Technical Evaluation

Sound Propagation Modelling for Offshore Wind Farms

June 1, 2016
Project: 114-362

Prepared for

Ministry of the Environment and Climate Change

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CHAPTER 1 INTRODUCTION

1.1 Background

Wind power is a renewable energy source that has the potential to contribute significantly to meeting energy needs around the world. As the sites on land with good wind potential become less available, an alternative approach is to locate wind farms offshore. Offshore wind resources may be stronger and more reliable than wind over land. However, no offshore wind energy project has been constructed in the Province of Ontario to-date. The European Union leads in developing offshore wind turbine technology and offshore wind farm construction.

Propagation of sound from offshore wind turbines over water is different from propagation from land-based wind turbines. Prediction of noise from offshore wind turbines generally involves propagation of noise over large distances meaning small inaccuracies in the prediction models can become significant. It has been shown that under downward refracting atmospheric conditions, sound can propagate for extended distances over water. Different meteorological conditions that occur over water may attenuate or enhance sound propagation. The sound prediction models commonly used for land-based wind turbines may not be suitable for offshore wind farms. Consequently, the setback distances appropriate for a land-based wind farm may not be suitable for offshore wind farms.

1.2 Objectives

Valcoustics Canada Ltd. was retained by the Ontario Ministry of the Environment and Climate Change (MOECC) to complete a literature review and consult with experts in other jurisdictions to identify and compare the models that are available to analyze and predict the propagation of sound over water specifically from wind turbines located offshore.

This report has been prepared to assist the MOECC in determining an appropriate sound propagation model for offshore wind farms to be used in the Province of Ontario. The sound propagation models discussed in this report are only applicable to the sound frequencies within the human audible range of frequencies, with the exception of the Parabolic Equation method. Infrasound and underwater sound propagation modelling are not part of the scope of work of this study. Purchasing, training, and use of commercial modelling software is also beyond the scope of this study.

This report is divided into five (5) chapters. The overall study consists of:

- Chapter 1: Introduction;
- Chapter 2: Sound Propagation Model Identification: description of each model and its inputs, constraints, assumptions;
- Chapter 3 International Offshore Model Application: comparison of models, practical use and application, commercial status;

- Chapter 4: Jurisdictional Review: a description of guidelines and/or regulatory requirements in various jurisdictions which have implemented offshore wind farms;
- Chapter 5: Offshore Model Application in Ontario: identify models which may be suitable for use in Ontario, discussing their advantages and disadvantages; and
- Chapter 6: References.

1.3 Definitions

- Sound: Oscillations of pressure in the atmosphere (air).
- Infrasound: Sound below the normal human audible frequency range, that is, below about 20 Hz.
- Ultrasound: High frequency sound above the normal human audible frequency range that is, above about 20 kHz.
- Noise: Unwanted sound. Noise may be considered as sound that serves little or no purpose for the exposed person. If a person's attention is unwillingly attracted to the noise it can become distracting and annoying, and if this persists it will provoke a negative reaction. However, low or controlled levels of noise are not necessarily unreasonable.
- Frequency: The number of oscillations per second, typically referred to in units of Hertz (Hz) or kilohertz (kHz) for sound waves.
- Spectrum: The distribution by frequency of the energy content in a sound.
- Octave band and fractional band: Frequency bands in accordance with IEC 61260.
- Decibel (dB): The term used to identify 10 times the logarithm to the base 10 of the ratio of two like quantities proportional to intensity, power, or energy. Sound pressure levels and sound power levels are expressed in decibels.
- Level: The term used to indicate that a quantity is being expressed as a decibel value.
- Weighting: The introduction of an electronic process to modify the response of a sound level meter in accordance with relevant IEC Standards, for example A-frequency-weighting.
- A-weighting: A-weighting is the most commonly used of a family of curves defined in the International standard IEC 61672:2003 and various national standards relating to the measurement of sound pressure level. A-weighting is applied to instrument-measured sound levels in effort to account for the relative loudness perceived by the human ear, as the ear is less sensitive to low audio frequencies.
- Sound pressure: The local pressure deviation from the ambient atmospheric pressure, caused by a sound wave.
- Sound pressure level: Ten times the logarithm to the base 10 of the ratio of the square of the sound pressure to the square of the reference value of 20 μPa.
- Sound power: A measure of the total sound energy radiated by a source per second.
- Sound power level: Ten times the logarithm to the base 10 of the ratio of a sound power to reference value of 1 picowatt.

- Percentile level (L_n): The sound level which is exceeded for n% of the measurement time interval. For example, L_{90} is the level exceeded for 90% of the measurement time.
- Equivalent sound level (L_{eq}): The A-weighted sound level of a steady sound carrying the same total energy in the same time period as the observed fluctuating sound.
- L_{eq} (T) The A-weighted sound level of a steady sound carrying the same total energy in the time period T as the observed fluctuating sound.
- Wind turbine: A device that converts kinetic energy from wind into electrical power.
- Wind farm: A wind turbine or a group of wind turbines installed in close proximity to one another and electrically interconnected to a common grid.
- Wind speed: A measurement of the speed of the prevailing wind over a discrete time period at a specified height above the ground.
- Grazing angle: The angle between the sound ray and the surface. It equals to 90 degrees minus the angle of incidence. It is commonly used when dealing with a ray that is nearly parallel to a surface.
- Geometrical divergence/spreading: The spreading of sound waves which, in a free field, causes sound pressure levels in the far field of a source to decrease with increasing distance from the source.
- Atmospheric absorption: Absorption of sound through the atmosphere. The sound attenuation due to its propagation in the atmosphere can be described in terms of its total attenuation in dB between the source and the receiver.
- Ground attenuation: The change in sound level, either positive or negative, due to intervening ground between source and receiver. Ground attenuation is a relatively complex acoustic phenomenon, which is a function of ground characteristics, source-to-receiver geometry, and the spectral characteristics of the source.
- Sound barrier attenuation: The net sound attenuation due to sound barrier.
- Pasquill stability: A method of categorizing the amount of atmospheric turbulence present developed by Pasquill in 1961. He categorized the atmospheric turbulence into six stability classes named A, B, C, D, E and F with class A being the most unstable or most turbulent class, and class F the most stable or least turbulent class.
- Roughness length: The height at which the mean wind becomes zero when extrapolating the logarithmic wind speed profile downward through the surface layer. The wind at this height no longer follows a mathematical logarithm. It is so named because it is typically related to the height of terrain roughness elements.

CHAPTER 2 SOUND PROPAGATION MODEL IDENTIFICATION

2.1 Introduction

This chapter describes, on the basis of the literature search, several noise propagation prediction models developed or used by authorities in different countries, as well as published, numerical (theoretical), methods, to predict receptor sound levels. The numerical methods which can calculate sound pressure levels by including various meteorological conditions and are widely accepted as an accurate estimation tool for long range outdoor sound propagation are also investigated.

2.2 ISO 9613-2

2.2.1 Summary

The ISO 9613-2 standard "Acoustics – Attenuation of Sound During Propagation Outdoors – Part 2, General Method of Calculation" describes an engineering method for prediction of environmental noise outdoors at a given distance from a variety of sources of sound [1]. It calculates the attenuation of sound outdoors over the distance between the source of sound and the point of reception. The result of this method is the equivalent A-weighted sound pressure level of a known source under meteorological conditions favourable to propagation (e.g., downwind). The ISO 9613-2 method has a stated tolerance of ±3 dB for a source height of up to 30 m and a distance from 100 m up to 1000 m). For distance greater than 1000 m, the accuracy is not given in the standard. This model has been commonly used in Ontario by the MOECC for sound level prediction from land-based wind farms as well as stationary sources of sound.

The ISO 9613-2 model accounts for downwind conditions as well as a moderate temperature inversion over ground with wind speeds ranging from 1 to 5 m/s measured at a height between 3 and 11 m above ground. The sound pressure level resulting from this method is considered to be a level that is seldom exceeded. However, temperature inversions over water are not accounted for. This can lead to lower predicted sound pressure levels over water than those observed.

The method also predicts a long-term average A-weighted sound pressure. The long-term average A-weighted sound pressure level encompasses levels for a wide variety of meteorological conditions.

The method consists of octave-band algorithms (with a nominal mid-band frequency from 63 Hz to 8 kHz) for calculating the attenuation of sound which originates from a point sound source or an assembly of point sources. The source (or sources) may be moving or stationary. It does not apply to sound from aircraft in flight, or to blast waves from mining, military or similar operations.

The physical effects included in the algorithms are geometrical divergence, atmospheric absorption, ground attenuation, reflection from surfaces and sound barrier attenuation.

To apply the method of this part of ISO 9613, several parameters need to be known with respect to the geometry of the source and of the environment, the ground surface characteristics and the source strength in terms of octave-band sound power levels for directions relevant to the propagation.

2.2.2 Basic Equation

The equivalent continuous downwind octave band sound pressure level (in decibels) at a receiver location, $L_{ft}(DW)$ is calculated for each point source, and its image sources, for the eight octave bands with nominal mid-band frequencies from 63 Hz to 8 kHz, from equation:

$$L_{ft}(DW) = L_W + D_c - A$$

Where

L_W is the octave-band sound power level, in decibels, produced by the point sound source relative to a reference sound power of one picowatt;

D_c is the directivity correction, in decibels, that describes the extent by which the equivalent continuous sound pressure level from the point sound source deviates in a specified direction, from the level of an omnidirectional point sound source producing sound power level L_W;

A is the octave-band attenuation, in decibels, that occurs during propagation from the point sound source to the receiver.

The parameter A is the octave-band attenuation in decibels from source to receiver point and is given by:

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc}$$

Where

A_{div} is the attenuation due to geometrical divergence
A_{atm} is the attenuation due to atmospheric absorption
A_{gr} is the attenuation due to ground effect
A_{bar} is the attenuation due to a barrier
A_{misc} is the attenuation due to miscellaneous other effects.

2.2.3 Attenuation Due to Geometrical Divergence

The geometrical divergence accounts for spherical spreading in the free field from a point sound source.

$$A_{div} = 20\log(4\pi d^2)$$

Where

d is the distance from the source to receiver, in metres.

2.2.4 Attenuation Due to Atmospheric Absorption

Attenuation due to atmospheric absorption A_{atm} is mainly dependent on frequency, temperature and relative humidity of the air, as well as to a smaller extent ambient pressure. The parameter is calculated with the following formula:

$$A_{atm} = \alpha d/1000$$

Where

α is the atmospheric absorption coefficient in decibels [dB] per kilometre for a distance d in metres, from source to receiver. The ISO 9613-1 standard provides the equations for the calculation of the attenuation coefficients [2].

2.2.5 Attenuation Due to Ground Effect

Ground attenuation, A_{gr} is mainly the result of sound reflected by the ground surface interfering with the sound propagating directly from source to receiver.

This method of calculating the ground effect is applicable only to ground which is approximately flat, either horizontally or with a constant slope. Three distinct regions for ground attenuation are specified.

- The source region is the distance along the line (path) from the source to the receiver, of 30 times the height of the source, with a maximum of the distance from source to receiver.

- The receiver region is the distance along the line (path) from the receiver back to the source, of 30 times the height of the receiver, with a maximum of the distance from source to receiver.

- The middle region is the distance between the source and the receiver regions. If the source and receiver regions are overlap, there is no middle region.

According to this scheme, the ground attenuation does not increase with the size of the middle region, but is mostly dependent on the properties of source and receiver regions.

The acoustical properties of each ground region are taken into account through a ground factor G. Three categories of reflecting surface are specified: (i) G=0 for hard ground including pavement, water, ice, concrete and all other ground surfaces having a low porosity; (ii) G=1 for porous ground including ground covered by grass, trees or other vegetation, and all other ground surfaces suitable for the growth of vegetation, such as farm land; and (iii) G can be between 0 and 1 for mixed ground. The ground attenuation can be calculated in each octave band, for each of the three regions. In many cases, propagation of sound over water can be calculated assuming a “hard”, reflective surface: G=0.

2.2.6 Barrier Attenuation

The net reduction by a barrier, A_{bar} is given by the insertion loss. Insertion loss is the barrier geometric attenuation adjusted for ground effect. Diffraction over the top edge (horizontal) and around a vertical edge of a barrier may both be important. For downwind sound propagation, the effect of diffraction (in decibels) over the top edge would be calculated by

$$A_{bar} = D_Z - A_{gr} > 0$$

and for diffraction around a vertical edge by

$$A_{bar} = D_Z > 0$$

Where

D_Z is the barrier attenuation for each octave band
$A_{gr}$is the ground attenuation in the absence of the barrier.

D_Z is calculated in each octave band based on various factors such as path length difference, wavelength, meteorological effect, etc. The barrier attenuation D_Z in any octave band should not be taken to be greater than 20 dB in the case of single diffraction and 25 dB in the case of double diffraction.

2.2.7 Meteorological Correction

In order to account for longer time periods where both favourable and unfavourable meteorological conditions can occur, a meteorological correction factor is introduced. The long-term average A-weighted sound pressure level is calculated according to

$$L_{AT}(LT) = L_{AT}(DW) - C_{met}$$

Where C_{met} is a meteorological correction.

However, no guidelines are given by the ISO 9613-2 as to how to set the meteorological correction factor. Therefore, it is difficult to implement, in practice and its inclusion has generally been abandoned [3].

2.3 Swedish Model

2.3.1 Summary

The Swedish Environmental Protection Agency (SEPA) has issued an alternative engineering method to the ISO 9613-2 procedure for sound propagation from distant off-shore wind turbines. For ranges up to 1000 m, hemispherical spreading is used for both land and water. For distances greater than 1000 m (break point), cylindrical spreading is used. The SEPA method assumes hard ground and a standard atmospheric attenuation [3, 4, 5].

It should be noted that initially in 2002, the Swedish model set the break point distance at 200 m. This was later corrected to 700 m and finally set to 1000 m.

It should be noted that the Swedish model considers the frequency spectrum from 63 Hz to 4 kHz and not up to the usual 8 kHz.

The Swedish model is only valid for downwind conditions.

2.3.2 Basic Equation

For distances up to 1000 metres the official Swedish method for calculating noise of wind turbines, for both on land and on water, assumes hemispheric spreading above a totally reflective surface.

$$L_A = L_{WA} - 10\log(2\pi R^2) - 0.005R$$

Where

L_{WA} is the A-weighted sound power level at hub height for a specific wind speed measured at 10 m height

R is the distance between the source and receiver.

It also includes a standard coefficient for atmospheric attenuation of 0.005 dB/m from source to receiver. Octave band data is not required as it assumes a constant atmospheric damping coefficient of 0.005 for all frequencies.

For distances greater than 1000 m, the calculation model for sound propagation over the water assumes cylindrical sound dispersion.

$$L_A = L_{WA} - 10\log(2\pi R^2) - \Delta L_a + 10\log(R/1000)$$

Where

L_{WA} is the A-weighted sound power level at hub height for a specific wind speed measured at 10 m height
R is the distance between the source and receiver
ΔL_a represents the atmospheric attenuation.

2.4 Danish Model

2.4.1 Summary

In 1991, the Danish Ministry of Environment published a method for determination of noise from wind turbines. The Danish model, assuming hard ground, overestimates the levels of noise propagating over ground, but gives reasonable results offshore for limited distances up to 500 m for the overall A-weighted sound pressure level. In the octave band version, the reliable distance extends to 2 to 5 kilometres. The models fail at large distances because of multiple reflections from the sea surface building up and leading to cylindrical spreading of the sound energy [3, 6, 7, 8].

The Danish model gives reasonable result at small distance for air absorption, but may result in considerable error over large distances.

The Danish model is only valid for downwind conditions.

Moreover, the Danish authorities have developed a method to calculate indoor sound levels for low frequencies from wind turbines.

2.4.2 Basic Equation

The Danish method assumes spherical propagation for both land and water.

$$L_{pA} = L_{WA} - 10\log(4\pi R^2) + \Delta L_g - \Delta L_a$$

Where

ΔL_g is the ground reflection factor. This is the only parameter that changes depending on the surface type. For land surface, $\Delta L_g = 1.5$; for water surface $\Delta L_g = 3$
ΔL_a is the atmospheric absorption.

$$\Delta L_a = a_a\sqrt{d}$$

Where

a_a is the atmospheric absorption coefficient
d is the distance from the source to receiver.

2.4.3 Low Frequency Noise

In accordance with the Danish statutory order enforced on January 1, 2012, due to the increased coherence between direct and reflected sound at low frequencies, a more specific and detailed approach was chosen to avoid underestimation of the noise levels in the frequency range from 10 to 160 Hz, independent of distance and height of the wind turbine. For land based wind turbines, the ground correction is +6 dB at 10 Hz and decrease to 0 dB at 160 Hz. For off-shore wind turbine, the ground correction is +6 dB at 10 Hz and decreases to +4 dB at 160 Hz.

2.5 CONCAWE Model

2.5.1 Summary

The CONCAWE model dates back to 1981; the method is focused on the propagation of noise from petroleum and petrochemical complexes to neighbouring communities. The model takes into account not only significant topographical features, but also the meteorological conditions prevailing at the site. The latter feature allows the prediction of long term equivalent continuous sound levels and long term statistical sound levels, in addition to probable maxima and minima, on the basis of the statistical distribution of wind velocity and Pasquill Stability for the area [9, 10].

The CONCAWE model has based many of the algorithms on experimental data. This was done for the ground attenuation and all the meteorological effects.

The CONCAWE model enables octave band sound pressure levels to be calculated at a receiver point for a given meteorological scenario. The CONCAWE model considers the range of octave bands from 63 Hz to 4 KHz.

2.5.2 Basic Equation

The sound pressure level (in decibels) in any octave band may be derived from the equation below.

$$L_p = L_w + D - K_1 - K_2 - K_3 - K_4 - K_5 - K_6 - K_7$$

Where

- L_w is the octave band sound power level
- D is the directivity index of source
- K_1 is the attenuation due to geometric spreading
- K_2 attenuation due to atmospheric absorption
- K_3 is the attenuation due to ground effect
- K_4 is the attenuation due to meteorological effect
- K_5 is the correction for source/receiver height
- K_6 is the attenuation due to barrier shielding
- K_7 is the attenuation due to in-plant screening.

2.5.3 Geometrical Spreading (Divergence)

Only point sources are considered in CONCAWE. It assumes spherical spreading.

2.5.4 Atmospheric Absorption

The recommendations of the American National Standard, ANSI S1.26, "Method for the Calculation of the Absorption of Sound by the Atmosphere" were adopted in CONCAWE [11]. For octave band width considerations, the values corresponding to the lower one-third octave band centre frequency should be chosen. For pure tone considerations values of the atmospheric absorption at the particular frequency should be used.

2.5.5 Attenuation Due to Ground Effect

The CONCAWE model uses experimental data to account for ground attenuation rather than more complex theoretical models.

For acoustically 'hard' surfaces, such as concrete or water $K_3 = -3\ dB$ for all frequencies and distances. For all other surfaces experimental data is used.

2.5.6 Attenuation Due to Meteorological Effects

CONCAWE grades meteorological effects into six categories based on a combined vertical gradient. The temperature gradient is determined by Pasquill Stability Categories A to G. Category A represents a strong lapse rate condition (i.e., large temperature decrease with height) where Category G represents a temperature inversion as may be found on a calm starlit night.

The attenuation is a function of frequency, distance and meteorological category.

2.5.7 Barrier Shielding

The attenuation due to the presence of a barrier is calculated using Maekawa's method. This is based on the calculation of a Fresnel number, N, derived from diffraction theory [12].

$$N = \frac{Path\ Length\ Difference}{0.5 \times Wavelength}$$

If necessary, it can be modified to account for wind and temperature gradient using the approach of De Jong, et al [13].

2.5.8 Source/Receiver Height Correction

CONCAWE assumes that the ground effect decreases exponentially with an increase in grazing angle.

2.5.9 In-Plant Screening

This is an additional attenuation due to in-plant screening that may be observed in practice for a large complex site but this cannot be predicted with certainty.

The propagation of noise from a source surrounded by a process plant will be influenced by adjacent equipment which can provide not only screening but also reflecting surfaces. The complexity of these localized effects makes a generalized theoretical prediction technique difficult and a paucity of conclusive experimental data did not allow a reliable empirical analysis to be deduced. A tentative method based on the conclusions of Judd and Dryden [14] was proposed in the preliminary study, based on distance travelled through the plant and equipment density.

