1 Wind Turbine Acoustics

- Wind turbines generate sound by both mechanical and aerodynamic sources.
- Sound remains an important criterion used in the siting of wind farms.
- Sound emission from wind turbines has been one of the more studied environmental impact areas in wind energy engineering.
- Acoustic "noise" is defined as any unwanted sound. Concerns about noise depend on:
  1. the level of intensity, frequency, frequency distribution, and patterns of the noise source,
  2. background sound levels,
  3. the terrain between the emitter and receptor,
  4. the nature of the receptor, and
  5. the attitude of the receptor about the emitter.

- The effects of noise on people can be classified into three general categories:
  1. subjective effects including annoyance, nuisance, dissatisfaction,
  2. interference with activities such as speech, sleep, and learning, and
  3. physiological effects such as anxiety, tinnitus, or hearing loss.
- In almost all cases, the sound levels associated with wind turbines, regardless of the size, produce effects only in the above Categories (1) and (2).
- Being **objectionable** depends on
  1. the type of sound (tonal, broadband, low frequency, or impulsive),
  2. the circumstances and sensitivity of the person (receptor) who hears it.
- There is no completely satisfactory manner to measure the **subjective effects** of noise, or the corresponding reactions of annoyance and dissatisfaction.
- The potential environmental impact of wind turbine noise involves the sound sources, sound propagation paths, and sound receivers

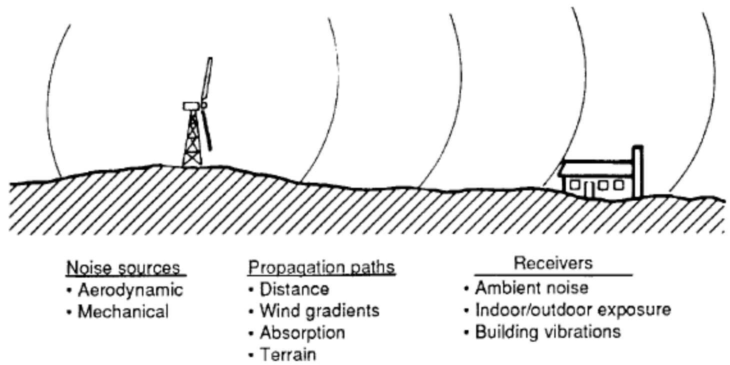

Figure 1: Schematic examples of wind turbine sound sources, propagation paths and receivers.

1.1 Acoustics Fundamentals

- Sound consists of pressure waves that travel through a medium.

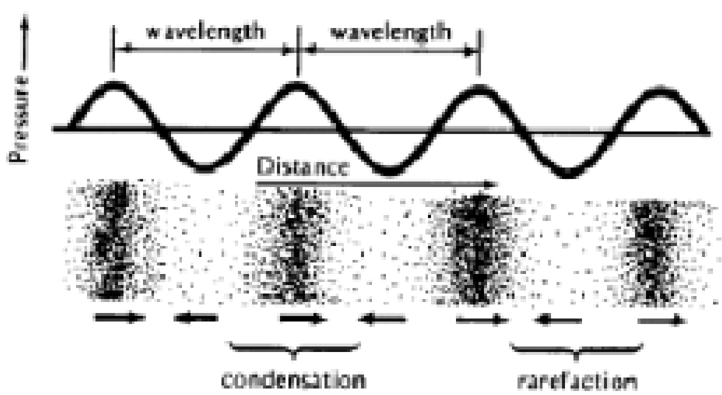

Figure 2: Schematic representation of a sound pressure wave.

- It is characterized by its wavelength, λ, frequency, ω and velocity, c, where

$$c = \omega\,\lambda \tag{1}$$

- The physical sound frequency is $f = \omega/2\pi$ with units of Hertz.
- The velocity of sound in air depends on the air density, which are functions of temperature, pressure and humidity.
- For air at standard temperature and pressure, the speed of sound is approximately 340 m/s.

- The intensity of sound is the average amount of **sound power** transmitted through a unit area in a specified direction with units of **Watts/m^2**.
- Sound frequency denotes the “pitch” of the sound, and in many cases corresponds to notes on the musical scale, for example Middle C is 262 Hz.
- An octave is a frequency range between a sound having one frequency and another having twice that frequency.
- Octaves are often used to define ranges of sound frequency values.
  - **The frequency range of human hearing corresponds to 10 Octaves, from about 20 Hz to 20 kHz.**
- Because of the five order of magnitude range of the human ear responds, it is convenient to represent sound levels on a logarithmic scale.
- Sound **intensity**, I, is then represented as

$$I = 10 \log_{10} (I/I_0) \tag{2}$$

  - I has units of decibels,
  - I_0 represents the lowest threshold of human hearing.

