of epidemiological studies of wind turbine noise, effects on the cardiovascular system by long-term exposure to wind turbine noise can not be completely excluded at the present time. I am therefore pleased today to announce that the Environmental Protection Agency will ask the Danish Cancer Society

to prepare a detailed description of a study of possible effects of wind turbine noise.

However, the results were not available at the time of writing.

1.7.4 Northern Ireland 2013

In November, 2013, the Committee for the Environment of the Northern Ireland Assembly agreed to carry out a full inquiry into wind energy. One of the terms of reference was 'To compare the perceived impact of wind turbine noise and separation distances with other jurisdictions and other forms of renewable energy development'. The recommendations, published in January, 2015 (Northern Ireland Assembly: Committee for the Environment 2015), that are related to noise are as follows.

- The standard conditions (see IOA (2013), Appendix B) which were developed by the Institute of Acoustics, and which have been endorsed in Scotland, England and Wales, should be routinely attached to planning consents in Northern Ireland.
- The Department should review the use of the ETSU-97 guidelines on an urgent basis, with a view to adopting more modern and robust guidance for measurement of wind turbine noise, with particular reference to current guidelines from the World Health Organisation.
- Arrangements should be put in place for on-going long-term monitoring of wind turbine noise.
- The Department, working with local universities, should commission independent research to measure and determine the impact of low-frequency noise on those residents living in close proximity to individual turbines and wind farms in Northern Ireland.
- The Department, taking into account constraints on the availability and suitability of land for the generation of wind energy, should specify a minimum separation distance between wind turbines and dwellings.

1.7.5 Scotland

In early 2015, the Scottish Conservatives, then a minor opposition party in the Scottish Parliament, launched an action plan for rural Scotland that included a pledge for local councils to be able to place a moratorium on new wind farms and facilitate compensation for those whose property prices had dropped. This was partly a result of the 6000 public objections to large-scale wind farms that had been lodged in the preceding year.

1.7.6 Wales

In 2011 the Petitions Committee was presented with a petition requesting that the Welsh Government pass a statute controlling the noise from wind turbines during the hours between 6pm and 6am. After an extensive investigation the committee made the following recommendations to the Welsh Government.

1. The Statutory Planning Guidance should be amended to introduce buffer zones that maintain the current 500 metres minimum distance between dwellings and turbines, and increase the separation distance in specified appropriate circumstances up to 1500 metres.

2. ETSU-R-97 guidelines should be revised to take into account the lower ambient noise levels in rural areas and the latest research and World Health Organisation evidence on the effects of noise on sleep disturbance.
3. Faulty turbines should be switched off at specified times overnight as soon as a fault affects its noise emissions
4. The Institute of Acoustics Working Group should carry out meaningful consultation with people living close to wind turbines so that their experiences can help to shape the conclusions and recommendations of the Group that are expected to be published in September 2012.

1.8 Current Consensus on Wind Farm Noise

The only consensus related to wind farm noise is that there is no consensus on wind farm noise. Wind farms are a political 'hot potato'. Governments and environmentalists see them as an easy way of achieving renewable energy targets and saving the planet from greenhouse gas overload. Wind farms are seen by many as a great economic benefit, so one can understand the lack of sympathy in the general population for wind farm neighbours who complain about the noise and/or attempt to halt wind farm developments or shut down existing wind farms. There are two main views on wind farm noise. One view is that wind farms do not produce any significant noise and certainly not any noise at a level that should annoy or affect the health of anyone. As may be expected, this view is held universally by wind turbine manufacturers and wind farm developers and most (but not all) other people who benefit financially from the wind farm industry. Another view that is held by many people living in the vicinity of wind farms (including some wind farm hosts) is that wind farm noise is annoying, it results in sleep deprivation and in some cases results in serious health problems. Whether health problems are a result of sleep deprivation and stress associated with continually experiencing an intrusive noise or whether they are a direct physiological result of the character of wind farm noise is not clear at the time of writing and a considerable amount of research is needed to clarify this issue. There are emotional outbursts on the web from people supporting both sides of the argument and unfortunately some of the personal insults and attacks that can be found on some pro-wind farm web sites are unhelpful at best.

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