2.6 Nordic Prediction Model (Nord2000)

2.6.1 Summary

Nord2000 is a calculation model developed as a joint project between the Nordic countries, Denmark, Norway, Sweden, Iceland and Finland [15, 16, 17, 18]. Nord2000 considers the influence of wind (direction, speed, gradient), temperature, ground absorption and screening. It is also possible to choose different wind speed and temperature gradients. Nord2000 is suitable for calculations over hilly terrain as it takes varying topography into account. It also takes into consideration the acoustic characteristics of water surface and therefore is appropriate for calculation of sound propagating over water.

The propagation model is based on analytical solutions - geometrical ray theory and theory of diffraction. The model calculates one-third octave band attenuation from 25 Hz to 10 kHz for a homogeneous or inhomogeneous atmosphere conditions. The input variables that may be taken into account are:

- The terrain profile defined by start and end coordinates of the straight-line segments and the ground flow resistivity and roughness (unevenness) of each segment;
- Height of source and receiver above the first and last terrain point, respectively;
- Aerodynamic roughness length of the ground (used to define the wind speed profile);
- The average wind speed component in the direction of propagation and the height the wind speed is specified for;
- The standard deviation of variations in wind speed component;
- Temperature along the propagation path near the ground;
- Standard deviation of temperature gradient variations;
- Turbulence strength parameters due to wind and temperature, respectively;
- Relative humidity of the air.

The Nord2000 model allows calculation of short-term levels for specified weather conditions such as short-term (less than 30 minutes or one hour) equivalent sound pressure levels or maximum levels. Long-term noise levels (e.g., yearly average of day, evening and night sound level) can be obtained by combining short-term noise levels calculated by Nord2000 with meteorological statistics. In practice, short-term level calculations are made for a limited set of meteorological classes, and the long-term levels are the weighted average of these results. This approach makes it possible to calculate long-term levels such as maximum sound levels for longer periods, or even complete statistical distributions of sound levels.

The model is particularly accurate at small distances. The model has only been validated by measurements at distances up to 200 m where good accuracy has been found (deviations within ±2 dB of overall A-weighted sound pressure levels in most cases). The method has been validated by comparison with measurements and with other prediction methods, such as Parabolic Equations (PE), which are believed to be more accurate. See Section 2.8.

2.6.2 Basic Equation

The sound pressure level (in decibels) at the receiver L_R can be calculated for each frequency band:

$$L_R = L_w + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r$$

Where

L_w is the sound power level within the considered frequency band
ΔL_d is the propagation effect of spherical divergence of the sound energy (distance effect)
ΔL_a is the propagation effect of air absorption
ΔL_t is the propagation effect of the terrain (ground and barriers)
ΔL_s is the propagation effect of scattering zones
ΔL_r is the propagation effect of obstacle dimensions and surface properties when calculating a contribution from sound reflected by an obstacle.

The propagation effects mentioned above are assumed to be independent and can therefore be predicted separately with the exception of the effect of the terrain and the effect of scattering zones which may interact to some extent. A decrease in coherence introduced by the scattering effect may affect the prediction of the terrain effect.

2.6.3 Air (Atmospheric) Absorption

The calculation of air absorption is based on predictions at the centre frequency of the one third octave band by ISO 9613-1, but is supplemented by an analytical method for estimating the attenuation in the frequency band.

2.6.4 Ground Effect

The ground effect is defined as the difference between the sound pressure level in the presence of the ground and the free-field sound pressure level.

One of the cornerstones in the Nord2000 propagation model is the ground effect model which predicts the propagation effect of a flat homogeneous ground surface. The model is based on geometrical ray theory.

A sound wave transmitted from a point source is a spherical wave where the sound energy is spread equally in all directions. Both sound field amplitude and phase changes with the distance from the source. How fast the phase changes depend on the frequency as well.

When sound propagates close to the ground, the sound wave transmitted directly from source to receiver interacts with the sound reflected from the ground. If the ground is not hard, but has a finite impedance, the sound wave will be attenuated at the reflection and also shifted in phase. Due to the difference in travelling distance and the phase shift from the reflection, there will be a difference in phase between the direct and reflected sound wave. In general, the phase difference increases with frequency.

At low frequencies, the phase difference is small, and the combined sound pressure is doubled relative to the sound pressure without the ground, leading to a ground effect of +6 dB. At a higher frequency, the phase difference will increase to 180° (out of phase) in which case the direct and reflected fields tend to cancel each other. However, due to small differences in amplitude caused by the difference in travelling distance and by the attenuation at the reflection, the sound field is not totally cancelled. Increasing the frequency further, the phase difference becomes 360° (in phase) creating another constructive interference with a ground effect close to +6 dB. This pattern where destructive and constructive interferences replace each other continues at higher frequencies. However, as the pattern is repeated approximately on a linear frequency scale, it is often not observed at high frequencies when the results are shown as one-third octave band spectra, due to averaging within the bands.

The concept of Fresnel-zones has been widely used in the Nord2000 model. Fresnel zones are the regions around the point at which sound reflects from the ground to the receiver. When the sound field is reflected by a plane surface, the shape of the Fresnel zone is an ellipse. In the calculation of ground effect, the sound field at the receiver is assumed to be determined by the surface properties in the Fresnel zone.

2.6.5 Ground Impedance

In Nord2000, ground surfaces are divided into seven (7) ground classes. The acoustical properties of a ground surface are determined by its normalized characteristic impedance. Calculations can be made for any known such impedance. For practical prediction, however, it has been chosen to define the impedance indirectly by specifying the flow resistivity of the ground surface. The flow resistivity is a parameter describing the "softness" of the ground. The smaller the flow resistivity, the "softer" the ground. A fully reflecting ground corresponds to an infinite flow resistivity. When used in Nord2000, the impedance is calculated on the basis of the flow resistivity by the "Delany and Bazley" impedance model [19].

2.6.6 Screen Effect

Another basic model in Nord2000 propagation model is the screen effect model which predicts the sound pressure level when the receiver is in the shadow behind a sound barrier. The screen effect is based on geometrical theory of diffraction. In the model, it is assumed that the screen is infinitely long. With screens of finite length, the contribution from sound diffracted around the side edges is taken into account in an approximate manner.

The screen effect from a double-edge barrier or two barriers is based on the solution of the wedge-shaped screen. The screen effect is calculated for each edge or barrier separately, placing the source of receiver on top of the other edge or barrier. After the individual screen effect is calculated, the combined effect is calculated. In principle, this procedure can be extended to any number of screens. However, this will increase the complexity of the calculations. Thus, only the two most significant diffracting top edges are considered in the calculations.

2.6.7 Scattering of Sound into the Shadow Zone of a Screen

Turbulence caused by random wind and temperature variation causes part of the sound energy to be scattered into the shadow behind a screen and thus reduces the effect of the screen, particularly at high frequencies.

In Nord2000, a model is included for predicting the contribution of energy scattered into the shadow. This contribution is added to the result of the screen model. The predicted result depends on the screening geometry, the turbulence strength and the frequency.

2.6.8 Terrain Effect

The ground effect is calculated for each type of ground surface, and the resulting ground effect is a weighted sum of the calculated effects. The weights are determined by the fraction of the Fresnel zone occupied by the type of ground surface.

The Nord2000 model is further generalized to the case of arbitrary terrain profiles. The terrain is segmented into flat regions. Three distinct terrain profiles are considered:

- Flat terrain model
- Valley model
- Hill model.

The Valley model is used for non-flat cases with insignificant screening effect. In many cases, the valley introduces additional ground reflected rays and these are taken into account.

The Hill model is used for cases with significant screening effect. Screening is calculated using geometrical theory of diffraction as discussed later.

The total ground effect, including screening, is obtained by the use of transitional parameters that represent the effect of each segment of the total ground effect.
The model has provision to include a roughness parameter that is a quantification of terrain unevenness characterized by height variation. The variations are in general smaller than the height variations leading to segmentation of the terrain as described above. A classification is made that includes four (4) roughness classes N: Nill, S: Small, M: Medium and L: Large [20]. For example, small scale roughness is characterized by relatively small irregularities compared to the wavelength.

2.6.9 Incoherent and Averaging Effect

The basic propagation models assume that contributions from interacting rays are added coherently which produce much stronger dips in the attenuation spectrum at high frequencies than are observed in outdoor measurements. In practice, incoherent and averaging effects will smooth out the interference pattern in the frequency spectrum. A method for including incoherent and averaging effects has been included in Nord2000 and comprises the effect of:

- Frequency-band averaging
- Fluctuating refraction
- Turbulence
- Surface roughness
- Scattering zones.

The effect of frequency band averaging covers the averaging within each one-third octave band. The effect of fluctuating refraction covers the averaging due to short-term fluctuations in atmospheric refraction mainly due to fluctuations in the wind speed and direction. The effect of turbulence covers the reduction in coherence between the rays imposed along the ray path by atmospheric turbulence. The effect of surface roughness covers the effect that is observed when a reflecting surface is not perfectly even, but contains random height variations. Finally, the effect of scattering zones covers the reduction in coherence occurring when the sound field passes through a scattering zone.

2.6.10 Weather Influence

Meteorological parameters such as wind and temperature gradients are used to approximate the vertical effective sound speed profile. The effective sound speed is the sum of the sound speed and the component of the wind speed in the direction of propagation.

If the sound speed varies with the height (the vertical sound speed gradient differs from 0), atmospheric refraction will occur. Refraction is the effect where a sound wave is bent towards regions where the sound speed is low. If the wind is blowing from the source towards the receiver (downwind propagation), or if the temperature is increasing with the altitude (positive temperature gradient) which frequently happens at night, the sound wave will be bent towards the ground (downward refraction). On the other hand, if the wind is blowing from the receiver towards the source (upwind propagation), or if the temperature is decreasing with the altitude (negative temperature gradient) which frequently occurs during daytime, particularly with a clear sky, the sound wave will be bent away from the ground (upward refraction).

In the Nord2000 model the vertical sound speed profile in the atmosphere is considered to be the sum of linear and logarithmic components:

$$C_{eff} = C_0 + Bz + A \cdot ln(1 + z/z_0)$$

Where

C_{eff} is the effective sound speed (in m/s) at height z (in metres)
C_0 is the speed at ground level
z_0 is the "roughness length" of the ground, generally taken to be about 0.1m
A and B are coefficients to be determined.

The coefficient A is obtained from the wind speed component in the direction of propagation and the coefficient B is obtained from the average temperature along the propagation path.

In Nord2000, refraction is modelled by using curved sound rays. The curvature of the rays depends on the vertical sound speed profile. At the heart of the Nord2000 model is a procedure to represent the lin-log profile by an equivalent linear profile. When the sound speed varies linearly with the height above ground, the rays will be circular arcs leading to fairly simple equations. In downward refraction, the difference in path length between the direct and reflected path and the grazing reflection angle will increase while the opposite will happen in upward refraction. Generally, the resulting effect will be that the interference frequency dips move towards lower frequencies in downward refraction and towards higher frequencies in upward refraction.

Generally, the Nord2000 model is valid only for moderate refraction, defined as weather where the propagation effects are not dominated by multiple ground reflections and shadow zones.

In strong downward refraction, the number of rays will increase because the sound field may be reflected by the ground surface more than once. This is called multiple reflections. A method has been included for calculating the contributions from rays in excess of those already included in the base models. In the method, the number of additional rays and the corresponding energy are determined, and the latter is added to the result of the ray model.

In strong upward refraction, the receiver may be in a shadow zone. In this case, no ray will reach the receiver, and the sound pressure has to be determined by other means than a ray model. In Nord2000, a simple approximate approach has been used based on the wind and temperature turbulence strengths. The method is not very accurate, but is considered sufficiently accurate for engineering purposes.

2.6.11 Reflection from Vertical Obstacles

Sound reflected from an obstacle such as a building facade or a noise screen is dealt with by introducing an extra ray path from the source via the reflection point to the receiver. The reflection point is defined as the intersection between the straight line from the image source to the receiver and the plane which contains the reflecting surface. The propagation effect of a reflected ray path is predicted by the same propagation model as used for a direct path, but a correction is made for the reflection coefficient.

2.6.12 Scattering Zones

In Nord2000, it is possible to predict the propagation effect of "scattering zones" which are urban areas or vegetation. The effect of scattering zones depends on the length of the ray path through the scattering zone, the density and size of the scattering objects and their reflection coefficients.

2.7 Harmonoise P2P Model

2.7.1 Summary

The Harmonoise model is the result of a co-operation between a number of European countries [21, 22, 23]. It is an engineering model for predicting environmental noise levels. This prediction model is based on solutions and concepts close to those found in the Nord2000 model. It predicts the sound pressure level at the receiver position in one-third octave bands from 25 Hz to 10 kHz from the sound power level of the source. The effects of various factors are calculated separately and subtracted from the source sound power level. These factors include spherical divergence, air absorption, reflections from ground, diffractions from sound barriers, energy losses during side reflections, and effects of scattering zones.

Validations against in situ long term measurements have been achieved in several sites; agreement between reference model and experimental results ranges from excellent in flat terrain situations down to fairly good in more complex configurations (hilly, viaduct).

2.7.2 Basic Equation

The sound pressure level L at the receiver (in decibels) is calculated as the sum of a source level L_{source} and a propagation term ΔL_{prop},

$$L = L_{source} + \Delta L_{prop}$$

Where the propagation term ΔL_{prop} is given by

$$\Delta L_{prop} = \Delta L_{geo} + \Delta L_{air} + \Delta L_{excess}$$

Where

ΔL_{geo} is the geometrical attenuation
ΔL_{air} is the attenuation due to air absorption
ΔL_{excess} is the excess attenuation.

The Harmonoise model calculates "excess" attenuation ΔL_{excess} in one-third octave frequency bands by considering the combined effects the ground effect, shielding by topography (which may include barriers or buildings), atmospheric refraction and atmospheric scattering.

2.7.3 Geometrical Attenuation (Divergence)

The geometrical attenuation depends on the type of sources. For a point source, it assumes spherical spreading. For a line source (segment), a different formula applies.

2.7.4 Air (Atmospheric) Absorption

The calculation of air absorption is based on predictions at the centre frequency of the one-third octave band by ISO 9613-1.

2.7.5 Ground Effect and Shielding

The ground effects are calculated using a variation of the well-known ground attenuation formula which depends on the complex ground impedance. Using the model of Delaney and Bazley [19] this can be represented by a flow resistivity. The ground attenuation is calculated as a weighted average of two different ground attenuations: i) ground attenuation for relatively flat ground, ii) ground attenuation for valley-shaped terrain. See Reference 20 for more details.

Attenuation from shielding is calculated using a formula by Deygout [24] that is close to the traditional Maekawa formula [12] used in other algorithms. This is also based on the calculation of a Fresnel number as described in Section 2.5.7.

2.7.6 Atmospheric Refraction

Refraction effects due to meteorology are handled differently in the P2P model which is based on straight ray paths. To take into account the effect of atmospheric refraction (in an indirect way), a coordinate transformation is applied to the system such that circular ray paths transform into straight lines. The model allows the ground to bend up or down with a radius of curvature determined by a vertical linear sound speed gradient in the atmosphere.

Where the sound speed gradient is positive (i.e., sound is refracted down), the ground is "warped" downward using a conformal transformation of the coordinates and therefore the ground effect and shielding are both reduced. For a negative sound speed gradient, the reverse occurs.

In principle this is physically realistic, and certainly preferable to the addition of "corrections" after the effects of ground effect and shielding have been calculated in the absence of refraction.

The vertical sound speed profile in the atmosphere is considered to be the sum of linear and logarithmic components:

$$C_{eff} = C_0 + Az + Bln(1 + z/z_0)$$

Where

C_{eff} is the effective sound speed (in m/s) at height z (in metres)
C_0 is the speed at ground level
Z_0 is the "roughness length" of the ground, generally taken to be about 0.1m
A and B are coefficients to be determined.

Note that the definition of the two coefficients *A* and *B* differ from the Nord2000 model in the case of the P2P model.

The gradient of C_{eff}. directly related to the inverse of the radius of curvature for "ground-bending", is

$$dC_{eff}/dz = A + Az + B/(Z + Z_0)$$

Given sufficient data, or a sufficiently detailed model, C_{eff} can be calculated at a number of heights, values of A and B can be estimated from a linear/logarithmic regression.

Where only general meteorological properties are available, the situation is more difficult. In this case, A and B could be based on the Monin-Obukhov similarity theory of atmospheric stability [25] which postulates a set of dimensionless parameters known as friction velocity, temperature scale and Monin-Obukhov length.

Tables are provided to give the friction velocity, temperature scale, and Monin-Obukhov length from the component of the wind speed in the direction of propagation and a classification of atmospheric stability based on cloud cover.

2.7.7 Scattering by Atmospheric Turbulence

Scattering by atmospheric turbulence effectively sets a limit to the attenuation achievable through shielding, the ground effect and negative sound speed gradients. There are two separate “turbulence” effects which are both controlled by “turbulence strength” parameter.

- A loss of coherence between direct and reflected sound, due to the sound paths travelling by different routes, limits the ground effect.
- The barrier effect is limited by scattering of sound into areas that would otherwise be shielded. This also limits the reduction under negative sound speed gradients, since in this case the reduction is largely due to shielding by the “bent” ground.

2.8 Partial Differential Equation Based Methods

2.8.1 Summary

The parabolic wave equation is frequently used in acoustic engineering to estimate long range sound propagation. The method essentially calculates the sound pressure level in the direction of propagation by solving an approximate form of the Helmholtz equation. This partial differential equation can be discretized using various numerical methods such as the Crank-Nicholson Parabolic Equation (CNPE), the Green’s Function Parabolic Equation Method (GFPE) and the Extended Finite Element Method (XFEM). A brief discussion of each of these methods is summarized herein.

2.8.2 Crank-Nicholson Parabolic Equation (CNPE) Method

In the CNPE method, the sound speed and the ground conditions can vary with range and height. Axial symmetry is assumed. Parabolic Equation (PE) [26] methods can be used in three dimensions as well, though it would lead to quite time consuming calculations [3, 27, 28].

The advantage of this method compared to the engineering methods in the previous sections is that surface impedance and a sound speed profile, atmospheric turbulence and surface roughness can all be included in the calculations. For example, the sound speed profile can be obtained from wind and temperature profiles measured using weather balloons or similarity scaling theory.

For the two dimensional case, the three dimensional Helmholtz equation is reduced to a parabolic equation by assuming axial symmetry:

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial z^2}+k^2\Psi=0$$

Where

k is the wavenumber (i.e., $k=\omega/c$) (in m^{-1})
ω is the angular speed (in rad/s)
c is the sound speed (in m/s)
$\Psi=p\sqrt{x}$ and p is the complex pressure (in Pascals).

The CNPE parabolic equation is obtained by introducing the operator $Q = \partial^2/\partial z^2 + k^2$ and only considering outgoing waves and omitting second order derivatives

$$\frac{\partial \varphi}{\partial x} = i\left[\frac{1}{2k_0}\left(\frac{\partial^2}{\partial z^2} + (k^2 - k_0^2)\right)\right]\varphi$$

Where

k_0 is a reference wavenumber (i.e., $k_0 = \omega/c_0$)
c_0 is a reference sound speed
$\Psi(x,z) = \varphi(x,z)e^{ik_0x}$.

The CNPE is obtained by applying a finite difference discretization to the above equation; in the solution, the pressure at each range step is obtained from that at the previous range. The CNPE is especially suited for calculation of low frequencies. The CNPE method is limited to quite small propagation angles ($\pm 15°$), giving restrictions on the relation between the source and the receiver height. Later a so-called wide angle PE was developed, which increased the possible propagation angle, but it is still restricted to around ($\pm 30°$).

2.8.3 Green's Function Parabolic Equation (GFPE) Method

The GFPE method is a Fourier, split-step algorithm designed for atmospheric sound propagation and can use range-steps in the order of 10 wavelengths, considerably longer than conventional Parabolic Equation (PE) methods such as the CNPE. GFPE is suitable in the present application because of its computational efficiency and because it has been shown to give reasonably good agreement to measurements over a water surface [29, 30, 31, 32, 33].