- Sound **power** is also quantifiable by its relation to a reference pressure.
- The **sound power level** of a source in units of decibels (dB), is given as

$$L_W = 10\log_{10}(P/P_0) \tag{3}$$

  - P is equal to the sound power level in units of power density,
  - P_0 is the reference threshold sound power level, $P_0 = 1 \times 10^{-12}\,\mathrm{W/m^2}$.

- The **sound pressure level** of a source in units of decibels (dB), is given as

$$L_P = 10\log_{10}\left(P_{rms}^2/P_0^2\right) \;=\; 20\log_{10}(P_{rms}/P_0) \tag{4}$$

  - P_{rms} is the root-mean-square of the pressure fluctuations,
  - P_0 is the reference threshold sound pressure level, $P_0 = 2 \times 10^{-5}\mathrm{Pa}$.

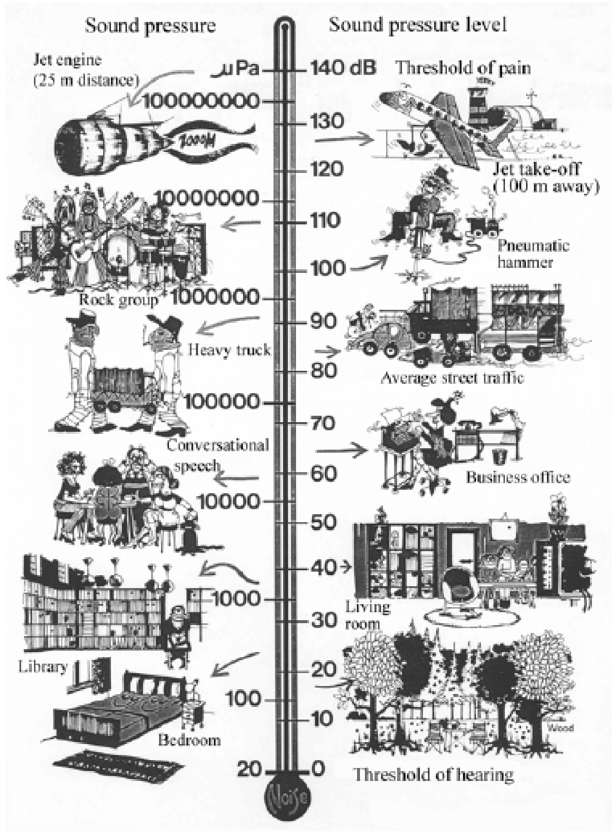

Figure 3: Examples of sound pressure levels that occur in different activities.

1.2 Sound Pressure Measurement and Weighting

- Sound pressure levels are measured using sound level meters that consist of a microphone that converts pressure variations into a voltage time series output that is calibrated in decibels.
- Sound level meters are generally equipped with band-pass frequency filters that shape the output response to simulate human hearing.
  - **A-scale Weighting**, is the most common scale for assessing environmental and occupational noise. It approximates the response of the human ear to sounds of medium intensity.

– **B-scale Weighting**, approximates the response of the human ear for medium-loud sounds, around 70 dB. (not commonly used)

– **C-scale Weighting**, approximates the response of the human ear to loud sounds. (Can be used for low-frequency sound)

– **G-scale Weighting**, used for ultra-low frequency, infrasound.

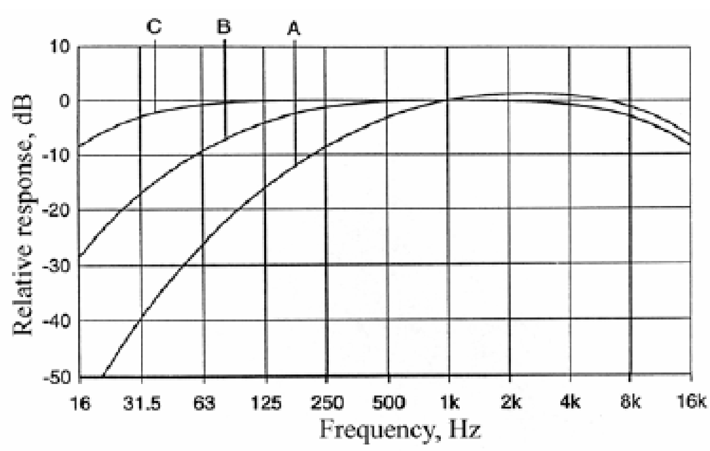

Figure 4: Frequency response curves for A, B, and C weighting scales.

