Wind Turbine Noise – Assessment and Planning

By

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Abstract

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Issues relating to noise from wind farm developments are currently not being dealt with either accurately or consistently throughout Ireland. Impact assessment studies show a high degree of variation throughout the country as also do the planning limits imposed by planning authorities.

These shortfalls may be attributed to the absence of, and also the misinterpretation of relevant guidance for wind farm developments. Much guidance is available nationally and internationally for industrial applications but wind turbine noise disturbance is quite unique and is not adequately addressed by common practices. Wind farm developments are normally located in quiet rural areas and although the noise generated may not necessarily be very high it has the potential to cause considerable nuisance. The preservation of natural quiet in areas of existing low background noise levels has been recognised in European environmental legislation [2002/49/EC] and its implementation is being gradually implemented in the EU and Ireland.

Wind turbine noise has evolved rapidly in recent years with taller and larger turbines with complex noise profiles. Based on the findings of this study, a more defined approach is required in order that potential noise problems are identified and addressed at the planning stage. Some of the major recommendations include

- The requirement of comprehensive baseline studies for all developments over a range of wind speeds and atmospheric conditions
- The use of the L_{90} noise descriptor for noise measurement for the baseline study and similar noise measurement procedures to be repeated once the wind farm is operational

- The necessity to conduct noise prediction modelling over a wide range of wind speeds to account for the variable noise characteristics of newer turbines

Noise limits imposed by planning authorities will need to be more defined in order to address potential noise problems. This can be achieved by setting noise limits in relation to background noise, including the requirement to conduct noise prediction and compliance assessment over a wide (but clearly defined) range of wind speeds and meteorological conditions.

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1.0 INTRODUCTION

Wind energy industry is the fastest growing energy source in Europe and due to Ireland’s location on the western edge of Europe, wind resources are among the best in the continent. With the increasing growth rate of wind energy, Ireland is expected to have the potential to achieve up to 50% of its total energy needs from wind power within the next 20 years. [SEI 2004]. The environmental and economic benefits of wind power include the reduction in greenhouse gasses (particularly CO_2), reduction in other combustion gases (NO_X, SO_2) and the availability of an inherent energy source reducing the requirement to import oil and coal.

Wind turbine noise is one of the major concerns affecting residents in close proximity to a wind farm development. Due to the nature of wind turbine noise and also because wind farms are generally built in rural areas where existing noise levels are low, wind turbine noise tends to be the primary issue for complaint by nearby communities. Control of the noise can have serious financial implications; limitations in the choice location of the wind farm, restriction in the number and position of turbines and often curtailment in operation of turbines is required to combat adverse noise impacts at nearby dwellings. A correct assessment of the potential impacts of wind turbine noise is essential to ensure that correct planning decisions and noise controls are enforced.

The main objectives of this study were:

- To investigate current practices in the assessment and planning of wind farm developments in Ireland,
- To provide direct noise measurement data for potential wind farm sites in rural locations and provide measurement data in the vicinity of operational sites,
- Based on shortfalls in current practice, direct noise measurement and detailed research, this study then offers a number of recommendations and ensuring that accurate impact assessment is conducted at the planning stage.

This will be of particular interest to developers and consultants in determining accurately the potential impacts a development may have and the mitigation measures that will be required. Findings will also assist planning authorities in decisions relating to location and sizing of wind farms and establishing will the noise climate be adequately maintained in the cases of existing areas of natural quiet and also for noise levels to avoid disturbance in nearby communities.

A detailed analysis of a number of potential wind farm sites and operational sites has been conducted. The common problems that are encountered in noise assessment monitoring and prediction have been addressed and solutions have been proposed. Illustrative examples have been taken

The study does not intend to provide answers regarding setting of absolute noise limits or offering guideline separation distances from wind farm developments and the like but it does offer the procedures that need to be followed in each specific case to yield these answers. It is hoped that the observations and recommendations made will allow for more accurate noise measurement, impact assessment and also offer suitable criteria on which appropriate noise mitigation and control limits may be applied.