The method computes a two-dimensional field in the rz-plane where *r* is the radial distance from the source and *z* is the height. From the three-dimensional Helmholtz equation, for the sound pressure *p* (in Pascal) in cylindrical coordinates combined with a variable substitution $\phi = \exp(-ik_0r)\,pr^{1/2}$, it can then derive:

$$\phi(r+\Delta r, z) = \exp\left(i\frac{\Delta r \delta k^2(z)}{2k_r}\right)\left[\frac{1}{2\pi}\int_{-\infty}^{\infty}\left(\Phi(r,k') + R(k')\Phi(r,-k')\right)exp\left(i\Delta r\left(\sqrt{k_r^2 - k'^2} - k_r\right)\right) \times e^{ik'z}dk' \right.$$
$$\left. + 2i\beta\Phi(r,\beta)exp\left(i\Delta r\left(\sqrt{k_r^2 - \beta^2} - k_r\right)\right)e^{i\beta z}\right]$$

and

$$\phi(r,k) = \int_0^\infty exp(-ikz')\phi(r,z')\,dz'$$

Where

Δr is the horizontal step size (in metres)
$k(z) = \omega/c(z)$ is the wave number (in m^{-1})
$c(z)$ is the sound speed (in m/s)
k_r is a reference wave number (in m^{-1})
$R(k') = (k'z_g - k_r)/(k'z_g + k_r)$ is the plane-wave reflection coefficient
$\beta = k_r/z_g$ is called the surface wave pole in the reflection coefficient
z_g is the normalized ground impedance.

The method is a marching algorithm which computes a vertical pressure distribution at each new range step.

The GFPE can deal with complex ground impedance, arbitrary wind and temperature vertical profiles, and atmospheric turbulence.

2.8.4 Fast Field Program (FFP)

The Fast Field Program (FFP) technique was developed for prediction of underwater sound propagation and has been adapted to propagation in the atmosphere by several authors. Four such adaptations are called the CERL-FFP, CFFP, SAFARI, and FFLAGS [34, 35, 36, 37].

The basis of the FFP method is to work numerically from exact integral representations of the sound field within a layered atmosphere. By taking the Hankel transform (i.e., the weighted sum of an infinite number of Bessel functions) of the wave equation it is possible to obtain a height-dependent transformed wave equation for the sound pressure. This forms the starting point of the FFP.

After application of the appropriate number of boundary conditions it remains to evaluate the Hankel transform integrals. The indefinite integrals are replaced by finite sums using discrete Fourier transforms. If K is the horizontal wave number and the maximum value of wave number in the sum is K_{max} and N discrete values of K are introduced, then the wave number intervals are given by $\Delta K = K_{max}/(N - 1)$ and correspond to range intervals $\Delta r = 2\pi/N\Delta K$; for example,

$$p(r_m, z) = 2(1 - i)\sqrt{\pi/r_m}\Delta K \sum_{n=0}^{N-1} P(K_n)\sqrt{K_n}e^{2i\pi nm/N}$$

Where $K_n = n\Delta K$, $r_m = m\Delta r$ (or $r_0 + m\Delta r$, where r_0 is the desired starting range) and z is the height above the ground.

Various numerical difficulties follow from the truncation of the integral to a finite sum and from the behavior of the integrand. Different methods of dealing with these difficulties are used in CERL-FFP, CFFP, SAFARI, and FFLAGS.

CHAPTER 3 INTERNATIONAL OFFSHORE MODEL APPLICATION

3.1 Introduction

This chapter describes the current status of each of the sound propagation models described in Chapter 2. This includes the commercial status and commercial application of each model as well as the available application software packages. Case studies of offshore wind farm development are also presented in this chapter where available.

Appendix A summarizes the limitations and application status for the sound propagation models discussed in Chapters 2 and 3.

3.2 ISO 9613-2

3.2.1 Model Application

ISO 9613-2 provide an engineering method for the prediction of environmental noise propagation outdoors over various distances from a variety of sources of sound [1]. This model is commonly used to assess sound propagation from different types of sources of sound at industrial/commercial facilities.

As indicated in Chapter 2, the ISO 9613-2 method calculates sound propagation outdoors for downwind conditions with moderate ground-based temperature inversion. The model has a stated tolerance of ±3 dB for a source height of up to 30 metres (m) and for distances from 100 m up to 1000 m. For distances greater than 1000 m, the accuracy is not given in the standard. It should be noted that for situations not in compliance with the stated parameters such as source height and distances between the sources and receptors, this does not mean that the model is invalid, but that the model was not validated when the standard was prepared. This model has been commonly used and accepted in Ontario by the MOECC for environmental noise analysis as part of the Environmental Compliance Approval (ECA) process for industrial/commercial facilities. It has also been used in Ontario and accepted by MOECC for Renewable Energy Approval (REA) applications for onshore wind farms [38, 39].

Although, the standard is explicitly not intended for calculating sound propagation for inversion conditions over water (in addition to the distance and source height limitations), it has been used to assess noise impact from offshore wind turbines [40, 41, 42, 43].

Kelsall concluded that ISO 9613-2 may be suitable for predicting noise propagation from wind turbines over water at the distances of up to 9 kilometres (km), based on sound level measurements. There was good agreement between the measured results and ISO 9613-2 modelling results at 31.5, 63, 125 and 250 Hz octave frequency bands. At long distances (e.g., 3 km or greater), the wind turbine noise is dominated by frequencies of 500 Hz or below due to significant air absorption of the frequencies above 500 Hz [44].

The noise assessment report for the Atlantic Array Offshore Wind Farm, dated June 2013, Revision A, prepared by Channel Energy Limited [45], was undertaken using the octave band method of ISO 9613-2 but with cylindrical spreading at 2000 m and beyond, instead of spherical (point source) spreading.

The ISO 9613-2 model has been implemented in a variety of commercial software packages including CadnaA, SoundPlan and WindPro [46, 47, 48].

3.2.2 Case Studies

A couple of offshore wind farms in the UK were found to be approved based on the ISO 9613-2 model. A brief description of each of these projects is summarized below.

Greater Gabbard Offshore Wind Farm, United Kingdom [49]

The Greater Gabbard Offshore Wind Farm is located in the Outer Thames Estuary in the United Kingdom, approximately 23 km at its closest point from the Suffolk Coast. The wind farm was approved by the Department of Energy and Climate Change (DECC) and the Marine Management Organisation (MMO) and is currently operational. It was constructed in September 2012.

The wind farm consists of two arrays of wind turbines totaling 140 wind turbine generators (WTG) with a total capacity of 500 MW.

The operational noise from the turbines was assessed using a bespoke (custom tailored) model called WINDFARM. The noise modelling in WINDFARM is based on the ISO 9613-2 model for noise assessment [50].

For the noise assessment, the ETSU-R-97 guidance developed by the Noise Working Group (NWG) for the UK Department of Trade and Industry (DTI), was used to scope the impact of the wind turbines on onshore and off-shore (near-shore) sensitive receptors [51]. ETSU-R-97 recommends the following noise limits:

- Day-time: 35 to 40 dB L_{90} over 10 minutes when the prevailing background noise level is below 30 dBA L_{90}; the range allowing for considerations of number of dwellings, the amount of energy generated and the duration and level of sound exposure);
- Night-time: 43 dB L_{90} over 10 minutes (derived from the L_{eq} over 10 minutes of 35 dBA referred to in Planning Policy Guidance Note 24. An allowance of 10 dBA has been made for attenuation through an open window (free-field to internal) and 2 dB subtracted to account for the use of L_{90} rather than L_{eq});
- If a developer can demonstrate that the minimum absolute noise criteria of 35 dBA L_{90} over 10 minutes can be achieved at high wind speeds of 10 m/s at 10 m height, then measurement of the background noise levels would be unnecessary.

The assessment of noise from the operation of wind farms is undertaken in two phases. Initially, noise levels (L_{90}) resulting from the operation of the wind farm at a wind speed of 10 m/s at 10 m height experienced at the closest residential receptors are predicted using noise propagation software. If these predictions show that noise levels at the closest receptor are below 35 dBA (L_{90}), there is no requirement to take the noise assessment further. Otherwise, a full assessment according to the Noise Working Group guidelines needs to be carried out.

The noise study recognized that there are two types of noise associated with wind turbines; aerodynamic and mechanical noise. Aerodynamic noise is broad-band in nature, relatively unobtrusive and is strongly influenced by incident conditions, i.e. wind speed and turbulence intensity. As a result, aerodynamic noise is wind speed dependent, and the sound power output from a turbine must be measured and quoted relative to wind speed. The reference sound power output of a wind turbine is typically defined at a reference wind speed of 8 m/s measured at a height of 10m above the ground (although adjusted for other wind speeds). As the largest wind turbine considered for the proposed Greater Gabbard Offshore Wind Farm was only a prototype, a conservative estimate of the operational Sound Power Level was provided, this being 110dBA, measured at a wind speed of 8 m/s at a height of 10m above the ground, according to IEC Standard 61400-11 [52].

Mechanical noise is generated by components inside the turbine nacelle (usually the gearbox and generator) and can be radiated by the shell of the nacelle, blades and the tower structure. Unlike aerodynamic noise, the mechanical noise can be tonal in nature, i.e., it is concentrated at a few discrete frequencies. This form of noise can be more intrusive than broadband noise. Mechanical noise can be successfully controlled at the design stage of the turbine, using advanced gearbox design and anti-vibration techniques. The present generation of turbines considered for the proposed Greater Gabbard Offshore Wind Farm incorporates design features which ensure that such tonal noise emissions are not significant.

Based on ISO 9613-2 modelling, the noise study concluded:

- Except in the immediate bounds of the wind farm array, the impact of operational airborne noise from the proposed Greater Gabbard Offshore Wind Farm Array on the receiving maritime environment (including shipping) is considered to be very low.
- Noise levels from the turbine array are predicted to be below 50 dBA L_{eq} beyond 490 m from the closest turbines to the coast and below 35 dBA L_{eq} at a distance of 3.1 km. Furthermore, noise levels are predicted to fall below 25 dBA L_{eq} at a distance of 6.2 km. In terms of assessment against ETSU-R-97 criteria, the noise from operation of the wind farm will be imperceptible at a distance of 23 km (i.e. at the coast), thus the noise impact is assessed to be negligible.

North Hoyle Offshore Wind Farm, United Kingdom [53, 54]

North Hoyle Offshore Wind Farm is Wales' first offshore wind farm, and the United Kingdom's first major offshore renewable power project. It is located in Liverpool Bay approximately 7.5 km off the coast of North Wales, between the towns of Rhyl and Prestatyn. The wind farm was developed, built and is operated by RWE Innogy UK Ltd. (formerly RWE Npower Renewables and National Wind Power). It commenced operation in 2003.

The North Hoyle Offshore Wind Farm is the first of the UK's Round 1 offshore wind farms. It is noted that the Round 1 projects were intended to act as testbeds; building the UK's understanding of offshore wind. All of the Round 1 offshore wind farms were limited to a maximum area of 10 square kilometres and no more than 30 wind turbines.

The wind farm consists of 30 Vestas V80 Offshore wind turbines, each rated at 2 MW capacity, giving a maximum project output of 60 MW.

As in the Greater Gabbard noise study, this study recognized that airborne noise emissions from the wind turbines can be categorized into an aerodynamic and a mechanical component.

The assessment of operational noise was based on the recommendations of the Department of Trade & Industry Noise Working Group, who define a framework which is used to measure and rate the noise from wind turbines and to provide indicative noise levels thought to offer a reasonable degree of protection to wind farm neighbours.

The noise prediction was based on a reference sound power level for the wind turbine type of 106 dBA at 8 m/s (10m height above the ground), varying by 0.25dB per m/s. The prediction method assumed hemispherical spreading, as recommended by the IEA (International Energy Agency), with an atmospheric absorption of 1 dB/km for all frequencies. This is essentially based on the ISO 9613-2 model.

The predicted noise at Prestatyn Sea Front was calculated to be 23.8 dBA at a wind speed of 10 m/s at 10m height. Note, the exact modelling parameters were not given in the environmental impact assessment report. In these circumstances the Noise Working Group recommendations indicate that wind farm noise levels below L_{90} over 10 minutes of 35 dBA offer sufficient protection, and as such the airborne noise from the operation of the wind farm will not have a significant effect. For such conditions, the Noise Working Group have recommended that background noise measurements are not required.

3.3 Swedish Model

3.3.1 Model Application

The Swedish Environmental Protection Agency (SEPA) has issued an alternative engineering method to the ISO 9613-2 procedure for sound propagation from distant off-shore wind turbines. For ranges up to 1000 m, hemispherical spreading is used. For distances greater than 1000 m (break point), cylindrical spreading is used. The SEPA method assumes hard ground and a standard atmospheric attenuation [3, 4, 5].

The Swedish model only considers the frequency spectrum from 63 Hz to 4 kHz.

Similar to ISO 9613-2, the Swedish Model makes minimal assumptions about the atmospheric conditions such as temperature gradients above the sea and wind conditions (which are difficult to implement into the modelling).

Notwithstanding the limitations, this method has been used to assess noise impact from offshore wind farms. References 55, 56, 57, 58 and 60 relate to two example offshore wind farm projects in the UK using the Swedish Model.

In Sweden, no example projects were found using the Swedish Model.

The model has been implemented in the commercial software packages CadnaA and WindPro [47, 49].

3.3.2 Case Studies

Burbo Bank Extension Offshore Wind Farm – United Kingdom [55, 56]

The Burbo Bank Extension Offshore Wind Farm is located approximately 7 km north of Hoylake and Meols in the Wirral, 8.5 km from Crosby beach and 12.2 km from the Point of Ayr in Wales. To the northeast it is bordered by the Queens Channel navigation channel into the Port of Liverpool, 7 km north off the north Wirral coast. The maximum capacity of the wind farm is up to 252 MW. It consists of a total of 36 wind turbine generators each with a 7 MW capacity. The wind farm project was developed by

DONG Energy Burbo Extension (UK) Ltd. The wind farm was approved by Department of Energy & Climate Change on September 26, 2014.

In the noise study, the criteria used for assessing the impact of airborne noise on human populations are those in the World Health Organization (WHO) Guidelines for Community Noise and the WHO Night Noise Guidelines for Europe. Furthermore, when considering operational noise, results are referenced to ETSU-R-97.

The noise study recognized that the wind farm may result in airborne noise levels which have the potential to impact human receptors on the coast. Sound level prediction was carried out using the Swedish propagation model [57, 58]. The noise study also indicated that the Swedish propagation model has been found to provide a good estimate of received levels for noise propagating over water – by combining spherical and cylindrical spreading models. The model makes minimal assumptions about the atmospheric conditions – such as temperature gradients above the sea and wind conditions which are notoriously difficult to integrate into such modelling. As such the model results are considered as indicative of expected levels. It was indicated that the Swedish model does tend to provide a lower bound for the transmission loss over water and hence an upper bound for the sound levels expected to be received at the shore.

In this modelling, the whole wind farm was considered to be operating at a single point with a total sound power level of 125.86 dBA, at the nearest point (7.5 km) to shore. The assessment was based on a breaking point of 200 m instead of 1000 m breaking point recommended in the latest standard.

The noise study concluded that the effects of airborne noise are found to be negligible at the coast with the likely highest received level being 29 dB(A) – very quiet even relative to rural areas with negligible wind. This is more than 10 dB below the guidelines set out by the WHO in the more recent publication on Night Noise Guidelines [59]. From other guidance, ETSU-R-97 states that a level of 43 dB is appropriate to such situations. The WHO guidelines are more restrictive and thus, were used. Note, detailed description of modelling parameters (e.g., wind turbine height, coordinates, etc.) were not given in the study report.

Walney Extension Wind Farm

This is a proposed 750 MW extension with a total of 209 wind turbines each rated at 3.6 MW, over 749 km^2, to the existing, operating Walney offshore wind farm. The closest wind turbine is to be about 19 km from shore with the furthest at 36 km. The noise assessment report [60] has its major focus on underwater sound during both construction and operation and the potential impact on a variety of marine species. Noise impact on land based humans is considered briefly. Simple predictions of on-shore sound levels were done with the Swedish model, indicating quite low operating sound levels (about 18 dBA) at the shore based on a sound power level of 110.3 dBA for each wind turbine. Thus, more detailed analysis of impact on humans on shore was considered not necessary.

The assessment was based on a breaking point of 200 m instead of 1000 m breaking point recommended in the latest standard.

On shore sound levels due to pile construction appear to also have been estimated using the Swedish model; again concluding adequately low sound levels and no impact at on-shore communities. Note, a sound power level of 145 dBA was used to assess noise impact from pile driving.

The noise study indicated:

- When sound reaches the water shore interface the sound level is reduced (a typical loss would be about 3 dB).
- A variation (error) of 10 dB or more has been found between the model and measurements.
- The Swedish model tends to capture a maximum adverse effect scenario.

3.4 Danish Model

3.4.1 Model Application

The Danish model, assuming hard ground, overestimates the levels of sound propagating over ground, but gives reasonable results offshore for limited distances up to 500 m, for the overall A-weighted sound level [3, 6, 7, 8]. In the octave band version, the reliable distance extends to 2 to 5 kilometres. The model fails at large distances because of multiple reflections from the sea surface building up and leading to cylindrical spreading of the sound energy. If a turbine has a pure tone component, a penalty of +5 dB is applied.

The model has been implemented in the commercial software package WindPro [49].

3.4.2 Case Studies

Anholt Wind Farm – Denmark [61, 62]

Anholt Wind Farm is located between Djursland and the island of Anholt in the Kattegat (the sea between Denmark and Sweden). The wind farm was developed by DONG Energy and has a capacity of 400 MW with 111 wind turbines. The distance from the Anholt wind farm to the closest shoreline (Djursland) is 15 km. Instead of the usual grid or row distribution, the turbines of Anholt were placed by two governing principles: placing most of them along the edges of the perimeter; and placing most in undisturbed airflow from the main direction (west-southwest). This would increase the production by 1.5%. The wind farm was completed in May 2013. It achieved full power a month later [61].

Sound propagation modelling was performed using the Danish model implemented in the commercial software package, WindPro. A worst case scenario of 174 turbines with a sound power level of 107 dBA at a wind speed of 8 m/s for each wind turbine was modelled and the results showed that the nearest land based receptors would be unaffected, estimating a level below 34 dBA (the Statutory limit) [62].

Myreton Wind Farm – United Kingdom [63]

Myreton Wind Farm consists of only three Enercon E48 turbines with a total capacity of 2.5 MW. It is located near the town of Keith in north east Scotland. It is land based but is one of the few farms found that has used the Danish model. Mention is also made that infrasound or low frequency noise and aerodynamic modulation are not significant issues.

Sound propagation modelling was performed using the Danish model implemented in the commercial software package, WindPro. The potential noise impact was assessed by predicting the noise at a wind speed of 10m/s. The sound power level of each wind turbine is 100.6 dBA. In addition, a safety factor of 1 dBA was added to the sound power level. The nearest residential property to the wind farm is owned and occupied by the applicant. It is situated approximately 550 m from the nearest turbine. A sound level of

40.4 dBA was predicted at the residential property. Following the ETSU-R-97 guideline, noise monitoring is required at two receptor locations because the sound levels at these receptor locations are slightly over 40.0 dBA.

3.5 CONCAWE Model

3.5.1 Model Application

The CONCAWE model takes into account not only significant topographical features, but also the meteorological conditions prevailing at the site. The latter capability allows the prediction of long term equivalent continuous sound levels and long term statistical sound levels, in addition to probable maxima and minima, on the basis of the statistical distribution of wind velocity and Pasquill (atmospheric) Stability for the area [9, 10].

The CONCAWE model has also been used for offshore wind farm projects in the UK [64, 65, 66].

The CONCAWE model has been implemented in the commercial software package CadnaA [47].

3.5.2 Case Studies

Teesside Offshore Wind Farm – United Kingdom [64, 65]

Teesside Offshore Wind Farm is located just east of the mouth of the River Tees and 1.5 km north of Redcar off the Teesside coast, in the North Sea, England. The maximum capacity of the wind farm is 63 MW with 27 Vestas V90 wind turbine generators with a rated sound power level 108 dBA at a wind speed of 9 m/s. The wind farm was developed by EDF Energy (Northern Offshore Wind) Ltd., and is operated by Teesside Windfarm Ltd.; the owner (100%) is EDF Energy Renewables. The wind farm was completed in June 2013 and is currently operational.

In the noise study, the sound level criteria were those from the Noise Working Group (NWG) Report – ETSU-R-97. The ESTU-R-97 noise criteria are found in Section 3.2.2 above.

The noise assessment was based on spherical propagation and air absorption at 20 degrees Celsius and 50% relative humidity. The assessments were made for both calm conditions and worst case propagation due to onshore wind, using the CONCAWE meteorological propagation algorithms for 'met category D". The noise model predicts noise levels in terms of L_{A90}.The sound levels at the closest noise sensitive receptor at a distance of 1.5 km from the wind farm was predicted to be 41 dBA (L_{A90}) in meteorologically neutral conditions, increasing to a maximum sound level of 47 dBA for the worst case onshore wind conditions.