1.3 dB Math

- The logarithmic nature of sound intensity level requires care in determining the sound level from multiple sound sources.
- For example, the sum of two sound sources of 90 dB and 80 dB, in decibels, is

$$\begin{aligned} 90\text{dB} &= 20\log\left(\frac{P'_{90}}{2\times10^{-5}\text{Pa}}\right) &= 0.632\text{Pa} \\ 80\text{dB} &= 20\log\left(\frac{P'_{80}}{2\times10^{-5}\text{Pa}}\right) &= 0.200\text{Pa} \\ \text{therefore} & & \\ (90+80)\text{dB} &= 20\log\left(\frac{0.832}{2\times10^{-5}\text{Pa}}\right) &= 92.38\text{dB} \end{aligned} \tag{5}$$

1.4 Low Frequency and Infrasound

- **Low frequency sound** consists of pressure fluctuations that can be heard near the lowest end the frequency response of the human ear, from **10-200 Hz.**
- **Infrasound** is pressure fluctuations at frequencies that are below the common limit of the human ear, **below 20 Hz**.
- Some characteristics of the human perception of infrasound and low frequency sound are
  1. Perceived as a mixture of auditory and tactile sensations.
  2. Such lower frequencies must be of a higher magnitude (dB) to be perceived.
  3. Tonality can not be perceived below around 18 Hz.

4. Infrasound may not appear to be coming from a specific location, because of its long wavelengths.

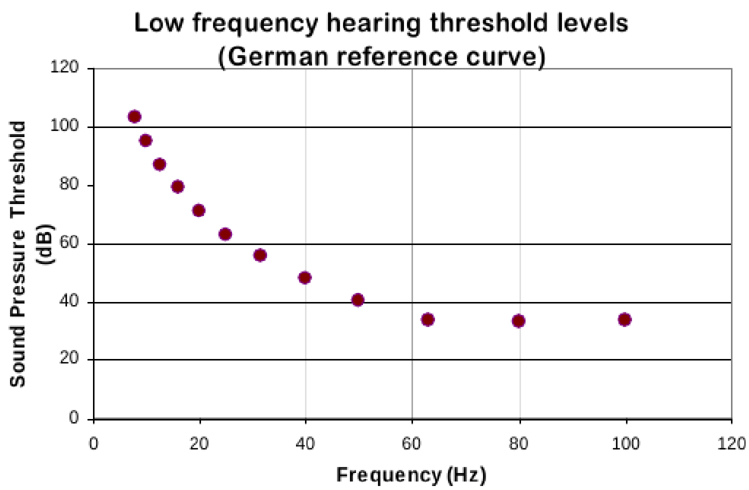

Figure 5: Perception threshold of the human ear for low frequency sound.

- Human response to perceived infrasound is annoyance, with resulting secondary effects:
  1. A feeling of static pressure.
  2. Periodic masking effects in medium and higher frequencies.
  3. Rattling of doors, windows, etc. from strong low frequency components.
- Human effects vary by the intensity of the perceived infrasound:
  1. 90 dB and below, where there is no evidence of adverse effects,
  2. 115 dB, where fatigue, apathy, abdominal symptoms, and hypertension in some humans occurs,
  3. 120 dB, which is the approximate threshold of pain at 10 Hz, and
  4. 120-130 dB and above, where exposure for 24 hours causes physiological damage.

1.5 Wind Turbine Sound Sources

Figure 6: Color rendering of the sound pressure levels obtained with a focused microphone array that pin-point the broadband noise source on the downward moving rotor.

- Wind turbines generate four types of sound characteristics: tonal, broadband, low frequency, and impulsive.
- **Tonal** sound is defined as sound that occurs at discrete frequencies.
- **Broadband** sound is characterized by a broad spectrum of frequencies, generally greater than 100 Hz.
  - Caused by the interaction of wind turbine blades with atmospheric turbulence.
  - Commonly described as a **"swishing" or "whooshing"** sound that accompanies the rotor rotation.

- **Low frequency** sound occurs in the range from 20-100 Hz.
  - Primarily associated with rotors that are *downwind* of the tower support and results from an interaction between the rotor wake and the support tower.