2.0 LITERATURE REVIEW

2.1 NOISE

2.1.1 Sound and Noise

Sound may be defined as any pressure variation that can be detected by the human ear, or as the mechanical vibration of a medium through which energy is carried by sound waves away from the source. The particular medium will determine the speed at which sound travels. Sound needs a medium to travel (will not travel in a vacuum) and generally the denser the medium, the faster sound travels. In air, sound travels at approximately 340m/s while in water it will travel at approximately 1,500 m/s. [Brüel & Kjær, 2001] Sound travels in a wave form and can be described by its magnitude (loudness) based on the amplitude, or by frequency which determines its pitch. The wavelength of a sound wave is also an important factor and is related to the frequency by the relation:

$$v = \lambda f$$

where

v = the speed of transmission of the wave, (in m/s), as determined by the medium

λ = the wavelength of the wave, (in metres) is the distance a wave travels in one complete cycle

f = the frequency of the wave, in Hertz (Hz).

The period (T) of a wave is the time for one complete cycle for an oscillation of a wave. The frequency (f) is how many periods per unit time (for example one second) and is measured in hertz. These are related by:

$$f = \frac{1}{T}.$$

Sound waves exhibit the phenomena common to all wave forms:

- Reflection – the turning back of a wavefrom the direction it was travelling, due to interaction with a reflective material;
- Refraction - the change in direction (or bending) of waves upon entering a new medium or a change in density of a medium;
- Diffraction - the spreading out of waves, for example when they travel through a small slit or bend around corners;
- Interference - the addition of two waves that come in to contact with each other, can be positive or negative;
- Dispersion - the splitting up of a wave up dependant on frequency.

All types of energy waves undergo some type of energy transformation as the wave propagates. Sound waves readily pass through water because it is slightly elastic, and very little acoustic energy is lost in the transfer of energy from one particle to another. The amount of energy lost to the medium (absorbed) is a function of the frequency of the wave. The higher the frequency, the more energy will be absorbed into the medium. Conversely, at lower frequencies, less energy is lost to absorption [Pierce, 1992]. The result of this is that at lower frequency waves tend to travel further, with ranges decreasing as the frequency increases.

Noise can be described as unwanted sound. This definition itself poses problems in that what may be perceived as an enjoyable sound to one may to another be unwanted noise. Noise and sound are thus used interchangeably and are somewhat subjective in their definition.

2.1.2 Measurement Units and Scales

Sound Pressure and Sound Pressure Level

The human ear can detect very minor pressure, generally varying from 20μPa, referred to as the threshold of hearing, to 100Pa at the upper end of the scale referred to as the threshold of pain. Sound Pressure in measured in pascals (Pa) but in order that noise be described in terms of a workable scale, Sound Pressure Levels (SPL) are used. These are based on a logarithmic scale with the **decibel (dB)** as the measurement unit which is defined as follows:

$$\text{Sound Pressure Level, SPL (dB)} = 20\log_{10}(\mu\text{Pa} / 20\mu\text{Pa})$$

This scale relates the effective (or root mean square, rms) sound pressure variation (μPa) to the reference pressure level of 20μPa (the sound pressure at the threshold of hearing). From the above relation 20μPa, the threshold of hearing corresponds to 0dB and 100Pa, the threshold of pain corresponds to 140dB.

Sound Pressure and Sound Power

Sound power is the acoustic power in Watts radiated from a sound source. The sound power is source specific and essentially independent of the surroundings, while the sound pressure depends on the surroundings (reflecting surfaces) and distance to the receiver. [Brüel & Kjær, 2001]. When the sound power is known the sound pressure at a particular point can be calculated.

Sound pressure levels are important in measuring effects at the receiver but source characteristics and prediction techniques require knowledge of the sound power. Sound power is measured using sound power level (L_W), also expressed in decibels where 0dB corresponds to 1 picowatt ($1\text{x}10^{-12}$ W).

Sound Power Level, $L_W = 20\log_{10}(P/P_o)$

Where P is the sound power of the source and P_o the reference sound power 10^{-12} W.