A background noise survey was conducted over a period of about 40 days from July 7 to August 15, 2003, with correlated wind data reflecting a range of meteorological conditions. These conditions included wind speeds close to zero and in excess of 12 m/s, enabling worst case comparisons to be made. As agreed with Redcar and Cleveland Borough Council, the monitoring location was selected at the most noise sensitive receptor at the Redcar Caravan Park, off Majuba Road. The council agreed that this location would provide representative background noise data for the Redcar area.

The background noise survey was made at approximately 3.5 m above grade and away from obvious local sources of noise. The measurement parameters are L_{A90} and L_{Aeq} over 10 minute intervals. The measured background noise levels were 42 to 73 dBA (L_{Aeq}) and 38 to 69 dBA (L_{A90}) during the quiet daytime and 37 to 67 dBA (L_{Aeq}) and 34 to 58 dBA (L_{A90}) during the quiet nighttime. The survey measurements indicate that the minimum background sound level were seldom fall below 40 dBA (L_{A90}) with a typical minimum values being 42 to 43 dBA during the day and 40 to 41 dBA at night.

Beatrice Offshore Wind Farm – United Kingdom [66]

The Beatrice Wind Farm, located in the Moray Firth off the east coast of Scotland, is planned for construction in 2016. The planned total capacity is expected to be 664 MW from an array of up to a total of 184 wind turbines each rated at 3.6 MW. The sound power level of each wind turbine is 112 dBA.

Currently two demonstrator turbines are operational to examine the feasibility of creating a commercial wind farm in deep water,

Modelling was performed using Version 8.01 of Brüel & Kjær's Predictor 7810 computer noise modeling software package which utilize the ISO 9613-2 in combination with CONCAWE algorithms for meteorological effects. It was predicted that noise at the nearest onshore location (13km away) would be 27 dBA, using a receiver wind speed of 3 m/s and temperature inversion class G.

3.6 Nordic Prediction Model (Nord2000)

3.6.1 Model Application

Nord2000 is a calculation model developed as a joint project between the Nordic countries, Denmark, Norway, Sweden, Iceland and Finland [15, 16, 17, 18]. Nord2000 model has been used to assess noise from offshore wind farms as well as other sources of noise.

Nord2000 considers the influence of wind (direction, speed, gradient), temperature, ground absorption and screening. It is also possible to choose different wind speed and temperature gradients. Nord2000 is suitable for calculations over hilly terrain as it takes varying topography into account. It also takes into consideration the acoustic characteristics of water surface and therefore is appropriate for calculation of sound propagating over water.

Nord2000 has been validated by more than 500 propagation cases based on measurements on land for various non-wind turbine sources as well as by reference results obtained from accurate numerical prediction methods [67].

The propagation model has been widely used to assess noise from offshore wind farms in the Nordic countries as well as in the UK [68, 69, 70].

The model has been implemented in commercial software packages such as CadnaA, SoundPlan, exSound2000 and SPL2000 [47, 48].

3.6.2 Case Studies

Hornsea Wind Farm – United Kingdom [68]

The Hornsea Wind Farm is located about 120km off the Yorkshire coast, covering approximately 407 square km and with an output around 1.2 GW from a total of 171 wind turbines each rated at 7 MW. The sound power level for each wind turbine is 111 dBA. The project, originally conceived by SMartWind has been bought outright by DONG Energy.

Although the project is very far from the coast, airborne noise modelling was carefully considered due to proximity to manned oil and gas platforms nearby and due to plans to include accommodation platforms within the construction zone to allow workers to stay near the project area. The criteria for these zones were considered the same as for passenger ferries, 70 dBA. The Nord2000 model was used as opposed to the ISO 9613-2 model as it was considered more accurate for predicting noise propagation over water at long distances.

The entire list of Noise Sensitive Receptors included:

- The closest existing offshore oil and gas manned platform with accommodation (Barque PB, 27.05 km from closest modelled turbine)
- The closest existing offshore oil and gas installation normally unmanned (i.e. personnel shall be on board during maintenance periods only) (Mimas, 7.9 km from closest modelled turbine)
- Proposed accommodation platforms (550 m and 670 m from closest modelled turbines. Note, it appeared that there are typographical errors in the Table 5.2 of the report.)
- The closest commercial shipping route (1.85 km from closest modelled turbine)
- Fishing Vessels (500 m during construction / 50 m during operation from closest modelled turbine)
- United Kingdom Exclusive Economic Zone Boundary (45.56 km from closest modelled turbine); and
- East Riding of Yorkshire coastline (103.33 km from closest modelled turbine).

The noise model also included the cumulative effects of an extension project estimating sound output from 692 turbines in total.

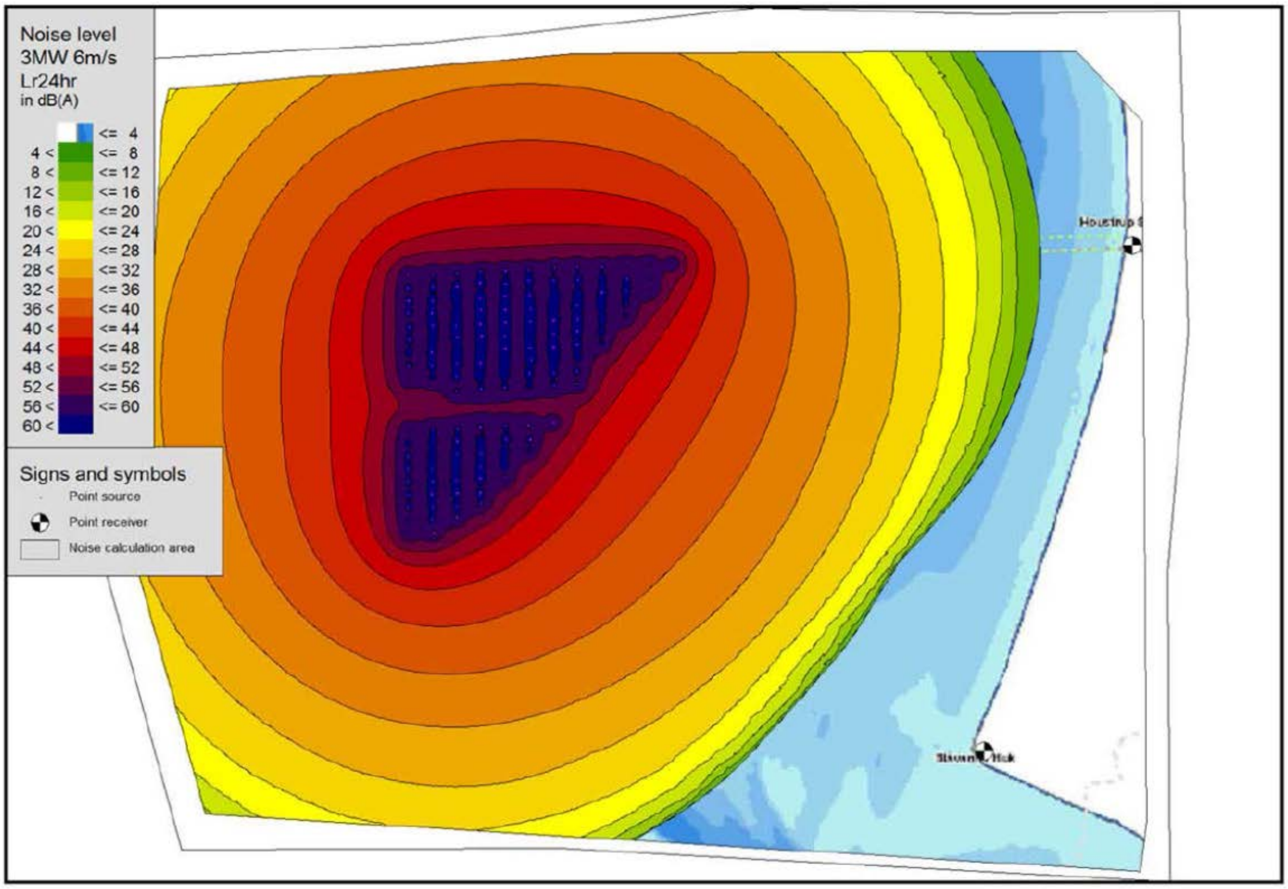
In the noise study, the assessment criteria for onshore residential and leisure receptors are those from the Noise Working Group (NWG) Report – ETSU-R-97. The ESTU-R-97 noise criteria are found in Section 3.2.2 above. The assessment criterion for offshore accommodation platforms is an indoor noise level of 45 dBA (L_{Aeq}) for sleeping. A sound level reduction of 30 dB from the walls, roofs and windows of the accommodation units was used to establish the outdoor sound level criterion. This results in an outdoor sound level criterion of 75 dBA (L_{Aeq}) for the noise assessment.

The maximum noise immission level predicted at the coast was 12 dBA and the level at the proposed accommodation platforms was 50 dBA, well within the above sound level criteria.

Horns Rev 3 – Denmark [69]

Horns Rev 3 will be located 17 km off the coast of Denmark expanding on the current two existing wind farms. The installed power will be approximately 400 MW with various turbine size and number configurations still being decided. The project is currently being developed by Energinet.dk and Vattenfall.

The available noise report is a draft, dated February 2014. Acoustic modelling of the wind turbine operations is indicated as being done using the Nord2000 model incorporated into the commercial software package SoundPlan. Detailed results are not presented for on-shore sound levels, except to note that the sound levels fall below the Danish Environment Agency (DEA) limits as given in DEA Statutory Order no. 1284 (Dec.15, 2011). However, detailed noise contour isopleths are provided for offshore noise, determined with SoundPlan, using Nord2000, for the area in the sea around the wind farm.



Example Noise Contour Isopleths Around Horns Rev 3 Wind Farm

The above mentioned DEA sound level limits are: 44 dBA at wind speed 8 m/s and 42 dBA at wind speed 6 m/s in outdoor areas at a maximum of 15 m from residential receptors; and 39 dBA at wind speed 8 m/s and 37 dBA at wind speed 6 m/s at residential receptors. If a wind turbine has a pure tonal element, a penalty of +5 dB should be applied.

Suurhiekka Wind Farm – Finland [70]

Suurhiekka offshore wind farm is located about 25 km from the coast of Ii in the Gulf of Bothnia. The project includes 80 wind turbines with a capacity of approximately 400 MW of electricity.

Modelling was performed based on the Nord200 model using SoundPlan software and assuming three scenarios:

- A layout of 120 turbines of 5 MW output with a sound power level of 107 dBA each;
- A layout of 80 turbines of 5 MW output with a sound power level of 107 dBA each; and
- A layout of 95 turbines of 3.6 MW output with a sound power level of 107 dBA each.

The conditions assumed for calculation were:

- Air humidity – RH 70%
- Temperature – 15 C
- Air pressure – 1013 mbar
- Roughness length – 0.055 m.

This noise report also comments on the choice of Nord2000 model over the Swedish model. It states that the Swedish model is based on a rare meteorological situation of low-level jets which can amplify the propagation. The report also mentions that the Swedish EPA has removed their direction to the Swedish model since 2006.

This noise report concluded that calculations based on Nord2000, downwind conditions at 8 m/s, hard surface (water) show good agreement with calculation model ISO 9613-2 which is used in many countries for offshore wind farms.

This report recommended that calculations should be performed with hard surface (water) and wind speed corresponding to 8 m/s at 10 m height.

The report concludes that all layouts are within the Swedish EPA Guideline of 40 dBA at land-based receptors

3.7 Harmonoise P2P Model

3.7.1 Model Application

The Harmonoise model is an engineering model for predicting environmental noise levels. This prediction model is based on solutions and concepts close to those found in the Nord2000 model. It predicts the sound pressure level at the receiver position in one-third octave bands from 25 Hz to 10 kHz starting with the sound power level of the source. The effects of various factors are calculated separately and subtracted from the source sound power level. These factors include spherical divergence, air absorption, reflections from ground, diffractions from sound barriers, energy losses during side reflections, and effects of scattering zones.

A series of measurements was conducted in the Collie Basin, W.A., to provide reliable measurements of actual noise levels under various meteorological conditions [71, 72]. It involved a loudspeaker source producing 1/3 octave bands of filtered pink noise, with measurements at distances from approximately 1000 m to 3000 m and simultaneous monitoring of meteorological conditions using a tethered balloon. Attenuations between the loudspeaker and the measurement locations were recorded for a total of 37 measured 1/3 octave attenuation spectra. These measurement data points were compared with the predictions from Harmonoise P2P model based on the measured meteorological data (i.e., wind speed at 10 m and temperature gradient between 10 m and 30 m). It is concluded that agreement between reference model and experimental results ranges from excellent in flat terrain situations down to fairly good in more complex configurations (hilly, viaduct) [23]

We have not been able to find any example of the use of Harmonoise for wind farms.

The model has been implemented in the commercial software package CadnaA [47].

3.8 Partial Differential Equation Based Methods

The parabolic wave equation is frequently used in acoustic engineering to estimate long range sound propagation. The method essentially calculates the sound pressure level in the direction of propagation by solving an approximate form of the Helmholtz equation. This partial differential equation can be discretized using various numerical methods such as the Crank-Nicholson Parabolic Equation (CNPE), the Green's Function Parabolic Equation Method (GFPE) and the Fast Field Program (FFP) technique.

The above techniques to solve the parabolic wave equation are mainly within the academic domain. The use of such methods is undoubtedly limited in practice to relatively complex situations. The general principle of these methods is to solve the wave equation or Helmholtz equation such as to deduce the sound field generated by a source of sound. The procedure for solving the wave equation is generally difficult to implement due to the complexity of the atmospheric environment. These numerical methods to solve the wave equation provide highly accurate representations of propagation effects for individual frequencies. They have been used as a "reference model" to validate/verify a variety of engineering models such as the models discussed above [27].

These techniques are generally complex and computationally intense. These methods are not generally available within commercial software applications.

We have not been able to find any example of the use of partial differential equation based method for wind farms.

3.9 Fees for Commercial Models/Software Packages

The commercially available software packages referenced above typically

- Can optionally be configured to include various computations under national or international standards as well as various recognized, published sound propagation models;
- Require a one-time license fee per user, subject to the optional components included; such license fee applicable to the specific software versions;
- Require an annual maintenance fee per license, in order to receive software updates and support.

CHAPTER 4 JURISDICTIONAL REVIEW

4.1 Introduction

This chapter summarizes various regulations, guidelines, codes of practices and best practices for assessment and control of environmental noise jurisdictions other than Ontario. Current available noise guidelines from various jurisdictions including British Columbia (Canada), New Brunswick (Canada), Nova Scotia (Canada), Manitoba (Canada), Alberta (Canada), Oregon (USA), Flanders and Wallonia (Belgium), Denmark, Finland, France, Germany, Ireland, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom, Hong Kong, New Zealand, South Australia, Queensland (Australia), Western Australia, Victoria (Australia), Tasmania (Australia), New South Wales (Australia) are reviewed. Many jurisdictions treat wind farms as they do any other industrial noise source. Some jurisdictions have noise regulations/guidelines/criteria specific to wind farms.

From our review of the noise documents and various communications with the approval authorities/agents, it is observed that there are currently no noise guidelines/regulations pertaining specifically to offshore wind turbine noise. Offshore wind turbines are bound to the same noise criteria as onshore wind turbines. Requirements for wind turbine noise vary in strictness from country to country. The strictest noise requirements are found in Sweden, Germany, Finland, New Zealand, the United Kingdom and parts of Australia. Several countries internationally have penalties for tonal, impulsive, and low frequency noise. New Zealand, Finland and parts of Australia (Tasmania and Victoria) are found to be the only regions to include a penalty for amplitude modulation of wind turbine noise.

Some jurisdictions indicate a particular acoustical modelling method (e.g. international or national standard or other technical procedure) should be used for wind farm noise assessment. Many do not specify or require a particular modelling method. Of those that do indicate a specific acoustical model/analysis method, only a small subset requires modifications to the methods to account for propagation of sound over water, that is, for offshore wind farms.

The report “International Review of Policies and Recommendations for Wind Turbine Setbacks from Residences: Setbacks, Noise, Shadow Flicker, and Other Concerns” by Kathryn M. B. Haugen for the Minnesota Department of Commerce: Energy Facility Permitting, dated October 19, 2011, has been useful in determining many of the guidelines for setback distance for wind farms [73]. In general, such setback requirements are usually implicitly applicable to onshore situations.

4.2 Canada – British Columbia

4.2.1 Reference

The document, “Best Practice for Wind Power Project Acoustic Assessment”, dated 2012, was reissued as part of the more comprehensive Clean Energy Guidebook [74]. Based on telephone discussions with Monica Perry, Executive Project Director of the Environmental Assessment Office of the Province of British Columbia, it is understood that the noise guidelines remain unchanged. The document makes recommendations in three areas:

- Interpretation of the Land-Use Operational Policy criteria;
- Requirements for assessment reports; and

- Predictive modelling techniques.

There were no specific provisions for offshore wind farms found.

4.2.2 Noise Limit Criteria

The Land-Use Operational Policy requires that sound emitted from wind turbines is not to exceed a maximum of 40 dBA on the outside of an existing permanently-occupied residence (not owned by the wind farm proponent) or the nearest property line of existing, undeveloped parcels zoned residential (not owned by the wind farm proponent) in existence at the time of application for a Land Act tenure to construct a wind farm (Ministry of Forests, Lands and Natural Resource Operations 2011).

The interpretation of the Policy for the assessment of sound levels is:

- Where ambient conditions are 35 dBA or less (assumed to be L_{eq} over the same period):
  - Night-time (10:00pm to 7:00am) criterion: L_{eq} over 9 hours of 40 dBA,
  - Day-time (7:00am to 10:00pm) criterion: L_{eq} over 15 hours of 40 dBA,
  - Ambient conditions are to be assumed at 35 dBA for calculation purposes.
- Where ambient conditions are shown to be greater than 35 dBA during either the day or night (except where another wind power project is present), a 5 dBA increment may be applied to a measured background sound level to determine the day or night criterion, to a maximum of 50 dBA.

4.2.3 Acceptable/Recommended Acoustic Model

The BC guidelines recommend ISO 9613-2 model as the sound propagation model to be used for predicting noise levels. However, the guidelines also indicate that CONCAWE, Harmonoise and Nord2000 models may be used if explanations are given as to what particular effects are being modelled.

4.2.4 Software Identified as Acceptable

Software recommended in the guidelines includes:

- Cadna/A by Datakustik GMBH
- SoundPLAN by SoundPLAN International LLC
- Predictor by Bruel and Kjaer
- WindPro by EMD International A/S
- WindFarmer by GL Garrad Hassan.

4.2.5 Adjustments/Penalties

Not specified.

4.2.6 Setbacks

Not specified.

4.2.7 Study Requirements

Not specified.

4.2.8 Miscellaneous

Not specified.

4.3 Canada – New Brunswick

4.3.1 Reference

The report, "Model Wind Turbine Provisions and Best Practices for New Brunswick Municipalities, Rural Communities and Unincorporated Areas", dated November 25, 2008, is an assessment of all impacts from wind farms that would likely be a concern in the planning stages of a project [75]. Following research from other provinces and internationally, noise impacts were categorized into four options for the government to consider.

- Option 1 – Require a sound limit at the exterior of the nearest habitable dwelling (either specific dBA and/or dBA above background);
- Option 2 – Require an absolute separation distance from the exterior of the nearest habitable dwelling;
- Option 3 – Require a general provision for noise limits in municipal by-laws (there are few quantitative limits set in New Brunswick);
- Option 4 – Combining options 1 and 2 allowing setbacks to be forgone if the sound levels are shown to be within the limit.

Also the New Brunswick Government published a document, "Additional Information Requirements for Wind Turbines", which specified the model and guidelines [76].

There were no specific provisions for offshore wind farms found.

4.3.2 Noise Limit Criteria

In New Brunswick, the Ontario guidelines, NPC 232 [77] are used as a basis for modelling and deciding setback and sound level limits. The guideline is applicable to wind power sites with a combined design production rating of three megawatts or more. These criteria apply to all noise sensitive locations including recreational, residential and institutional uses.

4.3.3 Acceptable/Recommended Acoustic Model

Predictions of the sound levels must be made using an accepted method that takes into account the layout of the wind farm and the topography of the surrounding area. ISO 9613-2 is identified as the internationally recognized standard [76].

4.3.4 Software Identified as Acceptable

Not specified.

4.3.5 Adjustments/Penalties

Not specified.

4.3.6 Setbacks

Any setback from the turbine to the building exterior would be determined based on model results.