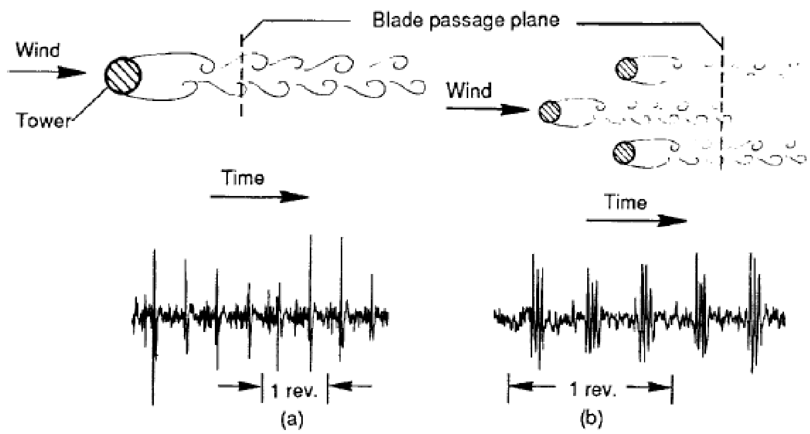

Figure 7: Example of the type of interaction that occurs, when the rotor plane cuts through the unsteady wake vortex street produced by the tower, resulting in "bursts" of sound observed in the time traces from a microphone.

- Aerodynamic acoustic sources originate from the flow of air around the blades.
- Aerodynamic sources are typically the largest component of wind turbine acoustic emissions.
- Mechanisms for on the rotor are generally divided into three groups:
  1. **Low frequency sound** generated when the rotating blade encounters localized flow deficiencies (wakes) due to the flow around a tower, wind speed changes, or wakes shed from other blades.
  2. **Inflow turbulence sound** resulting from unsteady aerodynamic loading (pressure fluctuations) caused by the passage of turbulent wind gusts.
  3. **Airfoil self noise** resulting from air flowing along the surface of the airfoil.
     (a) trailing-edge noise,
     (b) tip noise,
     (c) stall or flow separation noise,
     (d) laminar boundary layer noise,
     (e) blunt trailing edge noise,
     (f) noise from holes, slits, and intrusions.

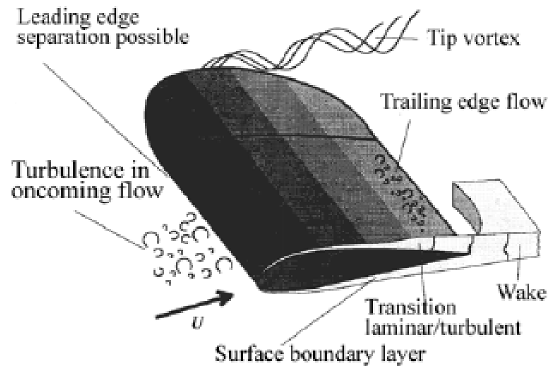

Figure 8: Mechanisms for sound generation due to the air flow over the turbine rotor.

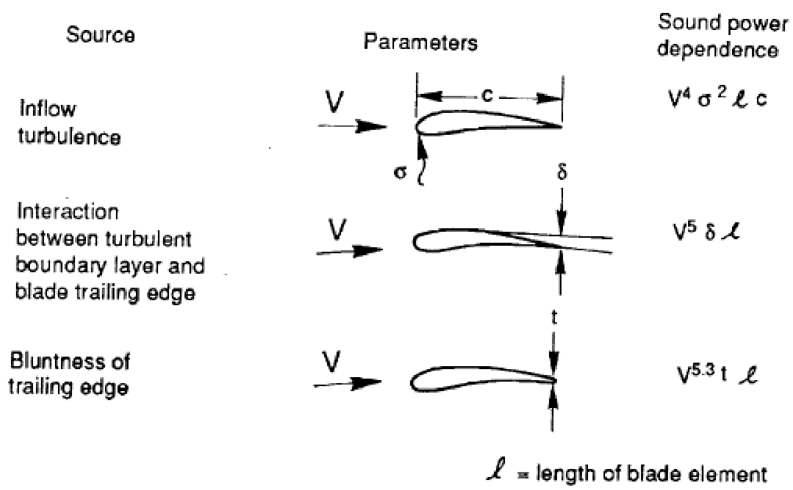

Figure 9: Sound level power scaling for different aerodynamic sound source mechanisms on the turbine rotor.