2.1.3 Frequency

The frequency of a sound wave is the rate of pressure fluctuations in unit time and is measured in cycles per second, or Hertz (Hz). Frequency determines the pitch or note of a sound -the middle C of a piano is 262Hz. [RERL, 2004]. For most people the audible range of acoustical frequencies is from 20Hz to 20,000Hz. Below 20Hz lies the infrasound range and above 20Hz is referred to as ultrasound.

Any particular sound will contain a number of different frequencies, unless it is a single defined note Frequency analysis is required to detect the presence of a particular note or tone. Measurement involves dividing up the sound spectrum into octave bands where each octave band is twice the value of each preceding band (eg 250Hz, 500Hz and 1kHz are three octave bands in sequence). For more detailed examination, 1/3 octave bands are often used - these divide each octave bands into three. Narrow-band analysis provides further detail again in the determination of audible tones. Noise is referred to as “tonal” if a particular tone or note is evident. Where no discernible tones are evident in the noise and the acoustic energy is distributed over a relatively wide range of frequencies it is generally referred to as broadband noise.

Vibration is similar to sound but is experienced in the lower ranges between 1-80Hz (sound is heard generally in the range 20-20,000Hz). Vibration is felt through solid structures whereas sound is heard. Vibration, however, can be induced in structures by sound waves in the audible or subsonic ranges; a common example of this is rattling in windows caused by the low frequency airborne waves of a passing truck.

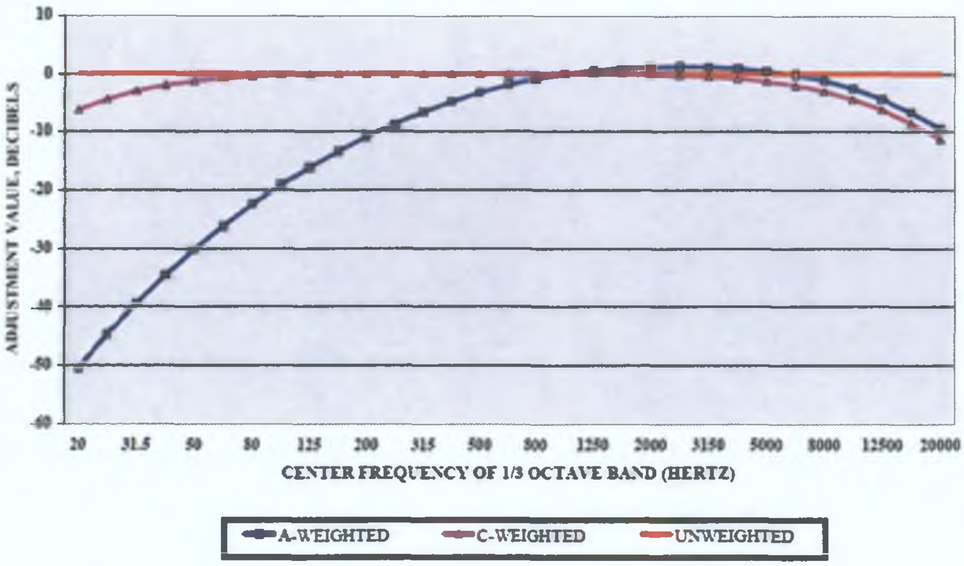
Low frequency noise (LFN) is the term usually used to describe noise around or below 100Hz. Frequency tones in houses are often observed around 50Hz, the frequency at which A/C mains current operates. Indoors, low frequency noise can pose problems by resonance effects and the production of standing waves. This occurs as the wavelength range for low frequency noise often coincides with normal room dimensions, for example: a sound wave of 50 Hz travelling at 340m/s will have a wavelength of 6.8m (as $v = \lambda f$). Research in Germany [SEN 1998] has shown significant annoyance to low frequency noise, even when the threshold of hearing is only slightly surpassed.

