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WIND TURBINE NOISE: REGULATIONS, SITING, PERCEPTIONS AND NOISE REDUCTION TECHNOLOGIES

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ABSTRACT

Wind turbines are supplying an increasingly larger portion of the world's energy production. Current wind contributions are at 487GW and this will only grow with time. With the emerging demand for energy comes the necessity to consider the environmental impact of wind energy. Preliminary studies for new sites should consider topics ranging from local State and Federal regulations to biological impacts such as hazards to birds, bats, other wildlife, vegetation, water resources, visual aesthetics, cultural and historic resources, public health and safety, impact on communications, air quality and climate impacts, and sound generation.

Particularly for land based wind turbines, noise generation is a necessary topic of study. As wind turbines become widespread and encroach on populated areas, the noise becomes more noticeable and annoying. In the United States, a large number of wind farms are located in unpopulated regions where noise is not a significant issue. In Europe and other locations with a high population density, the generation of noise from using wind turbines is more noticeable and problematic.

This paper will examine noise issues related to wind turbines. It will begin by describing how noise is generated. Next, perception of noise is discussed. This becomes important when people and dwellings are located near wind turbines. Background noise has an effect on how people perceive noise or, rather, how noise changes. The site setting/topography is an important part of the installation process and factor in the noise perception of the area surrounding the turbine.

Noise regulations worldwide are not standardized and usually depend on the local ordinances. A preliminary discussion of international regulations and how they vary between location and country will be undertaken. Regulations are important impacting possible site locations and, therefore, the growth of wind energy. Solving the issues associated with wind turbine noise generation will go a long way in promoting wind as one of the alternative energy generation technologies.

Noise should be considered when designing any wind turbine, specifically low frequency noise related to RPM and airfoil selection. Technologies are being studied for their contributions to noise reduction. The paper will examine some of the technologies intended to reduce noise on wind turbines.

INTRODUCTION

The world's population continues to grow and with it, energy demand will grow as well. Of the current 7.6 billion people on Earth (expected to reach 8.6 billion in 2030 and 9.8 billion in 2050), approximately 6 billion reside in developing countries which will need more energy to improve their quality of life (World Population Prospects, 2017). The developing world is expected to consume 65% of the total world energy use by the year 2040 (U.S. Energy Information Administration, 2013). World energy demand is expected to increase by 40% in that same time period (International Energy Agency, 2017a). Approximately 80% of the energy production for the world in 2015 came from non-renewable sources (International Energy Agency, 2017b). Only 1.5% is classified as "other" which consists of renewable sources, such as geothermal, solar, and wind energy. This is a small amount but it will continue to grow to meet the energy demands of the future. A major part of the renewable energy growth will be from an increase in wind energy. Wind energy is the fastest growing renewable energy source, with a growth rate of approximately 2.9% per year, more than any other power generation source (Global Wind Report: Annual Market Update, 2015 and Energy Information Administration, 2016). Worldwide generation is 487 GW of wind power in 2016 with 54.6 GW being added that year (Global Status of Wind Power, 2017). In 2016, China added 23.4 GW, less than the 30.8 GW in 2015 and the United States followed with 8.2 GW, less than the 8.6 GW for 2015. New statistics show that in 2017 renewables in the U. S. accounted 6.8 GW of the 25.0 GW of new generating capacity or 25% (Weaver, 2018). The cost of wind energy is very low, below the 2020 price targets, mostly due to new offshore markets.

With this large growth in wind energy and it's increasing place in the global power market, it becomes necessary to consider the environmental impact of wind energy. New sitings of wind turbines especially for land based wind turbines either individually or in a wind farm, require extensive studies. Included in these preliminary studies are topics such as local State and Federal regulations and biological impacts such as hazards to birds, bats, other wildlife, vegetation, water resources, visual aesthetics, cultural and historic resources, public health and safety, impact on communications, air quality and climate impacts, and sound generation. Noise, its generation and regulation, is the subject of this paper. For wind turbines to coexist with populated areas, noise must be addressed carefully when designing new wind turbines

An area long neglected and in need of study is the noise produced by wind turbines. Wind turbines are being built near populated areas where the noise becomes more noticeable and annoying. The large number of wind farms the West and Midwest United States are located in unpopulated regions where the production of noise is not a major consideration and as a result, noise does not seem an important topic to study to many people. Increasingly, wind turbines are being located nearer to major population centers, where approximately 75% of the global power is consumed, reducing the grid infrastructure necessary to support new wind energy (Dodman, 2009). In Europe and other locations where the population density is much higher, the generation of noise using wind turbines is more problematic. Some attention is being given to this topic resulting in regulations guiding the siting of wind energy.