- The sound generated from the rotor plane is **directional**.

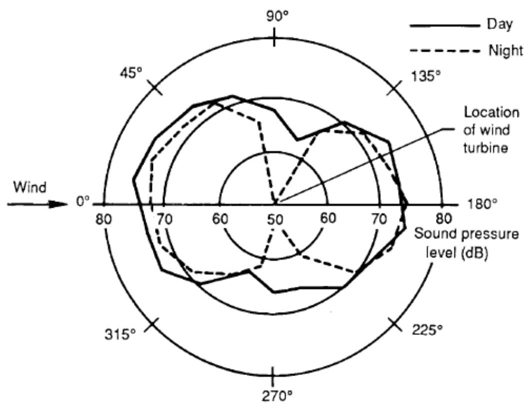

Figure 10: Sound pressure level azimuthal radiation pattern for a wind turbine.

- Efforts to reduce aerodynamic sounds have included:
  1. the use of lower tip speed ratios,
  2. lower blade angles of attack,
  3. upwind rotor designs,
  4. variable speed operation
  5. the use of specially modified blade trailing edges.
- In general, **sound pressure levels increases logarithmically with the rotor diameter**.
- Improvements reflect a better understanding and control of the sound sources.

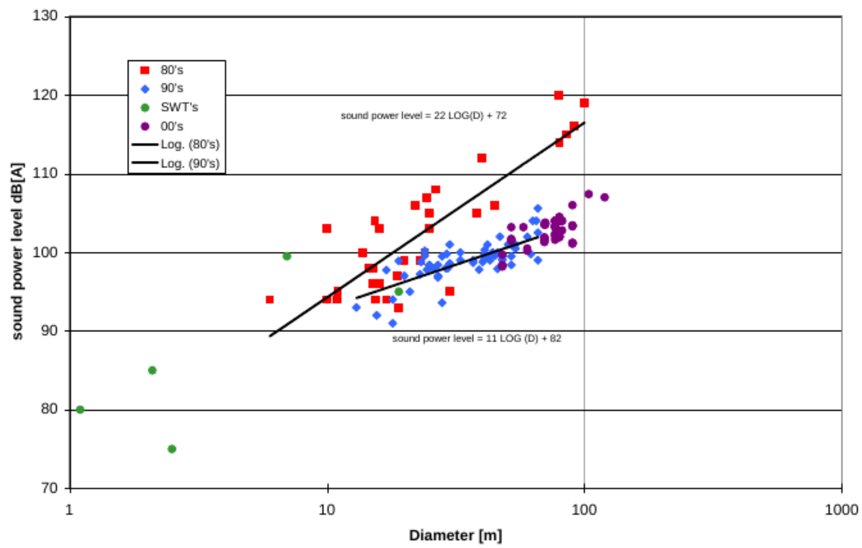

Figure 11: Trends in sound pressure levels as a function of rotor diameter for different generations of wind turbines.

1.6 Sound Propagation

- To predict the sound pressure level at a distance from source with a known power level, one must determine how the sound waves propagate.
- In general, as sound propagates without obstruction from a point source, the sound pressure level decreases.
- Assuming a spherical propagation, the same energy that is distributed over a square meter at a distance of one meter from a source is distributed over 10,000 meters at a distance of 100 meters away from the source.
- With spherical propagation, **the sound pressure level is reduced by 6 dB per doubling of distance.**
- This simple model of spherical propagation must be modified in the presence of reflective surfaces and other disruptive effects

that include:

1. source characteristics, for example directivity, height, etc.,
2. the distance of the source from the observer,
3. ground effects, for example reflection and absorption of sound on the ground which depend on the source height, the terrain cover, the ground properties, and the sound frequency,
4. blocking of the sound by obstructions and uneven terrain,
5. weather effects, for example wind speed, change of wind speed or temperature with elevation,
6. prevailing wind direction which can cause differences in sound pressure levels between upwind and downwind positions, and
7. the shape of the land whereby certain land forms can focus sound.