2.1.4 Weighting Systems and Measurement Parameters

Weighting Systems

Noise weighting systems were developed in the measurement of sound to examine particular areas of interest in the noise frequency spectrum. The A weighted system is the most widely used tool to account for the increased sensitivity of the human ear to certain frequencies particularly in the 800Hz –8kHz range. This gives more “weighting” to frequencies within this range and reduces the measured pressure level for low and high frequency sounds[Environment Agency (UK), 2002]. Other frequency scales include the C-weighted scale which only makes minor reductions for the lower frequency ranges and slightly higher reductions in the upper frequency ranges. The C-weighted scale in practice is used to characterise low frequency sounds capable of inducing vibrations in buildings and other structures. The Z-weighted scale is relatively newly used method to provide a flat frequency response between 10Hz and 20kHz. Un-weighted decibel measurements are used for refined frequency analysis across the sound spectrum (e.g., when determining the sound absorption or sound transmission properties of materials). Unweighted decibel measurements sometimes are termed flat or linear measurements. Fig 2. 1 presents the 1/3 octave band weighting factors for the A-weighted, C-weighted and Unweighted (Z-weighted) decibel scales.

Figure 2.1 Decibel weighting scale correction factors



Data Source: Ford (1987, page 2/14).

Table 2.1 A – Weighting Octave Band Adjustment

Octave band centre frequency, Hz	A-weighting adjustment, dB	Example linear sound level, dB	A-weighted sound level, dB
31.5	-39.4	63	24
63	-26.2	62	36
125	-16.1	68	52
250	-8.6	58	49
500	-3.2	50	47
1k	0	53	53
2k	+1.2	51	52
4k	+1.0	42	43
8k	+1.1	31	30
16k	-6.6	24	17
	Total Noise Level:	**70**	**58**

Source: [Environment Agency (UK), 2002].

Low frequency noise is the topic of much recent research in that it not adequately accounted for using A-weighting scale. Proposed alternative methods of note include the use of equal loudness level contours as a dynamic filter [Schomer, 2000], [Bite, Flindell, 2004] or Zwicker's loudness level weighting. The standard A-weighting curve takes no account of the mutual masking patterns produced in the auditory system [Zwicker E., 1990]. By manipulating the balance between random noise and tonal components in complex sounds it is even possible to reduce the A-weighted sound level at the same time as increasing the subjective loudness [Hellman R., Zwicker E., 1987]. The loudness level method is described in ISO 226, 1987 [Bite, Flindell, 2004] providing empirically determined equal loudness contours at 1/3 octave band centre frequencies between 20 to 12,500Hz. This will not be discussed further at this stage but the validity of A-weighted measurement must be questioned in its ability to describe low frequency components of noise.

Measurement Parameters

Most of the measurement parameters relating to human response are based on the A-weighted scale. Definitions of a number of measurement parameters are summarised below and can be found under British Standard BS4142, 1997.

$L_{Aeq,T}$: This is the most widely used parameter when assessing environmental noise and is defined as the equivalent continuous sound pressure level, which is the sound level that, if generated continuously would give the same energy over the specified time,T, as the fluctuating sound being measured. The “A” means that A-weighting is applied and normally for environmental noise measurement, the time response of the sound level meter is set to fast (F).

Percentiles Ln: The two most common percentiles used are the $L_{A90,T}$ and $L_{A10,T}$. These respectively define the sound level exceeded for 90% of the time and 10% of the time interval (T). The $L_{A90,T}$ is often used to describe the background noise level that exists in the absence of intermittent noisy events. The $L_{A10,T}$.is used to identify noise of short duration but high in energy, such as traffic noise. Percentiles are useful analytical tools to describe the noise climate, comparisons between the $L_{Aeq,T}$, $L_{A90,T}$ and $L_{A10,T}$ will indicate whether noise is continuous or intermittent, these are important in assessing community annoyance effects.

L_{Amax} and L_{Amin}: These are the A-weighted maximum and minimum root mean squared (rms) levels during the measurement period

Lpk: This is the peak level measured (not rms) and is often expressed as a linear , unweighted or C-weighted reading.