This paper will examine the noise issues related to the siting of wind turbines. It will begin by describing how noise is generated by wind turbines. This can be low frequency aerodynamic noise to higher tonal noise from gearboxes. Most noise measurements are done using Sound Pressure Level (SPL) however, there are different weighting systems depending on the desired result (what the noise measurement is trying to simulate). Also, perception of noise becomes important where people are concerned. Background noise also has an effect on how people perceive noise or, rather, how noise changes. The site setting/topography is an important part of the installation process and is a significant factor in the noise perception of the area surrounding the turbine. Lastly, the reduction of noise can be accomplished with technology improvements.

WIND TURBINE NOISE GENERATION

The source of wind turbine noise generation is typically broken in to two areas; mechanical noise and aerodynamic noise (Romero-Sanz and Matesanz, 2008). Mechanical noise comes from the machinery components such as the generator, pitch and yaw actuators, hydraulic systems and the gearbox. Comparison of mechanical and aerodynamic noise shows that aerodynamic noise is the main mechanism for generating noise, primarily air flowing over the blade/airfoil.

The aeroacoustic noise signature of an airfoil can be broken down into six categories, defined by Brooks et al. (1989). These categories are further discussed by Wagner et al. (1996). These categories can be seen in Fig. 1. The six wind turbine noise categories, as described by Van Treuren (2016), are:

1. *Turbulent Boundary Layer-Trailing Edge Noise*: At higher Reynolds numbers turbulent boundary layers develop over much of the airfoil and the noise occurs as the turbulent eddies pass over the trailing edge. This is considered broadband noise in the range of 750 Hz < f <2 kHz. It is the main source of high-frequency noise, especially for medium and large wind turbines.

2. *Laminar Boundary Layer-Vortex Shedding Noise*: At lower Reynolds numbers a mostly laminar boundary layer develops over the blade and instabilities create a feedback loop of excited pressure waves. This leads to vortex shedding and its associated noise near the trailing edge. This type of airfoil noise is of interest for small-scale wind turbines at low Reynolds numbers. The noise is tonal and can be avoided with careful airfoil selection/design.

3. *Separation-Stall Noise*: This is noise due to a non-zero angle of attack of the wind turbine blade creating a boundary layer separation wake at the trailing edge. Very high angles of attack lead to large-scale separation (deep stall) at the trailing edge causing the airfoil to radiate low-frequency noise. At high angles the airfoil is acting similar to that of a bluff body in the flow. This also leads to broadband noise.

4. *Trailing Edge Bluntness Vortex Shedding Noise*: This is noise generated by a small separated region located at the blunt trailing edges of the turbine blade. This source is controlled by the shape of the trailing edge of the airfoil. This noise is considered tonal and can be avoided with careful design of the trailing edge.

5. *Tip Vortex Formation Noise*: This noise is created due to the vortices generated by flow at the tips of the turbine blades. This is considered broadband noise and is not fully understood.

6. *Turbulent Inflow Noise*: This is noise that is generated based on the incoming turbulence of the free stream air contacting the airfoil's leading edge which can influence all other noise categories. This contributes to broadband noise in the lower frequencies (250 Hz < f < 1000 Hz) but it is not yet fully quantified.

Noise measurements are typically reported as dBA or A weighted measurements. This is a noise measurement that would be an expression of loudness as perceived by the human ear. Low frequencies are reduced in dBA measurements when compared with noise with no correction. The human ear has difficulty hearing below 100 Hz. The values in this paper are for dBA but are not written as such. Some researchers propose to use the dBC scale which would include the low frequency sound when compared to the A-Weighting. This dBC scale would seem the correct system to use as the low frequencies generated by wind turbines, even the frequencies below what is audible, are what is annoying to humans (AEI, 2009).