4.3.7 Study Requirements

A noise impact study is required for all noise sensitive locations (including recreational, residential and institutional uses) within 1 kilometre of the nearest turbine. The study must demonstrate compliance with the noise criteria (same as those in Ontario) at the building exterior.

4.3.8 Miscellaneous

Not specified.

4.4 Canada – Nova Scotia

4.4.1 Reference

In a similar study to New Brunswick, the report, "Model Wind Turbine By-laws and Best Practices for Nova Scotia Municipalities", dated January 28, 2008, gives the Ontario guidelines as a basis, with the same options for modelling, setbacks and sound level limits [78]. Also the "Proponent's Guide to Wind Power Projects: Guide for Preparing an Environmental Assessment Registration Document", updated January 2012, gave suggestions for setback distances [79].

There were no specific provisions for offshore wind farms found.

4.4.2 Noise Limit Criteria

Same as Ontario.

4.4.3 Acceptable/Recommended Acoustic Model

ISO 9613-2.

4.4.4 Software Identified as Acceptable

Not specified.

4.4.5 Adjustments/Penalties

Not specified.

4.4.6 Setbacks

Many municipalities have development land-use by-laws specifying setback distance requirements ranging from 400 m to 1 km from turbine to residence.

4.4.7 Study Requirements

Not specified.

4.4.8 Miscellaneous

Not specified.

4.5 Canada – Manitoba

4.5.1 Reference

"Land Use Planning for Wind Energy Systems in Manitoba", dated October 9, 2009 [80] specifies the expanded sound criteria recommended by the Canadian Wind Energy Association (CanWEA) in their document "Position on Setbacks for Large-Scale Wind Turbines in Rural Areas (MOE Class 3) in Ontario" [81].

There were no specific provisions for offshore wind farms found.

4.5.2 Noise Limit Criteria

Same as Ontario but expanded up to 53 dBA at a wind speed of 11 m/s.

4.5.3 Acceptable/Recommended Acoustic Model

ISO 9613-2.

4.5.4 Software Identified as Acceptable

Not specified.

4.5.5 Adjustments/Penalties

Not specified.

4.5.6 Setbacks

The reference document indicates that a setback of 500 to 550 m from an occupied dwelling to a wind turbine should be sufficient enough to ensure that sound level criteria are met based on sound modelling.

4.5.7 Study Requirements

Not specified.

4.5.8 Miscellaneous

The zoning by-law should also set prescribed separation distances from habitable buildings in areas where wind energy development will be allowed and mutual separation distances of habitable buildings from existing or approved wind energy systems. Early awareness and consultation between the proponent and landowners during the planning stage to address noise mitigation is encouraged.

4.6 Canada – Alberta

4.6.1 Reference

"Rule 12", published by the Alberta Utilities Commission, effective on April 1, 2013, concerns noise control for all facilities including wind farms [82].

There were no specific provisions for offshore wind farms found.

4.6.2 Noise Limit Criteria

Criteria at receptors are determined on a case by case basis from the basic sound criteria listed in Table 4-1 below, with additional adjustments for ambient sound levels, duration of noise imission and meteorological conditions.

Table 4-1 Sound Level Criteria - Alberta

Proximity to transportation	**1 to 8 dwellings Night time (8 hr) L_{eq} (dBA)**	**9 to 160 dwellings Night time (8 hr) L_{eq} (dBA)**	**>160 dwellings Night time (8 hr) L_{eq} (dBA)**
Category 1 (>500 m from heavily travelled roads or rail lines)	40	43	46
Category 2 (>30 m but <500 m from heavily travelled roads or rail lines)	45	48	51
Category 3 (<30 m from heavily travelled roads or rail lines)	50	53	56

4.6.3 Acceptable/Recommended Acoustic Model

The models recommended are ISO 9613-2 and CONCAWE but come with additional requirements (see 4.6.7 below) specifically for wind facilities.

4.6.4 Software Identified as Acceptable

Not specified.

4.6.5 Adjustments/Penalties

Not specified.

4.6.6 Setbacks

If there are dwellings within 1.5 km of the wind farm, then the permissible sound limit (PSL) is applied at the receptors. If there are no dwellings within that distance, then the PSL is applied at the 1.5 km distance.

4.6.7 Study Requirements

If there are no dwellings within the 1.5 km of the wind farm, a simplified approach (6 dB per doubling distance) can be used to show compliance. If there are dwellings within 1.5 km of the wind farm, then a detailed report by an acoustic practitioner is required. The sound power level from a turbine must correspond to the maximum noise emitted when the turbine operates under planned maximum operating conditions for both day and night time scenarios. The model must include the cumulative effects of adjacent wind turbines and other energy-related facilities that may impact a dwelling within the study area. In cases where no dwelling exists within a 1.5 km radius of the wind farm, and the proposed facility is adjacent to an existing facility, which also has no dwellings with a 1.5 km radius, then the sound level may exceed the permissible limit where the two radii overlap.

4.6.8 Miscellaneous

Not specified.

4.7 USA - Oregon

4.7.1 Reference

In the United States, each state decides on its own standards for noise. Oregon does not yet have any offshore wind farms in operation. The "Oregon Administrative Rules, Chapter 340, Division 35", shows the Department of Environmental Quality's guidelines for onshore projects are used in the consenting stages for offshore wind farms [83, 84].

There were no specific provisions for offshore wind farms found.

4.7.2 Noise Limit Criteria

New industrial and commercial noise source standards for an onshore wind energy facility allow the wind energy facility to increase the ambient statistical sound levels L_{10} and L_{50} over 1 hour by 10 dBA using either an assumed L_{50} of 26 dBA or the actual ambient background level measured at an appropriate measurement point, being the further of a point 25 feet in front of the receptor or the point on the property line nearest the noise source [83]. If the actual ambient L_{50} over 1 hour measured is higher than 26 dBA, the following upper limits apply:

- Night-time (22:00 to 07:00) criterion: L_{50} over 1 hour of 50 dBA, L_{10} over 1 hour of 55 dBA,
- Day-time (07:00 to 22:00) criterion: L_{50} over 1 hour of 55 dBA, L_{10} over 1 hour of 60 dBA [79].

4.7.3 Acceptable/Recommended Acoustic Model

Not specified.

4.7.4 Software Identified as Acceptable

Not specified.

4.7.5 Adjustments/Penalties

Not specified.

4.7.6 Setbacks

Not specified.

4.7.7 Study Requirements

Not specified.

4.7.8 Miscellaneous

Not specified.

4.8 Belgium – Flanders

4.8.1 Reference

In Belgium, the regions of Flanders and Wallonia have different regulations for wind turbines. Since 2012, the noise standards for wind turbines have been stated in "Flemish Environmental Permitting Regulations" (VLAREM - Vlaams Reglement betreffende de Milieuvergunning) according to the Euronoise paper, "Differences in Noise Regulations for Wind Turbines in Four European Countries", dated June 2015 [85].

There were no specific provisions for offshore wind farms found.

4.8.2 Noise Limit Criteria

The standards are different for 12 different destination areas such as industrial, recreational, rural, military and buffer zones. Generally, using the L_{eq} over nine hours during the night (22:00 – 07:00), the standard is 39 dBA for residential areas and 43 dBA for agricultural areas. In the event that background sound level L_{95} over 1 hour is greater than the above limit values, the actual background sound level with a tolerance of +1 dB applies.

4.8.3 Acceptable/Recommended Acoustic Model

ISO 9613-2.

4.8.4 Software Identified as Acceptable

Not specified.

4.8.5 Adjustments/Penalties

Not specified.

4.8.6 Setbacks

3 times the rotor diameter.

4.8.7 Study Requirements

In an agricultural environment, the ground is considered as 80% porous (sound absorptive) soil. If the tolerance of the sound power level of the turbine is greater than 1 dB that tolerance is added to the power rating minus 1 dB. For example, if the turbine we are modelling has a power rating of 105.4 dBA with a 2 dB tolerance then the power used in calculation would be 106.4 dBA.

4.8.8 Miscellaneous

Not specified.

4.9 Belgium – Wallonia

4.9.1 Reference

Since 2014, the Walloon Government adopted different criteria for various land uses on wind farms though less extensively than Flanders according to the Euronoise paper, "Differences in Noise Regulations for Wind Turbines in Four European Countries", dated June 2015 [85].

There were no specific provisions for offshore wind farms found.

4.9.2 Noise Limit Criteria

The noise criteria do not account for background ambient sound levels.

For the night period (22:00 to 06:00 or 07:00), depending on location) the limit L_{eq} over 1 hour is 43 dBA for all areas except residential and rural areas where the limit is reduced to 40 dBA.

4.9.3 Acceptable/Recommended Acoustic Model

ISO 9613-2.

4.9.4 Software Identified as Acceptable

Not specified.

4.9.5 Adjustments/Penalties

An adjustment of +1 dB is added to account for amplitude modulation.

4.9.6 Setbacks

To reduce visual impact, Wallonia specifies a setback distance of at least four times the total height of the turbine in residential zones or 400 m in rural zones.

4.9.7 Study Requirements

The Wallonia requirements include greater restrictions depending on the temperature, an unusual trait compared to other jurisdictions. The lower limit of 40 dBA applies if the temperature exceeds 16ºC at 22:00, thus ensuring an indoor noise level of 30 dBA even with open windows. Unlike some other countries, but similar to Ontario, the assessment of noise is not carried out over a larger time period but over one hour periods.

The turbine sound power for wind speeds of 10 m/s at a height of 10 m are used.

Ground attenuation is to be calculated as per the alternative method of Section 7.3.2 of ISO 9613-2.

4.9.8 Miscellaneous

Not specified.

4.10 Denmark

4.10.1 Reference

"Statutory Order 1284" of 15 December 2011 [6] sets out the Danish modelling method along with noise regulations. The "Danish Regulation of Low Frequency Noise from Wind Turbines", dated 2012, specifies some further adjustments for propagation over water for low frequency bands [86].

4.10.2 Noise Limit Criteria

The regulation noise limits (outdoors) for the time periods day (07:00 – 18:00), evening (18:00 – 22:00) and night (22:00 – 07:00) in terms of L_{eq} over the entire day, evening and night, respectively (i.e. over 11, 4 and 9 hours), are summarized in Table 4-2 below.

Table 4-2 Sound Level Criteria - Denmark

Zone	Wind Speed (m/s)	L_{eq} (T) Limit (dBA)
Noise sensitive areas, e.g. dwellings, summer cottages, etc.	8	39
	6	37
Dwellings in open country	8	44
	6	42

The low frequency limit is 20 dB (indoors) for the frequency range of 10 to 160 Hz.

4.10.3 Acceptable/Recommended Acoustic Model

The Nord2000 model is recommended for modelling noise including specifications to model low frequency noise.

4.10.4 Software Identified as Acceptable

Not specified.

4.10.5 Adjustments/Penalties

The correction for ground effect is simplified to +1.5 dB across all frequency bands for onshore propagation and +3 dB for offshore propagation

4.10.6 Setbacks

The Danish Environmental Protection Agency website specifies a setback distance of four (4) times the total turbine height from the turbine to a neighbouring home with no exceptions [87].

4.10.7 Study Requirements

Receptors are set no more than 15m from dwellings at the most noise-exposed point.

4.10.8 Miscellaneous

The regulations indicated that post-construction, sound measurements of wind turbine operation may be ordered to verify compliance with the provisions.

4.11 Finland

4.11.1 Reference

The Finnish Council of State issued a decree on August 27th, 2015 updating industrial noise regulations within the Environmental Protection Act (Decree 527/2014) [88] with specific outdoor criteria for wind farms. The indoor noise limit values are presented in guideline document, Decree 545/2015 [89]. The Finland Ministry of the Environment (MOE) provides guideline outdoor noise levels in the document, "Wind Turbine Noise Modelling" (Tuulivoimaloiden melun mallintaminen: Modellering av buller från vindkraftverk, 2014) for risk assessment in land use planning for wind turbine noise [90].

There were no specific provisions for offshore wind farms found.

4.11.2 Noise Limit Criteria

The noise limits for residential areas are:

- Daytime (07:00 – 22:00) L_{eq} over 15 hours: 45 dBA
- Nighttime (22:00 – 07:00) L_{eq} over 9 hours: 40 dBA.

In Recreational areas (protected areas where everyone may walk, ski or cycle freely while preserving the natural environment):

- Daytime L_{eq} over 15 hours: 35 dBA.

4.11.3 Acceptable/Recommended Acoustic Model

The Finland MOE recommends the use of ISO 9613-2 with provision for Nord2000 to be accepted with explanation necessary.

4.11.4 Software Identified as Acceptable

Not specified.

4.11.5 Adjustments/Penalties

There is a 5 dB sanction (penalty) applied if the sound signal is amplitude modulated, includes narrow-band frequency components or is impulsive.

4.11.6 Setbacks

There is no mandatory setback distance requirement in the guideline document. The setback distance would be determined by the modelling results, based on achieving the sound limits.

4.11.7 Study Requirements

Not specified.

4.11.8 Miscellaneous

Not specified.

4.12 France

4.12.1 Reference

French standard “Norme Française (NF) S 31-114”, dated August 11, 2015 outlines the noise criteria for wind turbines [91].

There were no specific provisions for offshore wind farms found.

4.12.2 Noise Limit Criteria

The basic limit is L_{50} over 10 minutes of 35 dBA [91]. If the existing ambient sound levels are greater than 35 dBA then the following receptor limits apply:

- 3 dBA over ambient during night-time (10:00pm to 7:00am)
- 5 dBA over ambient during day-time (7:00am to 10:00pm).

There are also maximum limits of the cumulative sound level, L_{50} over 10 minutes in the standard of:

- 60 dBA for night-time
- 70 dBA for day-time.

These limits do not apply within a radius of 1.2 times the sum of the hub height and the wind turbine blade length [92].

4.12.3 Acceptable/Recommended Acoustic Model

Not specified.

4.12.4 Software Identified as Acceptable

Not specified.

4.12.5 Adjustments/Penalties

If a tonal component is present for more than 30% of either the day-time or night-time period, a +10 dB penalty from 50 to 315 Hz and a +5 dB penalty from 315 Hz to 8 kHz is added.

4.12.6 Setbacks

Not specified.

4.12.7 Study Requirements

Not specified.

4.12.8 Miscellaneous

Not specified.

4.13 Germany

4.13.1 Reference

Germany's administrative regulations (Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz: Technische Anleitung zum Schutz gegen Lärm - TA Lärm GMBI Nr. 26/1998 S. 503) date back to August 26, 1998 and do not contain specific standards for wind turbines [93].

There were no specific provisions for offshore wind farms found.

4.13.2 Noise Limit Criteria

For all sources of noise, including wind turbines, the regulations set the night-time (22:00 – 06:00) limits in terms of L_{eq} over the entire period, as:

- 45 dBA in heartland (interpreted as rural), villages, mixed areas
- 40 dBA in general residential and small urban areas
- 35 dBA in purely residential areas (e.g., suburb).

These noise limits are the cumulative sound levels from all sources of noise in the area. This means that there is less room within which to make noise if there are other sources nearby.

Federal states are free to impose further requirements.

4.13.3 Acceptable/Recommended Acoustic Model

ISO 9613-2 is indicated in the regulations.

4.13.4 Software Identified as Acceptable

Not specified.

4.13.5 Adjustments/Penalties

In most federal states, the upper limit of the 90% confidence interval of all uncertainties related to the wind turbine rating level must be below the limit value. To be conservative, the sound power level of the wind turbine is increased by 2 dBA. The technical directive also states that calculation details must be provided for review.

4.13.6 Setbacks

Many states specify setback distances of 750 to 1000 m away from residences for both offshore and onshore wind farms. For solitary homes (e.g., a farm house), this distance is usually 400 m. Some states also require measurement to show compliance.

4.13.7 Study Requirements

Not specified.

4.13.8 Miscellaneous

There are also regulations on underwater noise from construction processes set by the German Federal Maritime and Hydrographic Agency (BSH – Bundesamt für Seeschifffahrt und Hydrographie) in the document "Offshore Wind Farms Prediction of Underwater Sound: Minimum Requirements on Documentation", dated July 2013, which limits underwater noise to 160 dB at a distance of 750 m around the piling source, to protect marine animals, especially harbor porpoise [94].

4.14 Ireland

4.14.1 Reference

In accordance with an email from Sean Dunne at Ireland EPA dated March 24, 2016, Ireland's noise guidelines are still to be finalized. [95]. There are some current guidelines available in the Planning Document, "Wind Energy Development Guidelines", which mentions similar limits used in the United Kingdom [96]. These expressly do not concern offshore wind farms.

4.14.2 Noise Limit Criteria

The L_{90} over 10 minutes is limited to 43 dBA at night and 45 dBA or 5 dBA over background limit during the day. Rural zones have a 35 to 40 dBA limit.

4.14.3 Acceptable/Recommended Acoustic Model

Not specified.

4.14.4 Software Identified as Acceptable

Not specified.

4.14.5 Adjustments/Penalties

Not specified.

4.14.6 Setbacks

The current draft for update includes a 500 m setback for amenity purposes [96].

4.14.7 Study Requirements

Not specified.

4.14.8 Miscellaneous

Not specified.

4.15 Netherlands

4.15.1 Reference

At the start of 2011, new standards for wind turbines were introduced in Netherlands. "Decree 749", dated October 14, 2010, from the "Netherlands' Book of Statutes" (Staatsblad van het Koninkrijk der Nederlanden), amends the environmental rules concerning wind turbines [97].

4.15.2 Noise Limit Criteria

The noise standards state that a limit of L_{eq} of 47 dBA over 24 hours is applicable in all noise-sensitive outdoor living areas. In addition, a night (23:00 – 07:00) limit value of L_{eq} 41 dBA over eight hours is also applied. These onshore limits are applied to offshore projects as well. However, there are only three existing offshore wind farms in the Netherlands and all of them are at least 10 km from the shore meaning that noise considerations were scoped out of their reports.

4.15.3 Acceptable/Recommended Acoustic Model

ISO 9613-2.

4.15.4 Software Identified as Acceptable

Not specified.

4.15.5 Adjustments/Penalties

Not specified.

4.15.6 Setbacks

According to an email from Robert Koelemeijer from the Climate, Air quality and Energy section of the PBL Netherlands Environmental Assessment Agency, dated March 23, 2016, there is a setback of 12 nautical miles from the shoreline preferred due to shipping lane and development access and to mitigate any visual impact. This boundary can be overcome but there is a lot more legislation to consider, including shipping lane setback, proximity to existing underwater infrastructure and other offshore activities (mining) [98].

4.15.7 Study Requirements

The standards require that noise emission levels of the wind turbine be calculated according to local meteorological conditions. The standards also indicate that model be used with additional factors for hard ground giving a 2 dB increase in the resulting sound level (i.e. a 2 dB reduction in ground attenuation) where the ISO model usually gives a 3 dB increase (i.e. a 3 dB reduction in ground attenuation).

4.15.8 Miscellaneous

The Royal Dutch Meteorological Institute provides meteorological data for the day, evening and night periods for common turbine heights using long-term wind statistics [99].

4.16 Norway

4.16.1 Reference

Erlend Bjerkestrand at Norwegian Water Resources and Energy Directorate provided the information in an email, dated August 3, 2015 [100].

4.16.2 Noise Limit Criteria

In Norway, the same noise criteria apply for both onshore and offshore wind farms.

In a Red Zone, an area where noise sensitive buildings are not recommended, the maximum $L_{den,}$ should be 55 dBA. For a Yellow Zone, an area where noise sensitive buildings are accepted, the maximum L_{den} should be 45 dBA, corresponding to a constant noise level or L_{eq} over 24 hours of 38.6 dBA. ($L_{den,}$ day/evening/night, is a 24 hour L_{eq} modified with a 10 dB penalty added to the levels between 23.00 and 07.00 hours and a 5 dB penalty added to the levels between 19:00 and 23:00 hours to reflect people's extra sensitivity to noise during the evening and the night.)

4.16.3 Acceptable/Recommended Acoustic Model

In Norway, acoustical modelling has primarily been done using ISO 9613-2. But now the Nord2000 model is recommended recognizing that it allows for greater accuracy when considering external factors such as ground conditions, wind shadow, echo and icing.

4.16.4 Software Identified as Acceptable

Not specified.

4.16.5 Adjustments/Penalties

Not specified.

4.16.6 Setbacks

Not specified.

4.16.7 Study Requirements

Descriptions of the various factors entered into the modelling are expected in Impact Assessments submitted to the Environment Agency [100].

4.16.8 Miscellaneous

Not specified.

4.17 Portugal

4.17.1 Reference

The Acústica conference proceedings from October, 2008, included a presentation on “Noise Mapping of Industrial Sources” which discussed modelling of many different sources, including wind farms, [101].