L_{night} and L_{den}: The new environmental directive [2002/49/EC] proposes the harmonised use of L_{night} to assess sleep disturbance and L_{den} to assess annoyance. L_{night} is the A-weighted long-term sound level as defined in ISO 1996-2:1987, determined over all the night periods of the year. …

L_{den} is the day-evening-night level defined by:

$$L_{den} = 10\lg 1/24\ [12 \cdot 10^{Lday/10} + 4 \cdot 10^{(Levening + 5)/10} + 8 \cdot 10^{(Lnight + 10)/10}]$$

2.2 NOISE MEASUREMENT

A wide range of standards and guidance is available either for the measurement of source noise characteristics, attenuation of sound along its propagation path or the assessment of noise at the receiver. The major standards in use in this country include those of the International Standards Organisation (ISO), e.g. ISO 1996 and ISO 9613, British Standards (BS), e.g. BS4142 and BS5228. Others include those of the International Electrotechnical Comission (IEC), European Standards (EN) approved by the European Committee for Electrotechnical Standardization (CENELEC) or the National Standards Authority of Ireland (NSAI)

2.2.1 BS4142

This standard introduces methods for measuring and rating noise levels from an activity and assessing their likelihood to give rise to complaints based on background noise levels.

The specific noise level ($L_{Aeq,\ Tr}$), produced by the particular noise source, is determined over a suitable time interval,T_r. A suitable time interval is chosen to account for the duration of intermittent or periodic characteristics of the noise in order to achieve a representative sample.

A rating level, $L_{Ar,Tr}$ is the specific noise level plus an adjustment to account for the characteristic features of the noise. An adjustment of 5 dB is recommended if the noise contains a distinguishable, discrete, continuous note (whine, hiss, screech, hum etc), if it contains distinct impulses (bangs, clicks, clatters or thumps), or if the noise is irregular enough to attract attention.

Residual noise is defined as the ambient noise remaining at a given position in a given situation when the specific noise is suppressed to a degree such that it does not contribute to the ambient noise.

Background Noise Level is described by $L_{A90,T}$, the A-weighted sound pressure level of the residual noise at the assessment position, that is exceeded for 90% of a given interval .

The **ambient noise** is measured by $L_{Aeq,T}$ to encompass sound from all sources. It is comprised of the residual noise and the specific noise when present.

In assessing the likelihood of annoyance and noise complaints, this standard recommends using the rating level for the assessment of the specific noise and examining the difference between this and the background level. A difference of 10 dB or higher is considered likely to cause complaints and a difference of 5dB is of marginal significance.

This standard is best applied to industrial situations and is not suitable in cases where background level is 30dB(A) or below. Wind farm developments are generally in rural areas with low background levels thus the use of this standard may not entirely suitable. Similar measurement principles can be applied but rating penalties need to be amended to suit the lower background levels and also, the criteria for predicting likely complaints will need to be addressed whereby a difference of 5 to 10 dB would have a more significant impact at lower background noise than a similar increase at higher background noise levels.

2.2.2 ISO 1996

ISO 1996 is comprised of three parts:

ISO 1996/1 - 1982: Basic quantities and procedures
ISO 1996/2 - 1987: Acquisition of data pertinent to land use
ISO 1996/3 - 1987: Application to noise limits

This standard is equivalent to BS 7445:1991 and has recently been updated by the ISO working group (TC 43/SC 1/WG 45). Measurement parameters are described and specifications are given for instrumentation types, measurement techniques and information requirements. The aim of the ISO series is to provide for the description of noise in community environments and is the most commonly used standard for the measurement of environmental noise in Ireland.

Acoustical data is determined using equivalent A-weighted sound pressure levels over reference time intervals. Further information to be reported includes rating levels based on the specific characteristics of the noise with adjustments for tones and impulses, meteorological adjustment and further quantitative and qualitative data.