WIND TURBINE NOISE REGULATION

The International Electrotechnical Commission (IEC) is the organization that developed standards for wind turbine

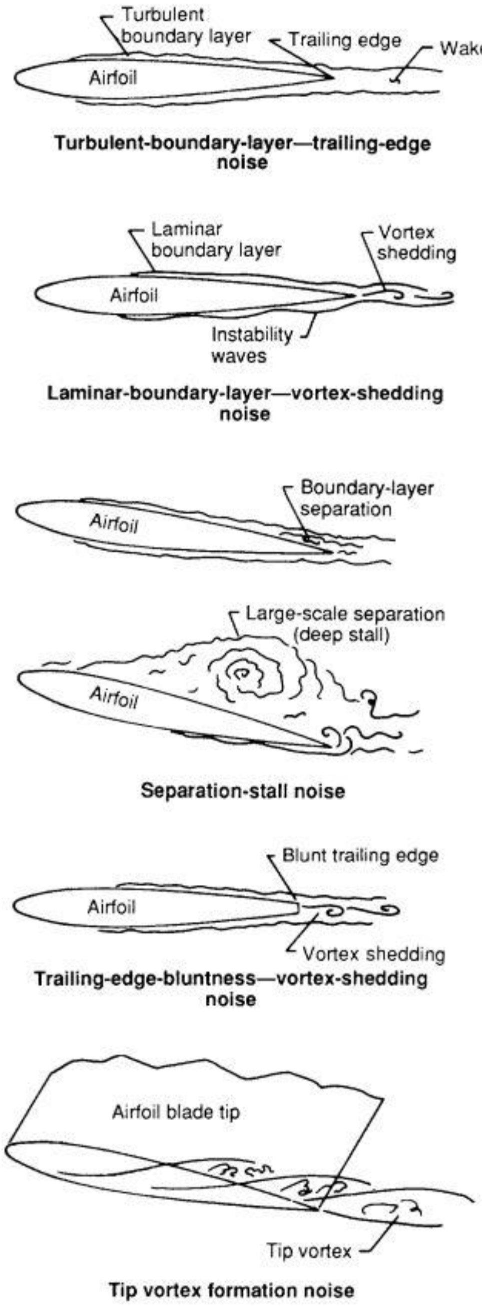

Figure 1 Types of Aeroacoustic Noise (Brooks et al., 1989)

design and testing. The IEC 61400 series of documents provide the standards for wind turbines and covers everything from design requirements to performance measurement including the measurement of acoustic noise. IEC 61400-11, Wind Turbine Generator System Part 11: Acoustic Noise Measurement Techniques, is the guide for any wind turbine noise measurements. While the IEC's central office is located in Geneva, Switzerland and the IEC documents might seem only applicable to European wind turbines, United States Standards are expected to be compatible with the IEC standards. Also used in wind turbine noise measurements is the International Organization of Standardization (ISO) document ISO 9613-2:1996 Acoustics-Attenuation of Sound During Propagation Outdoors – Part 2: General Method of Calculation to determine noise decay with distance from a wind turbine.

Noise regulation exists however there is a lack of standardization for noise thresholds or setback distances. Absolute Limits establish a fixed numeric noise threshold that cannot be exceeded and Relative Limits, which depend on the wind speed as wind and the terrain/vegetation, are strongly influenced by background noise (Batasch, 2011). Sometimes both are used as a bound. For instance, Australia has a guideline of 35/40 dB or existing value plus 5 dB. Denmark changes their values with wind speed, using 42 dB for 6 m/s and 44 dB for 8 m/s. Sometimes the threshold wording might read to make "a good faith effort" for maintaining wind turbine noise of not more than a measured level but "within a reasonable margin of error" (Storm, 2009) inviting complications in interpretation and enforcement. Most European countries have regulations that govern threshold limits with a common range of 35 to as high as 50 during the day and a 5 dB or so lower value in the evening. Different types of areas have different thresholds, such as rural, residential, residential near industry, and an other category (Fowler et al., 2013). Rural regions are very quiet in the evening and typically have a background noise level of 25 dB. Most evening threshold limits are 10-15 dB above this value making any wind turbine operating a night a potential annoyance (Harrison, 2009). In the United States, there is no national regulation and wind farm and turbine permitting is left to the state and local authorities (Raman et al., 2016). Each state can set its threshold values, which can differ from state to state, and the location where these values should be assessed (property line or at a microphone receiver) (Storm, 2009).