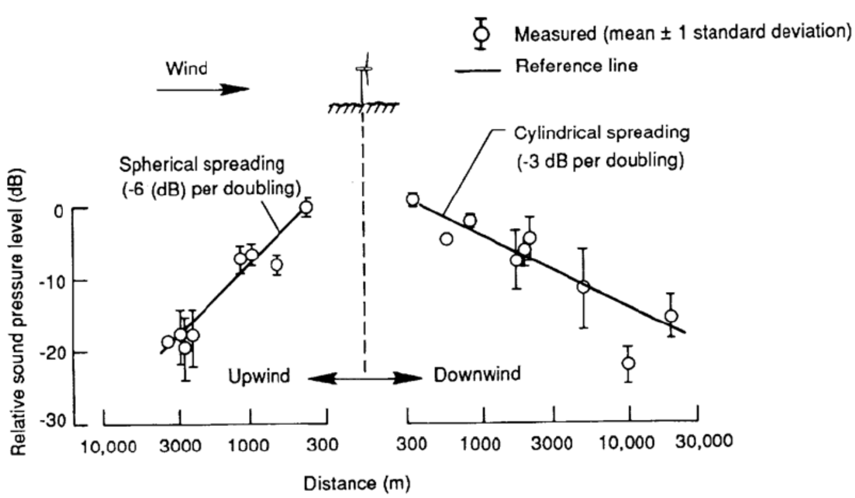

Figure 12: Example of the effect of wind on the propagation of low frequency rotational harmonic noise from a large-scale HAWT.

- A **simple model** based on the more conservative assumption of hemispherical sound propagation over a reflective surface, including air absorption is

$$L_p = L_w - 10\log_{10}\left(2\pi R^2\right) - \alpha R \tag{6}$$

  - L_p is the sound pressure level (dB) a distance R from a sound source radiating at a power level, L_w, (dB),
  - $\alpha = 0.005$ dB/m is the frequency-dependent sound absorption coefficient.

- Consider the sound **measured on the ground level** generated by a wind turbine on a 50 m tower, with a source sound power level of 102 dB(A).

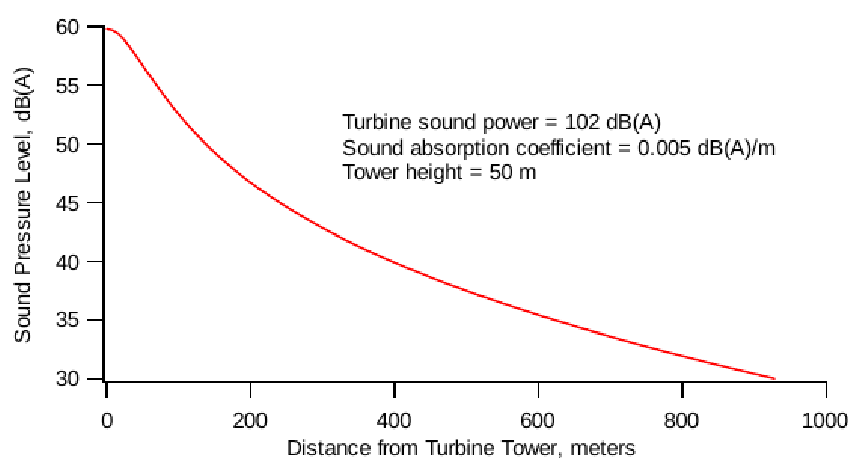

Figure 13: Example of the sound pressure as a function of distance from a wind turbine based on Equation 6.

1.7 Background Sound

- The ability to hear a wind turbine in a given installation also depends on the ambient sound level.
- When the background sounds and wind turbine sounds are of the same magnitude, the wind turbine sound gets lost in the background.
- The most likely sources of wind-generated sounds are interactions between the wind and vegetation.
- The equivalent A-weighted broadband sound pressure generated by wind in foliage has been shown to vary as

$$L_{A,eq} \propto log_{10}(U_\infty) \tag{7}$$

- Wind turbine noise is more commonly a concern **at lower wind speeds**.

1.8 Noise Standards

- At the present time, there are no common international noise standards or regulations for sound pressure levels.
- In most countries, noise regulations define upper bounds for the noise to which people may be exposed.
- These limits depend on the country, and are different for daytime and nighttime.
- In the U.S., the U.S. Environmental Protection Agency (EPA) has established noise guidelines.
- Most states do not have noise regulations, but many **local** governments have enacted noise ordinances.

Table 1: ISO 1996-1971 Recommendations for Community Noise Limits

Location	Daytime - db(A) 7AM-7PM	Evening - db(A) 7PM-11PM	Night - dB(A) 11PM-7AM
Rural	35	30	25
Suburban	40	35	30
Urban Residential	45	40	35
Urban Mixed	50	45	40