There were no specific provisions for offshore wind farms found.

4.17.2 Noise Limit Criteria

Portugal follows the WHO Guidelines for Night Noise (2008) where L_{eq} over 8 hours (23:00 – 07:00) outdoors should not exceed 40 dBA [59]. No guideline limits for the daytime period were found.

4.17.3 Acceptable/Recommended Acoustic Model

Portugal uses the ISO 9613-2 model for all industrial facilities including wind farms.

4.17.4 Software Identified as Acceptable

Not specified.

4.17.5 Adjustments/Penalties

Not specified.

4.17.6 Setbacks

Not specified.

4.17.7 Study Requirements

Not specified.

4.17.8 Miscellaneous

Not specified.

4.18 Spain

4.18.1 Reference

According to the “International Wind Energy Policies” report [73] Spanish Law 37/2003 [102] and Royal Decree 1513/2005 [103] provide general requirements setting criteria and for modelling industrial noise.

There were no specific provisions for offshore wind farms found.

4.18.2 Noise Limit Criteria

Spain allows each of its municipalities within each region to determine their own guidelines for acceptable noise. As a result, the night-time (23:00 – 07:00) sound level limits range anywhere from L_{eq} over 8 hours of 28 dBA to 40 dBA. The website for the Camposol District Journal has listed a selection of available guidelines [104].

4.18.3 Acceptable/Recommended Acoustic Model

ISO 9613-2 is used for all industrial noise modelling applications.

4.18.4 Software Identified as Acceptable

Not specified.

4.18.5 Adjustments/Penalties

Not specified.

4.18.6 Setbacks

As with the Noise Limit Criteria, each regional or municipal government is responsible for determining setback distances. The International Wind Energy Policies report found setbacks ranging from 150 m in the Canary Islands to 500 m, the general recommendation from National government. A 300 m setback was considered a large enough setback to meet a 45 dBA limit, by the Institute for Diversification and Saving of Energy.

4.18.7 Study Requirements

Not specified.

4.18.8 Miscellaneous

Not specified.

4.19 Sweden

4.19.1 Reference

The email of July 20, 2015 from Ingrid Johansson-Horner, Senior Scientific Officer at the Policy Implementation Department of the EPA outlined the criteria for wind farms [105].

No specific provisions for offshore wind farms were indicated.

4.19.2 Noise Limit Criteria

In Sweden, the noise limits at houses (including summer houses) are set to L_{eq} over 24 hours of 40 dBA. Sometimes the limit can be set at 35 dBA if the area is deemed part of the Natura 2000 (wildlife) protection zone.

Often a project will be rejected if construction noise is expected to be too loud in these zones because of impact on wildlife [105].

4.19.3 Acceptable/Recommended Acoustic Model

Not specified.

4.19.4 Software Identified as Acceptable

Not specified.

4.19.5 Adjustments/Penalties

There is a +5 dB adjustment for the presence of tonal components.

4.19.6 Setbacks

Not specified.

4.19.7 Study Requirements

Not specified.

4.19.8 Miscellaneous

Underwater noise is also a concern and the German standards (described in Section 4.13.8 herein) are advocated according to an email from Linus Hammar at the Swedish Agency for Marine and Water Management dated July 22, 2015 [106].

4.20 United Kingdom

4.20.1 Reference

In the UK, both the Marine Management Office (MMO) and Department of Energy and Climate Change (DECC) are responsible for assessing offshore wind farms. Usually the MMO would take small scale projects and the DECC would cover the larger wind farms.

For noise assessment, the ETSU-R-97 guidance developed by the Noise Working Group (NWG) for the UK Department of Trade and Industry (DTI) is used to scope the impact of the wind turbines on onshore and near-shore sensitive receptors [51].

4.20.2 Noise Limit Criteria

ETSU-R-97 recommends the following noise limits:

- Day-time: 35 to 40 dB L_{90} over 10 minutes when the prevailing background noise level is below 30 dBA L_{90}; the range allowing for considerations of number of dwellings, the amount of energy generated and the duration and level of sound exposure;
- Night-time: 43 dB L_{90} over 10 minutes (derived from the L_{eq} over 10 minutes of 35 dBA referred to in Planning Policy Guidance Note 24. An allowance of 10 dBA has been made for attenuation through an open window (free-field to internal) and 2 dB subtracted to account for the use of L_{90} rather than L_{eq});
- If a developer can demonstrate that the minimum absolute noise criteria proposed of 35 dBA L_{90} over 10 minutes can be achieved at high wind speeds of 10 m/s at 10 m height, then measurement of the background sound levels would be unnecessary.

4.20.3 Acceptable/Recommended Acoustic Model

Both agencies require projects to be assessed using the ISO 9613-2 Standard and/or the Swedish Model following the “Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise from the Institute of Acoustics”, dated May, 2013 [107].

It noted that the ISO 9613-2 standard, which is widely used in the UK, can be applied to obtain realistic predictions of noise from onshore wind farms, provided that the appropriate choice of input parameters and correction factors are made. In particular, the use of “soft ground” factor should be avoided and the full theoretical effects of terrain screening will usually not be achieved.

In the Institute of Acoustics’ “Supplementary Guidance Note 6: Noise Propagation Over Water for On-shore Wind Turbines”, dated July, 2014, the Swedish Model (cylindrical spreading) is recommended for application over long distances of water [108].

4.20.4 Software Identified as Acceptable

Not specified.

4.20.5 Adjustments/Penalties

Not specified.

4.20.6 Setbacks

Not specified.

4.20.7 Study Requirements

As can be seen in the Walney extension case study (Chapter 3.3.2 herein) operational noise can be scoped out of the environmental impact assessment process if, after a simple analysis, the designed setback distance is great enough to ensure that any sound exposure is well below the guideline limits.

4.20.8 Miscellaneous

Not specified.

4.21 Hong Kong

4.21.1 Reference

The government of Hong Kong has no specific guidelines for windfarms, offshore or onshore, but considers them under the group of places other than domestic premises, public places or construction sites. This means they are considered the same as other industrial facilities. The "Technical Memorandum for the Assessment of Noise from Places Other than Domestic Premises, Public Places or Construction Sites", updated June, 1997, outlines the requirements [109].

There were no specific provisions for offshore wind farms found.

4.21.2 Noise Limit Criteria

The document, "Noise Criteria For Places Other Than Domestic Premises, Public Places or Construction Sites" states that receptors in differing zones will have upper criteria L_{eq} over the corresponding time periods set 5 dBA below the prevailing background noise or the Criteria listed in Table 4-4, whichever is more stringent.

The Table 4-3 show how Noise Sensitive Receivers (NSR) are classified and Table 4-4 indicates what the corresponding noise criteria are.

Table 4-3 – Area Sensitivity Ratings (ASR)

Type of Area containing NSR	Degree to which NSR is affected		
	Not affected	Indirectly Affected	Directly Affected
Rural	A	B	B
Low density residential	A	B	C
Urban	B	C	C
Other	B	B	C

Note, any NSR shall, irrespective of Table 4-3, be assigned an ASR of "C" if it is within 100 m of a zone designated as "Industrial" or "Industrial Estate" on a statutory Outline Zoning Plan, or an ASR of "B" if it is between 100 m and 250 m from such a zone, except in cases where Table 4-3 indicates an ASR of "C".

Table 4-4 – Defined Upper Limit Criteria

L_{eq} over period T (dBA)	Area Sensitivity Ratings (ASR)		
Time Period	A	B	C
Day 12 hours (0700 to 1900) Evening 4 hours (1900 to 2300)	55	60	65
Night 8 hours (2300 to 0700)	45	50	55

4.21.3 Acceptable/Recommended Acoustic Model

CONCAWE.

4.21.4 Software Identified as Acceptable

Not specified.

4.21.5 Adjustments/Penalties

Not specified.

4.21.6 Setbacks

Not specified.

4.21.7 Study Requirements

Not specified.

4.21.8 Miscellaneous

Not specified.

4.22 New Zealand

4.22.1 Reference

The New Zealand Standard NZS 6808:2010, “Acoustics – Wind Farm Noise” provides guidelines for most of the processes involving noise from onshore wind farms [110]. It does state that the Standard may be applied to offshore wind farms if there are onshore effects on people and communities noting that, with appropriate modification, the prediction, measurement and assessment can be used for planning and management of wind farm sound received onshore.

4.22.2 Noise Limit Criteria

The criteria for wind farms are specified in Table 4-5 below.

Table 4-5 Sound Level Criteria – New Zealand

<table>
<tr><th>Background sound level
(L_{90} over 10 minutes) (dBA)</th><th>Noise Limit
(L_{90} over 10 minutes) (dBA)</th><th>High Amenity Noise Limit
(L_{90} over 10 minutes) (dBA)</th></tr>
<tr><td>> 35</td><td>Background + 5</td><td rowspan="2">Background + 5</td></tr>
<tr><td>30 - 35</td><td rowspan="2">40</td></tr>
<tr><td>< 30</td><td>35</td></tr>
</table>

Background sound level is defined as the A-weighted L_{90} measured prior to the installation of any wind turbines in an area.

4.22.3 Acceptable/Recommended Acoustic Model

Sound modelling is acknowledged as not being standardized but the ISO 9613-2 model is mentioned as correlating well with measured data for wind farms.

4.22.4 Software Identified as Acceptable

Not specified.

4.22.5 Adjustments/Penalties

Penalties are also applied up to 6 dBA for a range of characteristics such as tonality, impulsiveness and amplitude modulation. Also, infrasound accommodations are ruled out due to lack of evidence as to physical effect.

4.22.6 Setbacks

Not specified.

4.22.7 Study Requirements

The Guidelines indicate that, whichever model is used, the predictions should take into account:

- Sound power levels and positions of wind turbines;
- Directivity of propagation;
- Meteorological conditions;
- Attenuation due to geometric spreading;
- Attenuation due to atmospheric absorption;
- Ground attenuation;
- Miscellaneous attenuation, e.g. through foliage and buildings; and
- Barrier and terrain screening.

The propagation model output necessary to apply for planning is a wind farm site plan showing the position of the turbines and modelling noise contour lines representing the 40 dBA and 35 dBA thresholds.

4.22.8 Miscellaneous

Not specified.

4.23 Australia – South Australia

4.23.1 Reference

The “Wind Farms Environmental Noise Guidelines” from the South Australia Environment Protection Authority, dated July, 2009, covers all requirements for wind farm projects [111].

There were no specific provisions for offshore wind farms found.

4.23.2 Noise Limit Criteria

The sound level (L_{eq} over 10 minutes) due to the new wind farm developments at receptors in outdoor living areas shall not exceed:

- 35 dBA in rural areas
- 40 dBA in other areas
- the background ambient sound level L_{90} over 10 minutes by more than 5 dBA.

4.23.3 Acceptable/Recommended Acoustic Model

The South Australia Wind Farms Environmental Noise Guidelines state that a suitable model must be selected (or developed) to predict the worst-case sound level at all relevant receivers [111]. While recognizing that there is no standard procedure directly applicable to sound propagation from wind farms, the guidelines recommend that noise prediction methods in accordance with ISO 9613−2 or CONCAWE be used.

If other prediction methods and modelling inputs are employed to carry out the noise level prediction, the details of the model should be clearly stated and the approach discussed with the Environmental Protection Authority.

4.23.4 Software Identified as Acceptable

Not specified.

4.23.5 Adjustments/Penalties

There is a +5 dBA penalty if the characteristic wind turbine noise is shown to have tonal components.

4.23.6 Setbacks

Not specified.

4.23.7 Study Requirements

The following information should be provided as part of the development application:

- The propagation model, and any variation of the model, used for the prediction,
- An estimate of the model accuracy in dB(A).

The assumptions used as input to the model, including allowances for sound absorption due to air, ground, topographical and wind effects.

The guidelines suggest a conservative approach by using the following inputs:

- Atmospheric conditions at 10ºC and 80% humidity,
- Weather category 6 (if CONCAWE method is utilized),
- Hard ground (zero ground absorption factor).

4.23.8 Miscellaneous

Not specified.

4.24 Australia – Queensland

4.24.1 Reference

The Queensland “Wind Farm State Code Planning Guideline – Draft for Consultation from the Department of State Development, Infrastructure and Planning”, dated April, 2014, recommends that same modelling and noise guidelines as South Australia [112], except for stricter criteria and defined modelling parameters.

There were no specific provisions for offshore wind farms found.

4.24.2 Noise Limit Criteria

Queensland has the same modelling and noise guidelines as South Australia except that the limit L_{eq} over 10 minutes of 35 dBA applies throughout [112].

4.24.3 Acceptable/Recommended Acoustic Model

ISO 9613-2 or CONCAWE.

4.24.4 Software Identified as Acceptable

Not specified.

4.24.5 Adjustments/Penalties

Not specified.

4.24.6 Setbacks

Not specified.

4.24.7 Study Requirements

The guidelines suggest a conservative approach by using the following inputs:

- Atmospheric conditions at 10ºC and 80% humidity,
- Weather category 6 (if CONCAWE method is utilized),
- Hard ground (zero ground absorption factor).

4.24.8 Miscellaneous

Not specified.

4.25 Australia – Western Australia

4.25.1 Reference

Planning Bulletin 67 from the Western Australia Planning Commission, dated May, 2004, states that the Guidelines of South Australia should be followed while keeping the same criteria as Queensland [113].

There were no specific provisions for offshore wind farms found.

4.25.2 Noise Limit Criteria

The limit in terms of L_{eq} over 10 minutes is 35 dBA in all areas.

4.25.3 Acceptable/Recommended Acoustic Model

ISO 9613-2 or CONCAWE.

4.25.4 Software Identified as Acceptable

Not specified.

4.25.5 Adjustments/Penalties

Not specified.

4.25.6 Setbacks

The Planning Bulletin states that a setback distance of 1 km is to be expected. However, this limit can be overcome based on acoustical studies showing compliance with the criteria.

4.25.7 Study Requirements

The guidelines suggest a conservative approach by using the following inputs:

- Atmospheric conditions at 10ºC and 80% humidity,
- Weather category 6 (if CONCAWE method is utilized),
- Hard ground (zero ground absorption factor).

4.25.8 Miscellaneous

Not specified.

4.26 Australia – Victoria

4.26.1 Reference

According to the Department of Environment, Land, Water and planning document, "Policy and Planning Guidelines for Development of Wind Energy Facilities in Victoria", dated June, 2015, the New Zealand Standard NZS 6808:2010 should be used to provide guideline limits and modelling descriptions [114].

The New Zealand standards are applied for both onshore and offshore wind farms if there are onshore effects on people and communities.

4.26.2 Noise Limit Criteria

See New Zealand.

4.26.3 Acceptable/Recommended Acoustic Model

The ISO 9613-2 model is recommended but other calculation procedures may be used if there is sufficient justification for doing so.

4.26.4 Software Identified as Acceptable

Not specified.

4.26.5 Adjustments/Penalties

Penalties are applied, up to 6 dBA, for a range of characteristics such as tonality, impulsiveness and amplitude modulation. Also, infrasound accommodations are ruled out due to lack of evidence as to physical effect.

4.26.6 Setbacks

Victoria has also recently reduced their setback distance from 2 km to 1 km with enactment of Amendment VC 124 within Planning Advisory Note 61, dated April, 2015 [115]. This distance can be overcome with written landowner consent.

4.26.7 Study Requirements

Not specified.

4.26.8 Miscellaneous

The Guidelines indicate that whichever model is used, the predictions should take into account:

- Sound power levels and positions of wind turbines;
- Directivity of propagation;
- Meteorological conditions;

- Attenuation due to geometric spreading;
- Attenuation due to atmospheric absorption;
- Ground attenuation;
- Miscellaneous attenuation, e.g. through foliage and buildings; and
- Barrier and terrain screening.

4.27 Australia – Tasmania

4.27.1 Reference

Tasmania refers to the New Zealand Standard NZS 6808:2010 in their document, "Noise Measurement Procedures Manual", from the Department of Environment, Parks, Heritage and the Arts, dated July, 2008 [116].

The New Zealand standards are applied for both onshore and offshore wind farms if there are onshore effects on people and communities.

4.27.2 Noise Limit Criteria

See New Zealand.

4.27.3 Acceptable/Recommended Acoustic Model

The ISO 9613-2 model is recommended but other calculation procedures may be used if there is sufficient justification for doing so. The use of other models must be approved by the Director of the Environmental Protection Authority.

4.27.4 Software Identified as Acceptable

Not specified.

4.27.5 Adjustments/Penalties

Penalties are applied, up to 6 dBA, for a range of characteristics such as tonality, impulsiveness and amplitude modulation. Also, infrasound accommodations are ruled out due to lack of evidence as to physical effect.

4.27.6 Setbacks

Not specified.

4.27.7 Study Requirements

Not specified.

4.27.8 Miscellaneous

The Guidelines indicate that whichever model is used the predictions should take into account:

- Sound power levels and positions of wind turbines;
- Directivity of propagation;

- Meteorological conditions;
- Attenuation due to geometric spreading;
- Attenuation due to atmospheric absorption;
- Ground attenuation;
- Miscellaneous attenuation, e.g. through foliage and buildings; and
- Barrier and terrain screening.

4.28 Australia - New South Wales

4.28.1 Reference

The New South Wales Wind Energy "Fact Sheet" from the Department of Environment, Climate Change and Water, dated November 1, 2010, states that all guidelines from South Australia's "Wind Farms Environmental Noise Guidelines" are used in the assessment process for new projects [117].

There were no specific provisions for offshore wind farms found.

4.28.2 Noise Limit Criteria

See South Australia.

4.28.3 Acceptable/Recommended Acoustic Model

ISO 9613-2 or CONCAWE.

4.28.4 Software Identified as Acceptable

Not specified.

4.28.5 Adjustments/Penalties

Not specified.

4.28.6 Setbacks

Not specified.

4.28.7 Study Requirements

The guidelines suggest a conservative approach by using the following inputs:

- Atmospheric conditions at 10ºC and 80% humidity,
- Weather category 6 (if CONCAWE method is utilized),
- Hard ground (zero ground absorption factor).

4.28.8 Miscellaneous

Not specified.

CHAPTER 5 OFFSHORE MODEL APPLICATION IN ONTARIO

5.1 Introduction

This chapter summarizes the practical considerations of the acoustical models that are described in Chapter 2 and that may be suitable for use in Ontario to predict sound levels (noise) at land-based receptors, from offshore wind turbines. Each model is then summarized to allow comparison of the advantages and disadvantages, as well as the various parameters which each model takes into consideration.

Whatever the model used, sound propagation over both land and water must be taken into account as receptors will likely be both at the shoreline and further inland. It should be noted that while the change from water to land often represents a change in modelling technique or parameters, the ease of performing this calculation is heavily determined by how well the models are implemented in the computer application (software), not the models themselves. Similarly, the computing speed is related to how well the models are implemented in the computer application, aside from the complexity of the wind farm layout.

This chapter describes the analysis parameters including geometric divergence, meteorological conditions, air absorption, ground attenuation, barrier attenuation and frequency band; jurisdiction applications; ease of use; and Ontario application for each model that may be considered for use in Ontario.

Appendix A provides a brief tabular summary of the models.

5.2 Practical Considerations

5.2.1 Model Complexity

In principle, the more complex models, with the requirement for a larger number of input variables, have the potential to do a better job of predicting sound propagation and receptor sound levels. The opportunity is provided for the model to take into account more specific features and variations of particular circumstances (e.g. weather, coastline, receptor terrain/topography). However, the quality of the prediction/calculation results will be no better than the input data. In some or many situations, certain inputs, such as detailed meteorological statistics may not be available in remote areas. Thus, the added model complexity may not contribute to better results, in practice. For example, it should be noted that essentially all of the engineering models use generic meteorological data except Nord 2000 which requires detailed meteorological data such as wind and temperature gradient. This type of detailed information is generally not readily available from the published meteorological data.

5.2.2 Implementation

Some of the models can be implemented by programming the equations in a computerized spreadsheet. This typically would require extensive manual entry of data for individual source-receptor pairs for which calculations apply only within a single (vertical) plane. Such an approach can be very tedious and inefficient and dealing with multiple sound propagation paths is difficult. Also, dealing with even minor changes and readjustments to a wind turbine layout can be extremely time consuming (and expensive).