Setback from the wind turbine or wind turbine farm is another uncertain issue. Recommendations are a minimum of 1.5 to 2 kilometres from homes or microphone receptors (Harrison, 2011). All prediction algorithms typically use a spherical spreading from the sound source as the model. This can be easily influenced by wind, turbulence level, and hard surfaces. In the United States, often setbacks are as defined as a multiple of the turbine height (for example 5 times the height) or half a mile (800m) is marginally acceptable (AEI, 2009)

WIND TURBINE SITING

The steps to locate or site a wind turbine are quite lengthy and can be found in a number of sources (AEWA, 2008). Typically a range of topics must be covered such as environment issues, regulatory framework, impact analysis and mitigation, and public outreach. Sound falls under impact analysis and mitigation. Once the determination of the sound emitted from the source, the wind turbine, is known, there are a number of techniques to minimize the impact such as setback distance, noise abatement in new construction of buildings near the site, limiting the cutting of nearby vegetation, educating the public, and instituting a noise complaint resolution procedure. In the United States, state legislatures are involved in the siting process with each state having their own interpretation of what should be done (Heibe, 2016).

PERCEPTION OF NOISE

When is a wind turbine too noisy? The answer seems very subjective and not very scientific due to the many variables involved. Studies have been done on noise perception and the annoyance of noise, in particular low frequency noise, however, there is no agreement on the survey tools used yielding inconclusive results (Doolan, 2013). Typically, the regulations prescribe a minimum distance away from the wind turbine or wind turbine farm, approximately 1,500 – 2000 m, and minimum sound levels of 35-40 dB depending on the location and the time of day. Background noise measurement and definitions vary as well. These guidelines do not take into account variables like terrain, wind speed and direction, where the measurements were taken inside the dwelling, frequencies involved or annoyance and human perception. Thorne (2011) has extensively studied the conditions under which noise assessments are made for compliance with requirements and concludes that prior predictions as well as subsequent monitoring of wind turbine noise is not adequate to safeguard residents that are living near wind turbines and suggests that wind turbines be as much as 3,500 meters away from the nearest dwelling.

There is much debate on the detrimental effects of noise on the health of those living nearby wind turbines. What is an annoyance and when does this become a health hazard? Thorne reports that on wind noise surveys families list headaches, memory problems, nausea when the turbines are operating, sleep disturbances, anxiety stress, sore eyes, blurred vision, tinnitus, dizziness, vibration in the chest with flint/flicker and the red warning lights at night also being annoying. Sound measurements do record low frequency noise but are these enough to cause the listed infirmities? Studies on the effects of noise on children living in and around airports have shown a definite connection to a child's physical health and wellbeing prompting a concern about children living near wind turbines (Bronzaft, 2011). Horner et al. (2011) questions the literature reviews that have occurred on wind turbines and health because none are sufficient to resolve the complex problem surrounding these health issues. This leads them to the conclusion that repetitive literature reviews are of little value when there is a lack of original research.

A last consideration is the social cost of noise pollution defined as the additional cost to reduce the noise level at a receptor to an acceptable, non-nuisance value (Ehyaei and Bahjadori, 2006). This could include raising the height of a wind turbine or providing additional acoustic insulation to dwelling.

WIND TURBINE NOISE REDUCTION TECHNOLOGY

Noise is a topic that should be considered more critically as new wind generation capacities are increasingly being asked to co-exist with the general population. While people demand and enjoy the energy that is produced, often there is criticism of the noise generated. As wind turbines are machines, there will always be noise associated with their operation. Wind turbine engineers have a responsibility to address the objections and use the industry expertise to design new, quiet wind turbines or modify existing ones. There are many trade-offs to consider, such as cost and regulation, however, an effort must be made to keep the industry growing for it to provide a continued vital contribution to the world's energy usage. Available are some promising technologies and design considerations that should be incorporated. One can analyse noise sources and seek methods to reduce these sources with new wind turbine blade designs. Generators and gearboxes can also incorporate new technologies to reduce noise.

Barone (2011) and the Sandia National Laboratories (USA) reported that wind turbine blade noise sources were much louder than mechanical sources in the nacelle therefore, only aerodynamics sources of noise will be considered for noise reduction in this paper. Blade noise was greatest near the tip but was not the tip vortex itself. Their research found that the downward traveling blade could be as much as 15 dB louder than the upward traveling blade. They reinforced the physics that blade noise intensity scales as the fifth power of the flow velocity relative to the blade. Addressing any of these areas would likely reduce noise generation.