The rating level ($L_{Ar,T}$) is given by:

$$(L_{Ar,T})_i = (L_{Aeq,T})_i + K_{1i} + K_{2i}$$

where

$(L_{Ar,T})_i$ is the equivalent continuous A weighted sound pressure level during the ith reference time interval

K_{1i} is a tone adjustment applicable to the reference time interval

K_{2i} is an impulse adjustment applicable to the reference time interval

A method for detecting tonality and imposing penalty adjustment is described:

"In some practical cases a prominent tonal component may be detected in one-third octave spectra if the level of a one–third octave band exceeds the level of the adjacent bands by 5 dB or more, but a narrow–band frequency analysis may be required in order to detect precisely the occurrence of one or more tonal components in a noise signal. If tonal components are clearly audible and their presence can be detected by a one–third octave band analysis, the adjustment may be 5 – 6 dB. If the components are only just detectable by the observer and demonstrated by narrow–band analysis, an adjustment of 2 – 3 dB may be appropriate".

2.2.3 Wind Turbines Standards & Guidance

International Electrotechnical Commission

To determine specific wind turbine noise, the International European standard EN 61400-11 is recommended. This standard was prepared by the International Electrotechnical Commission (IEC) and approved by CENELEC (European Committee for Electrotechnical Standardisation) in 1998. A second edition of this standard was issued in 2002 as a technical revision [IEC 1998 and 2002].

Procedures are given to accurately determine the sound power level from a wind turbine based on ground level measurements. An acoustic reference wind speed of 8 m/s at 10 m height is used in the determination of sound power level. Detailed information is given including instrumentation specifications, measurement and data reduction procedures, corrections for background noise, apparent sound power, frequency analysis and tonality, wind direction, directivity and also information requirements are specified for measurement and reporting purposes. The revision of the standard details tonal assessment procedures and the determination of the sound power level over a range of wind speeds at 10 m height.

This standard is however primarily for use in identifying and characterising the noise associated with single turbines. From a practical point of view this standard will be of most use to turbine manufacturers in determining the precise turbine specification.

ETSU Report

Additional reference material of note includes the report published by the UK Department of Trade and Industry "Assessment and Rating of Noise from Wind Farms DTI ETSU for the Department of Trade and Industry [ETSU-R-97 (1996)].

Both the IEC standard methods mentioned recommend using a ground plane microphone to minimise the effects of wind induced noise on the microphone. In addition 1/3 octave frequency spectrum analysis will be required to be undertaken to assess the impact of tonal or impulsive noise at sensitive locations.

When assessing wind turbine noise the primary concern is the assessment of noise levels at dwellings or other sensitive locations in the vicinity of the wind farm. At the planning stage it is normal to conduct a baseline noise survey to examine existing noise levels in the area of a proposed development, particularly at noise sensitive dwellings. The international standard ISO 1996 (as referred to in section 2.2.2) is the most widely accepted method for assessing community noise levels.

2.2.4 EPA Guidance Document

This document provides guidance primarily for activities requiring an IPC Licence but measurement practices can be applied to locations in the vicinity of a wind farm development. It provides concise information on measurement methods, standards to be referenced, and considerations for external interferences in order to achieve representative monitoring. It recommends the use of International Standard ISO 1996: Acoustics Description and Measurement of Environmental Noise and also refers to the use of BS4142:1997 and BS 5228 to a certain degree. The main points of the guidance document are summarised below:

- Measurement Interval of 15-30 minutes for daytime and 15 minutes for night-time (or licence specific);
- Use of L_{Aeq} in measurement, and further analysis conducted using L_{Amax}, SEL (where appropriate) percentiles L_{A1}, L_{A10}, L_{A90} and 1/3 Octave Frequency Analysis for tonal noise;
- Suitable weather conditions and measures against wind-derived noise are outlined. It recommends that during attended monitoring notes of prevailing conditions are sufficient but for unattended long-term monitoring, continuous meteorological data must be given;
- Practical positioning of noise measurement locations in relation to noise sensitive locations (NSLs), site boundaries or on-site noise sources.

2.2.5 Uncertainties and Practical Considerations

For a wind farm development, noise monitoring is conducted before construction and again when the wind farm is in operation to determine the actual impact of the development. These surveys must be conducted in an identical manner in order to make substantiated comparisons between both.