The use of modern 3D modelling software is much more efficient and effective both in basic design and analysis of a wind farm as well as in considering revisions. Topography (shoreline and adjacent terrain), the effects of buildings and other obstructions that can create either screening or sound reflections, differing zones of ground absorption, are easily taken into account, as are factors such as atmospheric absorption and source characteristics. Examining the effects of wind farm design changes on all receptors at once is a relatively trivial exercise once a model has been created. These 3D models facilitate graphic output such as plan layouts of sound level isopleths, as well as 3D views of the acoustic model from any angle/perspective or height. This capability is very efficient for verifying the physical aspects of the model (source locations and height, receptors, terrain/topography, buildings, obstructions, etc.) and for discovering errors in the model due to mistakes in inputting data on physical features. Determining the change in receptor sound levels (and compliance) due to shifting the position of one or more wind turbines or adding or deleting one or more wind turbines is relatively straight-forward and efficient.

Thus, there is a major practical advantage to using an acoustical model as it is implemented in a commercial, 3D modelling package. This also has the potential advantage of uniformity in data and results presentations between projects. Such uniformity would be advantageous to the review and approval authority (MOECC).

(Note, the use and evaluation of commercial, acoustical modelling software was specifically beyond the scope of this project).

As it turns out, in Ontario, most, if not all of the acoustical consultants doing windfarm noise studies use CadnaA modelling software from DataKustik to assess noise from stationary sources of sound including noise from onshore wind farms. MOECC also has CadnaA in-house. Thus, for ease of review and consistency, there would be an advantage in using a suitable acoustic model available in this software modelling package. Because of the complexity of the modelling software, there is a significant learning curve involved in being able to use it and use it properly. (Note, the same is true of all of the commercially available software modelling packages). MOECC Approvals Branch staff have received training specific to CadnaA, furthering the advantage of continuing to use this software.

5.2.3 Basics of 3D Computer Modelling

The 3D computer modelling technology is extremely sophisticated in application but simple in principle. Setting up the model is generally the most-time consuming portion. Detailed data for topography, buildings, sources and receptors, as well as other parameters such as ground characteristics, meteorology and acoustical characteristics of sources must be entered and verified. Once this is done, and the model run, the model automatically identifies all sound transmission paths from each source to each identified receptor. There is one direct path between source and receptor. These may be multiple paths where there are reflective surfaces such as buildings. The model takes into account the varying conditions along each propagation path, for example whether soft, intermediate or hard ground. Thus, for the case of an off-shore wind farm, and in-land receptors the suitable models will calculate the propagation over water and over land, accounting for the type of terrain over land and whether elevated (cliffs) or essentially level with the water and any sound barrier effects due to topography (cliffs or hills). The result is the composite effect of the varying conditions along the full propagation path, in one pass, and ultimately the model result is the composite effect of all propagation paths and of all sources, for each receptor.

Subject to the complexity of the situation (number of sources, number of receptors, topography, etc.) a model run may require thousands or tens of thousands of calculations. This computational effort is also subject to the capacity and memory of the computer used to run the application.

In many cases, the computer model runs take less than 5-10 minutes, sometimes much less. In very complicated cases, for example, an urban area with thousands of buildings, the computer runs can take hours. Appendix A outlines an estimation of the computation time per model.

The computer models also typically have the ability to show ray tracing, so that specific sound propagation paths can be visualized and identified.

Also, the details of the analysis can be broken out to see the effects of each propagation factor (divergence, atmospheric attenuation, ground attenuation, between barriers, etc.) in each frequency band. When multiple sources are involved, the sound level result at any receptor for each source can be obtained, sorted by sound level so that the significance of each source in establishing the sound level at the receptor can be determined. This can be a very powerful tool to aid wind farm design and turbine placement to ensure compliance with noise criteria.

5.3 ISO 9613-2

5.3.1 Summary

As discussed in Chapter 2, the ISO 9613-2 model predicts the equivalent A-weighted sound pressure level of a known source or sources at a given distance under meteorological conditions favourable to sound propagation; that is, downwind or with a moderate, land-based temperature inversion.

The model accounts for the following input parameters summarized below: geometrical divergence, atmospheric absorption, ground attenuation, reflection from surfaces and sound barrier attenuation. However, it does not account for other meteorological conditions which could result in greater sound propagation, such as temperature inversion over water. This has led to lower predicted sound pressure levels with propagation over water than those observed.

5.3.2 Analysis Parameters

5.3.2.1 **Geometrical Divergence**
The model assumes that sound from a point source spreads spherically in a free field.

*5.3.2.2 **Meteorological Conditions***

ISO 9613-2 accounts for downwind propagation conditions (i.e., with a wind direction within ± 45 degrees of the direction connecting the source and receiver) from all sources to all receivers as well as a moderate temperature inversion over ground with wind speeds ranging from 1 to 5 m/s measured at a height between 3 and 11 m above ground. Also an elementary analysis of the local conditions is used to determine the duration of favourable propagation conditions. Alternatively, the value may be set by local authorities. The sound pressure level resulting from this method is considered to be a level that is seldom exceeded. However, temperature inversions over water are not accounted for. This can lead to lower predicted sound pressure levels over water than those observed.

It should also be noted that attenuation propagation effects due to temperature inversion over water are not covered under ISO 9613-2.

5.3.2.3 ***Atmospheric Absorption***

ISO 9613-2 calculates atmospheric absorption according to temperature and humidity (meteorological) conditions. The specific attenuation coefficient for each frequency band, which can vary with atmospheric temperature and humidity, is found in a table in the standard.

5.3.2.4 ***Ground Attenuation***

ISO 9613-2 divides the ground into three regions, the area around the source up to a distance of 30 times the height of the source, the area around the receiver up to a distance of 30 times the height of the receiver, and the middle area between those two areas. These areas are classified by how absorbent the ground is from hard (reflective) to porous (absorbent) or mixed (the fraction of porous ground). When used to assess noise from offshore wind farms, the ground attenuation over water is always set to G=0, i.e., to hard (reflective) ground.

5.3.2.5 ***Barrier Attenuation***

Barriers can give both screening and reflecting effects depending on their orientation to the source and receiver and surface characteristics. The screening effect (attenuation) of a barrier is limited to 20 dB for single diffraction and 25 dB for double diffraction. A separate value for screening from foliage can be included.

5.3.2.6 ***Frequency Bands***

ISO 9613-2 provides specific octave-band calculation algorithms (with octave band centre frequencies from 63 Hz to 8 kHz) for calculating the attenuation of sound which originates from a point sound source or an assembly of point sources.

5.3.3 Jurisdiction Applications

It was found that the ISO 9613-2 model is the commonly used model for both onshore and offshore applications in Alberta, British Columbia, Manitoba, New Brunswick, Nova Scotia, Belgium, Finland, Germany, Netherlands, UK, New Zealand and Australia.

5.3.4 Ease of Use

A major advantage of ISO 9613-2 is that it has been widely and successfully used in Ontario and elsewhere for the analysis and assessment of a large variety of sources, including land-based wind turbines. It is implemented in most commercially available modelling software such as CadnaA, SoundPLAN and windPRO for a number of years.

5.3.5 Limitations

The major disadvantages of the ISO 9613-2 model are:

- The standard warns that temperature inversions over water are not covered, only inversion conditions over land. This may result in lower predicted sound levels over water than those observed.

- The stated estimates of accuracy are for a very limited range of source heights and distances. An accuracy is indicated of ±1 dB for source heights between 5 and 30 m and distances of less than 100 m, and ±3 dB for heights up to 30 m and distances between 100 and 1000 m. Both land based and offshore wind farms will have greater source heights (currently up to 100 m) and greater distances to many receptors. The current MOECC noise guidelines for land-based wind farms require calculations up to 5000 m. Offshore wind farm distances can be expected to exceed the apparent distance limit of ISO 9613-2, as is the case for land-based wind farms.

Thus, the typical wind farm, whether land-based or off-shore, violates some of the apparent limitations of the model. However, it should be noted that exceeding the apparent limitations does not necessarily mean the results are invalid – just that the model has not been formally validated for those conditions and there is no stated estimate of accuracy when the stated limits are exceeded.

There are other limitations to the model, such as when there is ground attenuation and other than flat terrain. The derivation and theoretical basis of the ground attenuation equations are not given and the algorithms are not intuitive and not documented by any specific publications. However, these aspects are largely irrelevant to offshore wind farms, except perhaps where there may be relevant in-land receptors at a non-trivial distance from the shore line, opposite to an off-shore wind farm.

The evidence appears to be that ISO 9613-2 can under-predict sound levels propagated for long distances over water, but adjustments (as in the Swedish model below) can be made.

5.3.6 Ontario Application

Since the MOECC already adopts the ISO 9613-2 for land-based wind farm calculations, it is very easy to implement this model for offshore wind farms. Additionally, as it is available in CadnaA there will be little need for additional training for reviewers since the software is currently in common use in Ontario.

5.4 Swedish Model

5.4.1 Summary

The Swedish model uses the ISO 9613-2 method with hard ground (G=0) for distances up to 1000 m. As a result, the model predicts the equivalent A-weighted sound pressure level of a known source or sources at a given distance under meteorological conditions favourable to sound propagation; that is downwind or with a moderate, land-based temperature inversion.

The major difference between the Swedish Model and ISO 9613-2 is that the Swedish Model uses cylindrical spreading when the distance between source and receiver is greater than 1000 m. The Swedish model assumes hard ground and atmospheric attenuation at a temperature of 0^{o}C and 70% relative humidity according to ISO 9613-1 [3, 4, 5]. In addition, the Swedish model only considers the frequency spectrum from 63 Hz to 4 kHz.

Thus, the Swedish model has basically the same set of advantages and disadvantages as described for ISO 9613-2, except that propagation of sound beyond 1000 m (and potentially temperature inversions over water) over water has been addressed.

5.4.2 Analysis Parameters

5.4.2.1 Geometrical Divergence

The Swedish model uses the ISO 9613-2 method of spherical spreading for distances up to 1000 m. For distances greater than 1000 m (break point), the calculation is modified to use cylindrical spreading instead of spherical which may potentially address temperature inversion over water.

5.4.2.2 Meteorological Conditions

The Swedish model assumes atmospheric attenuation at a temperature of 0^{o}C and 70% relative humidity and does not allow for any other temperature/humidity conditions. The same downwind propagation conditions as ISO 9613-2 are used, with a wind direction within ± 45 degrees of the direction connecting the source and receiver with wind speed between 1 and 5 m/s at a height of 3 to 11m above the ground.

5.4.2.3 Atmospheric Absorption

Since the Swedish model assumes a standard coefficient for atmospheric attenuation of 0.005 dB/m from source to receiver - octave band data is not required as it assumes a constant atmospheric damping coefficient of 0.005 for all frequencies.

5.4.2.4 Ground Attenuation

The Swedish model uses the same calculation as ISO 9613-2, assuming that water is the same as hard ground i.e. G=0.

5.4.2.5 Barrier Attenuation

As with ISO 9613-2, barriers are treated as either screening or reflecting depending on their orientation to the source and receiver. For screening the attenuation is limited to 20 dB for single diffraction and 25 dB for double diffraction. A separate value for screening from foliage can be included.

5.4.2.6 Frequency Bands

The Swedish model provides octave-band algorithms but differs from ISO 9613-2 by reducing the number of octave band centre frequencies from 63 Hz to 4 kHz when calculating the attenuation of sound which originates from a point sound source or an assembly of point sources.

5.4.3 Jurisdiction Application

The Swedish Model has only been approved for use in Sweden. However, the model was used in projects in the UK where it was assumed to show a worst case propagation over longer distances (see Chapter 3.3). The Swedish model was also used to compare sound prediction results for three floating test wind turbines in the US, together with other models. However, it is unknown whether the Swedish model was an approved model in the US for permitting purposes.

5.4.4 Ease of Use

As the model is implemented in some of the commercially available software (CadnaA and windPRO) and is based upon the ISO 9613-2 model, it is expected that it would be simple to adjust the calculations after the breakpoint. However, evaluation of the commercial software implementation is beyond the scope of this project.

5.4.5 Limitations

As the basis of the Swedish model is ISO 9613-2, it inherently has the same limitations as the ISO 9613-2 model. The inclusion of cylindrical spreading is seen to alleviate the problem of propagation beyond 1000 m and propagation over water (and potentially inversions as well).

5.4.6 Ontario Application

Since the model is available in CadnaA and is based on the ISO 9613-2 model, it is should be quite easy to implement in Ontario. It is expected to be able to interface easily with the land-based model currently used in MOECC Guidelines.

5.5 Danish Model

5.5.1 Summary

The Danish model assumes hard ground which overestimates the levels of sound propagating over ground, but gives reasonable results offshore for limited distances up to 500 m for the overall A-weighted sound pressure level. In the octave band version, the reliable distance extends to 2 to 5 kilometres. The model fails at large distances because of multiple reflections from the water surface building up and leading to cylindrical spreading of the sound energy, as opposed to spherical propagation on which the model is based.

In accordance with the Danish statutory order enforced on January 1, 2012, due to the increased coherence between direct and reflected sound at low frequencies, a more specific and detailed approach was chosen to avoid underestimation of the sound (noise) levels in the frequency range from 10 to 160 Hz, independent of distance and height of the wind turbine.

5.5.2 Analysis Parameters

5.5.2.1 Geometrical Divergence

The Danish method assumes spherical propagation for both land based and offshore wind farms.

5.5.2.2 Meteorological Conditions

In Danish model, the meteorological conditions are set to a temperature of 10^{o}C and 80% relative humidity. The model is only valid for downwind conditions.

5.5.2.3 Atmospheric Absorption

Using the meteorological conditions above, a set of absorption coefficients has been determined for each octave band and 1/3 octave band from 10 Hz to 10 kHz

5.5.2.4 Ground Attenuation

The ground effect is simplified to a simple term of + 3 dB across each band for offshore wind turbines. For land based propagation the ground effect is +1.5 dB. For the low frequency analysis a ground correction term is specified for each 1/3 octave band. For land-based wind turbines, the ground correction is +6 dB at 10 Hz and decreases to 0 dB at 160 Hz. For off-shore wind turbines, the ground correction is +6 dB at 10 Hz and decreases to +4 dB at 160 Hz.

5.5.2.5 Barrier Attenuation

In the Danish model, a generic correction for roughness is used to represent residential areas, small towns and areas with tall dense vegetation.

5.5.2.6 Frequency Bands

The basic model includes calculations for octave bands from 63 Hz to 8 kHz or 1/3 octave bands from 50 Hz to 10 kHz. Also, the low frequency portion includes calculations for 1/3 octave bands from 10 Hz to 160 Hz.

5.5.3 Jurisdiction Application

The Danish model has been superseded by the Nord2000 model by the Danish Environmental Protection Agency as the latter model is more accurate over larger distances. However the Danish model is still used for the low frequency noise calculations with examples found in Denmark and the UK (see Chapters 3 and 4)

5.5.4 Ease of Use

The Danish Model is only implemented in the commercial software windPRO. Not having the model implemented in a variety of readily available commercial software packages is seen as a major disadvantage from a practical point of view.

5.5.5 Limitations

The Danish model gives reasonable results for air absorption at small distances, but may result in considerable error over large distances because of multiple reflections from the water surface building up and leading to cylindrical spreading of the sound energy.

5.5.6 Ontario Application

The low frequency propagation portion of the Danish Model may be useful for mitigating uncertainties regarding low frequency noise from wind farms. However, since the Ontario noise criteria do not extend down to 10 Hz, this refinement is not currently relevant in Ontario. Also, the general model may result in considerable error over large distances, and the limited number of parameters specific to Danish climate and topography may not be suitable for use in Ontario.

5.6 CONCAWE

5.6.1 Summary

The CONCAWE model takes into account geometrical spreading (spherical divergence), atmospheric absorption, ground attenuation, meteorological attenuation, barrier shielding, source/receiver height correction and in-plant screening. The algorithms governing the meteorological conditions prevailing at the site allows the prediction of long term equivalent continuous sound levels and long term statistical sound levels, in addition to probable maxima and minima, on the basis of the statistical distribution of wind velocity and Pasquill Stability for the area. These algorithms, along with the algorithms governing the ground attenuation are based on experimental data rather than theoretical models. While theoretically, it is advantageous to be able to include a wide range of meteorological conditions in the modelling analysis, in practice, the needed input information may not be available, negating this potential advantage.

5.6.2 Analysis Parameters

5.6.2.1 ***Geometrical Divergence***

Spherical spreading from point sources is used in CONCAWE.

5.6.2.2 ***Meteorological Conditions***

In CONCAWE, the meteorological effects are divided into six categories based on a combined vertical gradient. The temperature gradient is determined by Pasquill Stability Categories A to G. Category A represents a strong lapse rate condition (i.e., large temperature decrease with height) where Category G represents a temperature inversion as may be found on a calm, starlit night. The attenuation is a function of frequency, distance and meteorological category.

5.6.2.3 ***Atmospheric Absorption***

CONCAWE follows the recommendations of the American National Standard, "Method for the Calculation of the Absorption of Sound by the Atmosphere". A list of tables in the CONCAWE document show the atmospheric absorption values for one-third octave bands. For octave band width considerations, the method stipulates that the values corresponding to the lower one-third octave band frequency should be used. For pure tones the value of the atmospheric absorption at the particular frequency is used.

5.6.2.4 ***Ground Attenuation***

For acoustically 'hard' surfaces, such as concrete or water, the CONCAWE model specifies a correction of 3 dB for all frequencies and distances. For all other surfaces, experimental data is used rather than more complex theoretical models. It also assumes that the ground effect decreases exponentially with an increase in grazing angle. This can be expected to produce results for this aspect that are similar to ISO 9613-2 with hard ground; that is, under-predicting sound levels propagating over water.

5.6.2.5 ***Barrier Attenuation***

The attenuation due to the presence of a barrier is calculated using Maekawa's method. This is based on the calculation of a Fresnel number, N, derived from diffraction theory. If necessary, it can be modified to account for wind and temperature gradient.

5.6.2.6 ***Frequency Bands***

The CONCAWE model, like the Swedish model, only considers the range of octave bands from 63 Hz to 4 KHz and not up to the usual 8 kHz.

5.6.3 Jurisdictions

The CONCAWE model is used throughout Canada, UK, Hong Kong and Australia to assess noise from industrial facilities. This model is recommended in South Australia for assessing noise from wind farms. However, it is not explicitly specified for offshore wind farms.

5.6.4 Ease of Use

The model is implemented in some of the commercially available software (CadnaA and SoundPLAN). It is expected to be easy to implement. However, evaluation of the commercial software implementation is beyond the scope of this project.

5.6.5 Limitations

The CONCAWE model is based on empirical data from land-based petrochemical complexes for sound propagation over ground. The ground effect calculation produces results similar to ISO 9613-2 in that it under-predicts sound levels propagating over water.

5.6.6 Ontario Application

The CONCAWE model is based upon empirical sound data from petrochemical complexes. It has been used in Ontario as well as other provinces in Canada for stationary sources (industry). It is found that the CONCAWAVE model is recommended for assessing noise from wind farms in South Australia. However, it is not explicitly specified for offshore wind farms.

It should be recognized that the CONCAWAVE model was developed for assessing noise from land-based, complex industrial facilities, its applicability for off-shore wind farms could be questionable.

5.7 Nord2000

5.7.1 Summary

An advantage of the Nord2000 model is that it considers a wide variety of inputs: the influence of wind (direction, speed, gradient), temperature, ground absorption and screening. It is also possible to choose different wind speed and temperature gradients. Nord2000 is suitable for calculations over hilly terrain as it takes varying topography into account. This advantage is not necessarily always relevant for offshore wind farms. However, in some cases, where the shore may be a cliff substantially elevated above the water (e.g. Scarborough Bluffs), or with hilly terrain around lakes in Ontario, it may be very useful. It also takes into consideration the acoustic characteristics of water surface, such as turbulence and multiple reflections, etc., and therefore is appropriate for calculation of sound propagating over water.

The propagation model is based on analytical solutions - geometrical ray theory and theory of diffraction. The model calculates one-third octave band attenuation from 25 Hz to 10 kHz for homogeneous or inhomogeneous atmospheric conditions. A disadvantage is that all of the input data, such as temperature gradient variations, associated standard deviations and standard deviation of variation in wind speed may not be readily available.

The Nord 2000 model allows calculation of short-term (less than 30 minutes or one hour) energy equivalent sound pressure levels or maximum levels for specified weather conditions. Long-term noise levels (e.g., yearly average of day, evening and night sound level) can be obtained by combining short-term noise levels calculated by Nord2000 with meteorological statistics. In practice, short-term level calculations are made for a limited set of meteorological classes, and the long-term levels are the weighted average of these results. This approach makes it possible to calculate long-term levels such as maximum sound levels for longer periods, or even complete statistical distributions of sound levels. This appears to be the only model that calculates a statistical distribution of the predicted sound level. This could be advantageous to indicate the variation of sound level to be expected.