Techniques addressed by Sandia included serrated trailing edges, low-noise airfoils, trailing edge brushes, and porous surfaces. Other possible improvements would consist

Fig. 2 Trailing Edge Serrations (Oerlemans et al., 2009)

Fig. 3 Trailing Edge Brushes (Barone, 2011)

of tip treatments to reduce tip vortices, reduced design speeds, optimization of blade design and blade add-ons.

Serrated Trailing Edges

Sandia National labs highlighted serrated trailing edges as the most effective. They report that Oerlemans et al. (2009) placed a serrated trailing edge on the pressure side of the blade. They were installed on the outer part of the blade and had a length of 20% of the chord (see Fig. 2). The improvement was approximately 1.8 dB at low wind speeds, 3.2 dB at moderate wind speeds, and nearly 5.0 dB at higher wind speeds. Petitjean et al. (2011) saw a similar reduction with trailing edge serrations however they were able to specifically show that this reduction was mostly in the low frequency range below 2000 Hz. Fischer et al (2010) tested a proprietary saw-tooth serration design in an open loop wind tunnel and found that the serrations increased airfoil performance slightly because of a flap effect. At low angles of attack they found an 8 dB reduction in higher frequencies. At high angles of attack the saw-tooth serrations increased the noise generated.

Low-Noise Airfoils

Selection of an appropriate airfoil for performance is key to the energy production of a wind turbine. Van Treuren and Hays (2017) studied the four wind turbine airfoils for their aerodynamics and noise generation. Their conclusions were that a good airfoil has a high lift coefficient and a high L/D_{max} value. Low Re numbers, seen especially on small wind turbines, produce less noise however there can be issues with separation that must be addressed. Their research found that the lowest noise measured behind the airfoil corresponded to the angle for L/D_{max} so proper design twist is also important. Hays and Van Treuren (2016) measured the sound properties behind two small constant chord wind turbine rotors, one using an S823 and the other an Eppler 216, in a wind tunnel and showed the importance of proper airfoil selection for reducing noise generation, such as choosing the Eppler 216 over the S823. Their research also showed that the noise is higher towards the tip where the Re number is higher and the tip vortex is present.

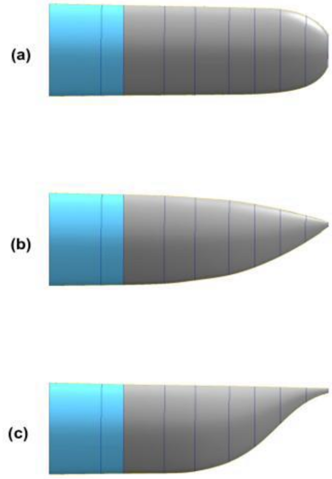

Fig. 4 Blunt tip (a), Slender tip (B), Ogee Tip (c) (Pettijean, 2011)

Much has been studied on optimizing airfoils for wind turbines. Gocmen and Ozerdem (2012) optimized six airfoils widely used on small-scale wind turbines. They focused on changing the geometry on the pressure side and trailing edge surfaces with a reduction in nose of 5 dB and a corresponding improvement in aerodynamic performance. Lutz et al. (2007) developed new airfoils, developed a prediction tool, and then tested the airfoils in the wind tunnel. Their airfoils produced less noise than most current airfoils and also had improved aerodynamic performance. Lee et al. (2013) also designed and tested new airfoils with up to a 2.6 dB reduction in noise production with the aerodynamics performance of the rotor remaining the same. These tests show that more research in airfoil design could have desirable results.

Trailing Edge Brushes

Some study has been given to the use of trailing edge brushes, as seen in Fig. 3. Experimental studies by Herr and Dobrzynski (2005) showed a reduction in broadband noise from 5-10 dB at zero angle of attack on a NACA 0012 and from 2-7 dB at 7 degrees angle of attack. Finez et al. (2010) also showed a 3 dB reduction in their studies and determined that the brushes reduced the boundary layer turbulence in the near wake. More recently Asheim (2014) saw a reduction of 1 to 5 dB on the National Renewable Energy Laboratory CART2 wind turbine. The reduction in acoustic performance came at a cost and the economics of such a modification is presented.