The baseline survey (pre-construction) must adequately describe the existing noise climate and the measured results are used together with turbine noise characteristics to predict the noise impact of the development. Extended noise monitoring over a period of several days will provide a sufficiently large data-set from which noise patterns can be observed over a range of wind-speeds and different times of the day.

For both the baseline noise survey (pre-construction) and operational noise survey (post construction) it is useful to identify and attempt to quantify all sources of uncertainty in noise measurement. Sources of measurement uncertainty can be grouped into three categories whether they relate to (i) the noise source (ii) the transmission path or (iii) the receiver. A summary of considerations for each are presented in Table 2.2.

Table 2.2 Measurement Uncertainty Factors

NOISE SOURCE	
Position of Source	Height above ground level
Operating Condition	Turbine operating ranges and settings
Character	Steady/Impulsive, Broadband/Tonal
Turbine condition	Age, maintenance etc.
Type of propagation	Spherical/hemispherical, point/area/line
Environmental Effects	Wind, temperature etc
TRANSMISSION PATH	
Weather	Propagation distance, wind speed and direction, temperature gradient, variability
Ground Reflection	Ground dip, surface variability
Barriers	Shielding/screening, variability
RECEIVER	
Measurement Position	Location choice, height, microphone orientation, tripod/hand-held, variations
Façade/surface reflections	Distance to surface, size and type of surface
Instrumentation	Accuracy, precision, type (type 1,2) calibration, accessories (windshield, leads etc), environmental influence (temp. humidity), data logging interval
Background Noise Level	Time of measurement, choice of position
Assessor and standards / procedures	Competence, interpretation, relevance

The range of potential disturbances depends on the topography, land use, turbine design, source characteristics, hub height, and distance to nearest receptors.

2.3 NOISE POLICY AND LEGISLATION

Environmental noise, often described as ambient noise, deals with noise from a very wide range of sources to include industrial sites, road and rail traffic, airports and all other background noise sources. From a global point of view, control of environmental noise is very much dependent on economy, culture and politics. Separate legislation exists for control of noise from specific sources (vehicles, equipment etc) or control of exposure to noise to noise at work. For our purposes here we will deal primarily with environmental noise and its affects on nearby communities.

2.3.1 Community Effects

The effects of noise on humans range from mild annoyance to stress to hearing loss. When dealing with environmental noise effects the upper noise levels leading to hearing loss are rarely an issue but extreme annoyance can be experienced depending on the nature or character of the noise, regularity of occurrence or the sensitivity of the receiver. It is expected that environmental and leisure-time noise with a $L_{Aeq,\ 24h}$ of 70 dB(A) or below will not cause hearing impairment in the large majority of people, even after a lifetime of exposure [WHO 1999]. Needless to say, noise at this level would cause serious disturbance. Noise can affect speech intelligibility, predominantly when it is in the range between 300 – 3,000Hz. Sleep disturbance is common when noise levels are excessively above background levels or when noise is impulsive or irregular. Prolonged exposure to elevated noise levels can cause stress, increased blood pressure and other physiological effects.

Regular variations of sound pressure level with time has been found to increase the annoying characteristics of noise, for example, noises that vary periodically to create a throbbing or pulsing sensation can be more disturbing than continuous noise. [Bradley, 1994]. Research suggests that variations at about 4 per second are most disturbing [Zwicker, E., 1989].

Table 2.3 Recommended community noise levels, WHO 1999

Specific Environment	Critical health effect(s)	L_{Aeq}, dB(A)	Time base, hours	L_{Amax}, (fast) dB(A)
Outdoor living area	Serious annoyance, day and evening	55	16	-
	Moderate annoyance, day and evening	50	16	-
Dwelling, indoors	Speech intelligibility, moderate annoyance, day and evening	35	16	-
Inside Bedrooms	Sleep disturbance, night-time	30	8	45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School classrooms & Preschools, indoors	Speech intelligibility, disturbance of information extraction, communication	35	During class	-
Pre-school bedrooms, indoor	Sleep disturbance	30	During sleep	-
School playground, outdoor	Annoyance (external source)	55	During play	-
Hospital ward rooms, indoors	Sleep disturbance, night-time	30	8	40
	Sleep disturbance, day and evening	30	16	-

These are acceptable average noise levels in terms of L_{Aeq} but do not account for noise characteristics such as tonality or impulsiveness that will increase the annoyance effects.