The model is especially accurate at small distances. This is not a particular advantage for offshore turbines because the distances involved will be much greater. The model has only been validated by measurements at distances up to 200 m where good accuracy has been found (deviations within ±2 dB of overall A-weighted sound pressure levels in most cases). The method has been validated by comparison with measurements and with other prediction methods, such as Parabolic Equations (PE), which are believed to be more accurate. See Section 2.8.

5.7.2 Analysis Parameters

5.7.2.1 ***Geometrical Divergence***

The Nord2000 model assumes spherical propagation from a point source to receiver points.

5.7.2.2 ***Meteorological Conditions***

The Nord2000 model accounts for meteorological parameters such as wind and temperature gradients to approximate the vertical effective sound speed profile (the sum of the sound speed and the component of the wind speed in the direction of propagation). If the sound speed varies with the height (the vertical sound speed gradient differs from 0), atmospheric refraction will occur. This manifests either in downward refraction creating multiple ground reflections or upward refraction creating a shadow zone.

Generally, the Nord2000 model is valid only for moderate refraction, defined as where the propagation effects are not dominated by multiple ground reflections and shadow zones.

5.7.2.3 ***Atmospheric Absorption***

As mentioned in Chapter 2.6.3, the calculation of air absorption is based on predictions at the centre frequency of the one third octave band by ISO 9613-1, but is supplemented by an analytical method for estimating the attenuation in the frequency band.

5.7.2.4 ***Ground Attenuation***

The ground effect is defined as the difference between the sound pressure level in the presence of the ground and the free-field sound pressure level.

The Nord2000 model includes a model of the ground effect based on geometrical ray theory which predicts the propagation effect of a flat homogeneous ground surface. One of seven ground impedance coefficients are used to determine where the direct and reflected sound waves produce either constructive or destructive interference up to +6 dB. The model also uses Fresnel zones to determine where sound reflects from the ground to the receiver. Where the surface properties intersect with the Fresnel zones determines the ground effect. Then an arbitrary terrain profile (flat, valley or hill) is added which either adds further reflection or adds screening including a roughness coefficient to characterize the unevenness.

The total ground effect, including screening, is obtained by the use of transitional parameters that represent the effect of each segment on the total ground effect.

_5.7.2.5_ _**Barriers Attenuation**_

The Nord2000 propagation model also includes a screen effect model which predicts the sound pressure level when the receiver is in the shadow behind a sound barrier. The screen effect is based on geometrical theory of diffraction. In the model, it is assumed that the screen is infinitely long. With screens of finite length, the contribution from sound diffracted around the side edges is taken into account in an approximate manner.

The screen effect from a double-edge barrier or two barriers is based on the solution of the wedge-shaped screen. The screen effect is calculated for each edge or barrier separately, placing the source or receiver on top of the other edge or barrier. After the individual screen effect is calculated, the combined effect is calculated. In principle, this procedure can be extended to any number of screens. However, this will increase the complexity of the calculations. Thus, only the two most significant diffracting top edges are considered in the calculations.

A model is also included for predicting the contribution of energy scattered into the shadow due to turbulence caused by random wind and temperature variations. This contribution is added to the result of the screen model. The predicted result depends on the screening geometry, the turbulence strength and the frequency.

Sound reflected from an obstacle such as a building facade or a noise screen is dealt with by introducing an extra ray path from the source via the reflection point to the receiver. The reflection point is defined as the intersection between the straight line from the image source to the receiver and the plane which contains the reflecting surface. The propagation effect of a reflected ray path is predicted by the same propagation model as used for a direct path, but a correction is made for the reflection coefficient.

In Nord2000, it is also possible to predict the propagation effect of "scattering zones" which are urban areas or vegetation. The effect of scattering zones depends on the length of the ray path through the scattering zone, the density and size of the scattering objects and their reflection coefficients.

_5.7.2.6_ _**Frequency Bands**_

The model calculates one-third octave band attenuation from 25 Hz to 10 kHz for homogeneous or inhomogeneous atmospheric conditions.

5.7.3 Jurisdictions

The Nord2000 model is predominantly used in Northern European countries (Denmark and Norway), for both onshore and offshore wind farms.

5.7.4 Ease of Use

Nord2000 is implemented in almost all commercially available modelling software (CadnaA, SoundPLAN, windPRO, exSOUND2000 and SPL2000). It may not be as easy to use as the ISO 9613-2 model since it requires more input parameters than ISO 9613-2.

5.7.5 Limitations

Compared to ISO 9613-2 model, Nord2000 is relatively complex in that all calculations in Nord2000 are done in one third octave bands and it takes into account a lot more input variables than ISO 9613-2. This means it has the potential for better accuracy. However, correctly selecting the input variables, such as temperature gradient variations, associated standard deviations and standard deviation of variation in wind speed, as they may not be readily available. This may be a major disadvantage in practice.

5.7.6 Ontario Application

While the Nord2000 model is available in CadnaA, to be applied for offshore wind farms would require the model to also be applied to onshore projects to ensure consistency.

5.8 Harmonoise

5.8.1 Summary

The Harmonoise model is an engineering model for predicting environmental noise levels. This prediction model is based on solutions and concepts close to those found in the Nord2000 model. It predicts the sound pressure level at the receiver position in one-third octave bands from 25 Hz to 10 kHz starting with the sound power level of the source. The effects of various factors are calculated separately and subtracted from the source sound power level. These factors include spherical divergence, air absorption, reflections from ground, diffractions from sound barriers, energy losses during side reflections, and effects of scattering zones.

This model has not been used for wind turbine/wind farm noise studies. It appears it should not be considered further and therefore, the input parameters are not discussed further in this report.

5.9 Partial Differential Equation Based Methods

5.9.1 Summary

As discussed earlier in Section 3.8, while these techniques can be highly accurate, they are complex, difficult, computationally intense, and tend to be used in academic and research environments. They are not implemented in commercial, modelling software and do not appear to be appropriate for general use in the commercial context of design and approval of wind farms or other industrial facilities with noise sources. Thus, the input parameters are not discussed further in this report.

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APPENDIX A SUMMARY OF MODEL COMPARISONS

CHARACTERISTICS	ENGINEERING MODELS						ANALYTICAL/NUMERICAL MODELS		
	ISO 9613-2	Swedish	Danish	CONCAWE	Nord2000	Harmonoise	CNPE	GFPE	FFP
Computation Time	Fast	Fast	Fast	Fast	Fast	Fast	Slow	Slow	Medium
Frequency	A-wt; 63 to 8000 Hz octave	A-wt	A-wt Octave, Low frequency also modelled	63 to 4000 Hz octave	25 to 10000 Hz 1/3 Octave	25 to 10000 Hz 1/3 Octave	Any (ideal for low freq.)	Any (ideal for low freq.)	Any (ideal for low to mid freq.)
Distance (m)	<1000	<500 A-wt; <5000 octave	Not given	Not given	Not given	Not given	Any	Any	Any
Source Height (m)	<30	<30	Not given	Not given	Not given	Not given	Any	Low	Any
Tolerance (Decibel)	±3	Not given	Not given	Not given	Not given	Not given	Good	Very good	Exact
Wind Condition	Downwind	Downwind	Downwind	Not given	All	Not given	All	All	All
Ground Absorption	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Barrier	Up to 20 dB for single barrier and up to 25 dB for double barrier	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Terrain	As Barrier	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Meteorological Data	Temperature and Humidity	Temperature 0 C, Humidity 70% RH	Temperature 10 C, Humidity 80%	Weather Categories	Site Specific	Site Specific	Site Specific	Site Specific	Site Specific
Range-dependent Conditions	No	No	No	No	No	No	Yes	Yes	No
Commercial Software Package	CadnaA, SoundPLAN, WindPro	CadnaA, WindPro	WindPro	CadnaA, SoundPLAN	CadnaA, SoundPLAN, exSound2000, SPL2000	CadnaA	No	No	No
Validated	Yes	No official validation study report can be found	No official validation study report can be found	Yes (not for wind farms)	Yes	Yes	Yes	Yes	Yes
Model Status*	Public	Public	Public	Public	Public	Public	Academic	Academic	Academic
Used for Offshore Wind Projects	Yes	Yes	Yes	Not Found	Yes	Not found	No	No	No

*Model may be public but the implementation in commercial software is proprietary and requires payment of fees to obtain.

APPENDIX B SUMMARY OF JURISDICTIONAL COMPARISONS

COUNTRY	REGION	APPROVAL AUTHORITY	DOCUMENT NAME (TYPE)	OFFSHORE APPLICATION	INDEX (TIME PERIOD)	TIME PERIOD	NOISE LEVEL LIMITS (dBA)	CONDITIONS	PENALTIES	MINIMUM SETBACK DISTANCE	MODEL RECOMMENDED	NOTES
Canada	British Columbia	Environmental Assessment Office of British Columbia	Best Practice for Wind Power Project Acoustic Assessment (Guidelines)	No specific offshore provisions	L_{eq} (9h)	Night (22:00 - 07:00)	40	For ambient levels below 35 dBA. Otherwise 5 dBA above ambient up to 50 dBA	Not specified	Not specified	ISO 9613-2	CONCAWE, Harmonoise and Nord2000 may be used with explanation
					L_{eq} (15h)	Day (07:00 - 22:00)	40					
	New Brunswick	New Brunswick Department of Environment and Local Government	Additional Information Requirements for Wind Turbines	No specific offshore provisions	L_{eq} (1h)		40 to 53 over wind speeds from 4 to 11 m/s		Not specified	Based on model results to the nearest dwelling	ISO 9613-2	Same as Ontario
	Nova Scotia	Nova Scotia Environment	Proponent's Guide to Wind Power Projects	No specific offshore provisions	L_{eq} (1h)		40 to 53 over wind speeds from 4 to 11 m/s		Not specified	400 m to 1 km location specific	ISO 9613-2	Same as Ontario
	Manitoba	Manitoba Intergovernmental Affairs	Land Use Planning for Wind Energy Systems in Manitoba	No specific offshore provisions	L_{eq} (1h)		40 to 53 over wind speeds from 4 to 11 m/s		Not specified	500 to 550 m recommended	ISO 9613-2	Same as Ontario
	Alberta	Alberta Utilities Commission	Rule 012	No specific offshore provisions	L_{eq} (9h)	Night (22:00 - 07:00)	40 – 50	1 to 8 dwellings	Not specified	If no dwellings within 1.5 km, criteria apply at 1.5 km, otherwise apply at dwellings	ISO 9613-2 and/or CONCAWE	Range of limits is determined by proximity to road/rail
							43 – 53	9 to 160 dwellings				
							46 – 56	> 160 dwellings				
USA	Oregon	Department of Environmental Quality	OAR 340-035-0035 (Standards)	No specific offshore provisions	L_{50} (1h)	Night (22:00 - 07:00)	50	For ambient levels of L_{50} over 26 dBA. Otherwise limited to 10 dBA above ambient.	Not specified	None	None found	
						Day (07:00 - 22:00)	55					
					L_{10} (1h)	Night (22:00 - 07:00)	55					
						Day (07:00 - 22:00)	60					
Belgium	Flanders	Flemish Environment Agency (VMM)	VLAREM II (Standards)	No specific offshore provisions	L_{eq} (9h)	Night (22:00 - 07:00)	39 Residential	If ambient L95 (1h) is greater than specified levels, then background level with 1 dB tolerance applies	Not specified	3 times the rotor diameter	ISO 9613-2	Other conditions listed in VLAREM such as 80% porous soil ground for agricultural environment
							43 Agricultural					
	Wallonia	Walloon Environment Agency	Walloon Law (Standards)	No specific offshore provisions	L_{eq} (1h)	Night (22:00 - 06:00 or 07:00 depending on area)	43 All Areas	Lower limit applies for summer (temperature of 16^0C at 22:00)	+1 dB for amplitude modulation	4 times the total turbine height or 400 m in rural zones	ISO 9613-2	Recommends using sound power at height 10 m and speed 10 m/s. Also ground attenuation factors
							40 Residential / Rural					

COUNTRY	REGION	APPROVAL AUTHORITY	DOCUMENT NAME (TYPE)	OFFSHORE APPLICATION	INDEX (TIME PERIOD)	TIME PERIOD	NOISE LEVEL LIMITS (dBA)	CONDITIONS	PENALTIES	MINIMUM SETBACK DISTANCE	MODEL RECOMMENDED	NOTES
Denmark	-	Danish Environmental Protection Agency	Statutory Order 1284 (Regulations)	Offshore included	L_{eq} (T)	Day (07:00 - 18:00) Evening (18:00 - 22:00) Night (22:00 - 07:00)	39 (@ 8m/s) 37 (@ 6m/s)	Noise sensitive Areas	+1.5 dB ground effect onshore +3 dB ground effect offshore	4 times the total turbine height mandatory	Nord2000	Also specifies low frequency noise limit guidelines of 20 dB
							44 (@ 8m/s) 42 (@ 6m/s)	Dwellings in open country				
Finland	-	Ministry of the Environment	Decree 545/2015 (Guidelines)	No specific offshore provisions	L_{eq} (15h)	Day (07:00 - 22:00)	45	35 dBA in Recreational Areas	5 dB sanction if amplitude modulated or tonal or impulsive	Based on model results	ISO 9613-2	Nord2000 accepted with explanations
					L_{eq} (9h)	Night (22:00 - 07:00)	40					
France	-	French Environment and Energy Management Agency	NF S 31-114 (Standards)	No specific offshore provisions	L_{eq} (15h)	Day (07:00 - 22:00)	Ambient + 5	If ambient over 35 dBA. Otherwise 35 dBA limit stands	Tonality should not exceed 30% of period. 10 dB penalty from 50 to 315 Hz, 5 dB penalty from 315 Hz to 8 kHz	Not specified	Not found	
					L_{eq} (9h)	Night (22:00 - 07:00)	Ambient + 3					
Germany	-	Federal Environment Ministry	GMBI Nr. 26/1998 S. 503 (Regulations)	No specific offshore provisions	L_{eq} (8h)	Night (22:00 - 06:00)	45 Heartland 40 Small Urban 35 Residential	Cumulative Sound levels	Turbine Sound Power level +2 dB	750 to 1000 m Residential 400 m Solitary Homes	ISO 9613-2	Other criteria may be applied by state. Calculations must be provided for review
Ireland	-	Environmental Protection Agency	Wind Energy Development Guidelines	Onshore Only	L_{90} (10m)	Day (07:00 - 23:00)	45 or 5 dBA over background	Rural zones have 35 to 40 dBA limit	Not specified	500 m for amenity purposes	Not specified	
						Night (23:00 - 07:00)	43					
Netherlands	-	Environmental Assessment Agency	STB-2010-749 (Standards)	Applies to offshore but no examples	L_{eq} (24h)	Night (23:00 - 07:00)	47	L_{eq} (8h) 41 dBA also applied	Not specified	12 nautical mile coast setback for shipping lanes	ISO 9613-2	Calculations should be done according to local meteorological conditions and include hard ground conditions
Norway		Norwegian Environment Agency	M-128 – 2014 (Guidelines)	Applies to both onshore and offshore	L_{den}		55 Red Zone 45 Yellow Zone	External Factors e.g. ground conditions, wind shadow, echo, icing	Not specified	Not specified	Nord2000	ISO 9613-2 used previously

COUNTRY	REGION	APPROVAL AUTHORITY	DOCUMENT NAME (TYPE)	OFFSHORE APPLICATION	INDEX (TIME PERIOD)	TIME PERIOD	NOISE LEVEL LIMITS (dBA)	CONDITIONS	PENALTIES	MINIMUM SETBACK DISTANCE	MODEL RECOMMENDED	NOTES
Portugal	-	Portugal Environment Agency	WHO Night Noise Guidelines for Europe (Guidelines)	No specific offshore provisions	L_{eq} (8h)	Night (23:00 - 07:00)	40		Not specified	Not specified	Not found	Same guidelines for all industrial facilities
Sweden		Swedish Environmental Protection Agency	Telephone conversation (Guidelines)	No specific offshore provisions	L_{eq} (24h)		40 Residential		5 dB penalty for tonal components	Not specified	Not specified	
							35 Natura 2000					
UK	-	Department of Energy and Climate Change	ETSU-R-97 (Guidelines)	Swedish model recommended over water	L_{90} (10m)	Day (07:00 - 23:00)	35 to 40	when background noise is below 30 dBA L_{90}	Not specified	Not specified	ISO 9613-2 and/or CONCAWE	Swedish model should be used over water
						Night (23:00 - 07:00)	43	if background noise is less than during quiet daytime periods				
Hong Kong	-	Environmental Protection Department	Technical Memorandum for the Assessment of Noise from Places other than Domestic Premises, Public Places or Construction Sites (Regulations)	No specific offshore provisions	L_{eq} (T)	Day (07:00 - 19:00)	55 to 65		Not specified	Not specified	CONCAWE	
						Evening (19:00 - 23:00)	55 to 65					
						Night (23:00 - 07:00)	45 to 55					
New Zealand	-	Environment Court of New Zealand	New Zealand Standard NZS 6808:2010 Acoustics – Wind Farm Noise	Applies to both onshore and offshore	L_{90} (10m)		Background + 5 dB	Background Sound Level >35 dBA	Up to +6 dBA for tonality, impulses and amplitude modulation	Not specified	ISO 9613-2 or other models	Models should account for all conditions and attenuation factors
							40 (background + 5dB for High Amenity)	30 – 35 dBA				
							40 (30 for High Amenity)	<30 dBA				

COUNTRY	REGION	APPROVAL AUTHORITY	DOCUMENT NAME (TYPE)	OFFSHORE APPLICATION	INDEX (TIME PERIOD)	TIME PERIOD	NOISE LEVEL LIMITS (dBA)	CONDITIONS	PENALTIES	MINIMUM SETBACK DISTANCE	MODEL RECOMMENDED	NOTES
Australia	South Australia	South Australia Environmental Protection Authority	Wind Farms Environmental Noise Guidelines (Guidelines)	No specific offshore provisions	L_{eq} (10m)		35 Rural 40 Other	Also should not exceed Background L_{90} (10m) by more than 5 dBA	+5 dBA for tonal components	Not specified	ISO 9613-2 or CONCAWE	Atmospheric Conditions at 10^{0}C and 80% humidity, Weather Category 6 (CONCAWE), Hard ground
	Queensland	Department of Environment and Heritage Protection	Wind Farm State Code (Guidelines)	No specific offshore provisions	L_{eq} (10m)		35	Also should not exceed Background L_{90} (10m) by more than 5 dBA	Not specified	Not specified	ISO 9613-2 or CONCAWE	Atmospheric Conditions at 10^{0}C and 80% humidity, Weather Category 6 (CONCAWE), Hard ground
	Western Australia	Western Australia Environmental Protection Authority	Planning Bulletin 67 (Guidelines)	No specific offshore provisions	L_{eq} (10m)		35	Also should not exceed Background L_{90} (10m) by more than 5 dBA	Not specified	1 km (expected)	ISO 9613-2 or CONCAWE	Atmospheric Conditions at 10^{0}C and 80% humidity, Weather Category 6 (CONCAWE), Hard ground
	Victoria	Department of Environment, Land, Water & Planning	Policy and Planning Guidelines for Development of Wind Energy Facilities in Victoria	Applies to both onshore and offshore	L_{90} (10m)		Background + 5 dB 40 (background + 5dB for High Amenity) 40 (30 for High Amenity)	Background Sound Level >35 dBA 30 – 35 dBA <30 dBA	Up to +6 dBA for tonality, impulses and amplitude modulation	1 km, but can be overcome with written landowner consent	ISO 9613-2 or other models	Models should account for all conditions and attenuation factors
	Tasmania	Environment Division	Noise Measurement Procedures Manual	Applies to both onshore and offshore	L_{90} (10m)		Background + 5 dB 40 (background + 5dB for High Amenity) 40 (30 for High Amenity)	Background Sound Level >35 dBA 30 – 35 dBA <30 dBA	Up to +6 dBA for tonality, impulses and amplitude modulation	Not specified	ISO 9613-2 or other models	Models should account for all conditions and attenuation factors
	New South Wales	Environment, Climate Change & Water	The wind energy fact sheet	No specific offshore provisions	L_{eq} (10m)		35 Rural 40 Other	Also should not exceed Background L_{90} (10m) by more than 5 dBA	Not specified	Not specified	ISO 9613-2 or CONCAWE	Atmospheric Conditions at 10^{0}C and 80% humidity, Weather Category 6 (CONCAWE), Hard ground