Porous Surfaces

Most studies on this technology have been experimental. Bae and Moon (2011) applied a porous surface to the trailing edge of a flat plate and saw a reduction of 3-10 dB at 5 degrees angle of attack (separated) over a wide range of frequencies. Geyer et al. (2010) measured a set of airfoils with several porous materials at the trailing edge in an open jet wind tunnel. Their conclusions showed that a reduction of 10 dB is possible depending on the material and the flow velocity over the airfoil. Entirely porous airfoils produce a lower lift and higher drag so only the trailing edge should be treated. Jakobsen and Anderson (1993) tested porous airfoils on a full scale VestasV-27 and saw no significant change.

Tip Treatments

A major source of noise generation is the tip vortex formation. Many different types of tips, such as shark fins and winglets, have been tried with the Ogee Tip in Fig. 4 being theoretically the best at reducing noise generation (Jakobsen and Anderson, 1993; Braun et al. 1995). When these tips were tested in the field they did not reduce the noise significantly. Pettijan et al. (2011) tested the three tips, shown in Fig. 3, on an actual wind turbine and found that the Slender and the Ogee tips reduced the noise over the blunt tip by 5-6 dB. Of the two, the Slender tip keeps the vortex away from the blade surface (not interacting with the trailing edge) and has a pleasing shape. Thus, it is used by many manufacturers of wind turbines.

Reduced Design Speeds

In order to meet noise regulations with a given wind turbine, it might be possible to reduce the rotational speed (Romero-Sanz and Matesanz, 2008). This is because the noise increases as the fifth power of the relative velocity to the blade. Unfortunately, a reduction is rotational speed translates to a reduction in power generated. An economic analysis should be done to examine if this is possible. If it is required, then an increase in turbine diameter might be appropriate to make up for the loss. Increasingly, wind turbines are being asked to work in less than optimum flow and increasing the diameter to compensate is already being investigated (Gitano-Briggs, 2012)

Optimization of Blade Designs

Much research has been done on the design of wind turbine blades however optimizing them for reduced noise has not typically been included. Understanding the noise sources and predicting how designs will work using computational fluid mechanics has been a subject of interest (Lutz et al., 2015). Many studies of blade design and associated design techniques are available (Clifton-Smith, 2010; Schubel and Crossley, 2012). The basic Blade Element Momentum Theory method for design, still used today, is found in most wind turbine textbooks.

Blade Add-ons

Add-ons are a way to improve existing wind turbine blades either by modifying the airfoil cross-sections, changing the flow surface or by adding a passive flow control device (Rodrigues and Marta, 2014). Vortex generators near the hub region reduce separation but can also increase boundary layer turbulence noise so the trade-off must be weighed carefully. A new blade covering being explored comes from the field of biomimicry, looking to the world around us for inspiration. Researchers have used the owl's wings, in particular the feather structure, to simulate a coating that reproduces the owl feather's "flexible fringe" The result is a quieter wind turbine when the blades are covered with this material (Peters, 2016)

Other Technologies

There are other technologies that should be mentioned in passing. Active control such as boundary layer suction has been considered and is thought to be able to provide a 3.5 dB reduction (Wolf et al., 2015 and Lutz et al., 2015). Leading edge treatments such a tubercles, another biomimicry inspired design from the leading edge flippers of humpback wales, also shows some promise to decrease flow separation (Thangarajan and Vivek, 2015). Other topics of interest could be the use of control systems (pitch angles) to control rotor speed and improved use of computational predictive models.

CONCLUSIONS

Wind energy is expanding and becoming a bigger part of the world energy market. As wind turbines are being built, their proximity to humans is coming into question. Regulations do exist worldwide however there is no standard being used to guide new installations. Each country in Europe and each state in the United States have their own regulations to guide new installations with much of the regulation being accomplished at the local level. The primary source of noise seems to be the aeroacoustic noise and its effect on people and dwellings depends on the setback distance. Threshold readings are what is expected at these distances however, there are many other factors that must be considered but do not appear in the regulations. Of concern is the impact of noise, or the perception of noise, on the residents living near wind turbines. It is alleged that health issues are the result of low frequency noise however other illnesses and annoyances abound. This must be addressed if people and wind turbines are to coexist. There are a number of technologies that promise to reduce the noise generated by the wind turbine, which can be between a 1 and 10 dB decrease. More research needs to be done to determine which technology is cost effective and reduces noise at the same time.

NOMENCLATURE

IEC	International Electrotechnical Commission
ISO	International Organization of Standardization
Re	Reynolds number
SPL	Sound Pressure Level

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