Sleep disturbance figures of 30dB L_{Aeq} for indoor noise are based on an outdoor noise level of 45dB and attenuation and a bedroom window, slightly open, providing a 15dB attenuation. This guidance acknowledges that special attention should be given in situations where the background noise is low and also suggests that additional disturbance may occur when low frequency components are present in the noise. Sleep disturbance covers inability to fall asleep, waking from sleep or poor quality sleep together with after effects such as fatigue, depressed mood or well being.

2.3.2 Relevant Legislation

In Ireland, environmental noise pollution is regulated for both directly and indirectly by a number of specific statutory provisions. The EPA Act 1992, specifically sections 106, 107 and 108 and the Environmental Protection (Noise) Regulations 1994 (S.I. No. 179 of 1994) are the main legislative controls. The provisions of the Planning and Development Act, 2000, serve to regulate noise pollution indirectly.

Under the Environmental Protection Agency Act, 1992 (Hereafter referred to as the EPA Act), environmental noise control is provided for where it may "give rise to a nuisance or disamenity, constitute a danger to health, or damage property" or harm the environment. Enforcement is often based on following up on complaints received or control where a perceived potential for nuisance may exist.

The EPA Act also provides for the licensing of major activities with specified conditions relating to noise. Control of noise from Wind Farms is usually provided for under conditions specified in Planning Conditions as under the Planning and Development Act 2000. Noise limits are normally set at the planning stage and control is maintained by the relevant local authority.

In Europe, following its 1996 Green Paper [COM(96)540], The European Commission developed a new framework for noise policy to include the creation of a Noise Expert Network and a new Directive on Environmental Noise. Commission proposal [COM(2000)468] resulted in the adoption of Directive 2002/49/EC on the 25th June 2002 by the European Parliament and Council. The main objective of this directive is to provide a common basis for addressing noise issues across Europe. Measures to be implemented include:

- strategic noise mapping throughout member states, including specific agglomeration types as defined by the directive;
- harmonising noise indicators; L_{den} to assess annoyance and L_{night} to assess sleep disturbance;

- action plans based upon mapping results with a view to preventing and reducing environmental noise where necessary and maintaining noise quality where it is good;
- limit values are to be determined separately for different situations and left to the discretion of the local authorities based on data collected.

L_{den} is derived from L_{day}, $L_{evening}$ and L_{night} using the following formula:

$$L_{den} = 10\lg 1/24\ [12 \cdot 10^{L_{day}/10} + 4 \cdot 10^{(L_{evening} + 5)/10} + 8 \cdot 10^{(L_{night} + 10)/10}]$$

Directive 2002/49/EC requires L_{day}, $L_{evening}$ and L_{night} to be long-term noise levels according to ISO 1996-2:1987. They are determined over all day, evening and night periods of a year. ISO 1996-2:1987 defines the average long-term level as an equivalent A-weighted continuous sound pressure level that can be determined by computation accounting for variations in both source activity and meteorological conditions influencing the propagation conditions. ISO 1996-2 allows the use of meteorological correction terms, and a reference is made to the meteorological corrections in ISO 1996-1, although no method to determine and apply such correction is provided.

$$L_{den} = 10 \cdot \lg 1/24[t_d \cdot 10^{L_{day}/10} + t_e \cdot 10^{(L_{evening}+5)/10} + t_n \cdot 10^{(L_{night}+10)/10}]$$

where:

t_e = length of the shorter evening period where $2 \leq t_e \leq 4$,

t_d = the resulting length of the daytime period,

t_n = the resulting length of the night-time period

and $t_d + t_e + t_n = 24$ hours

Receiver height

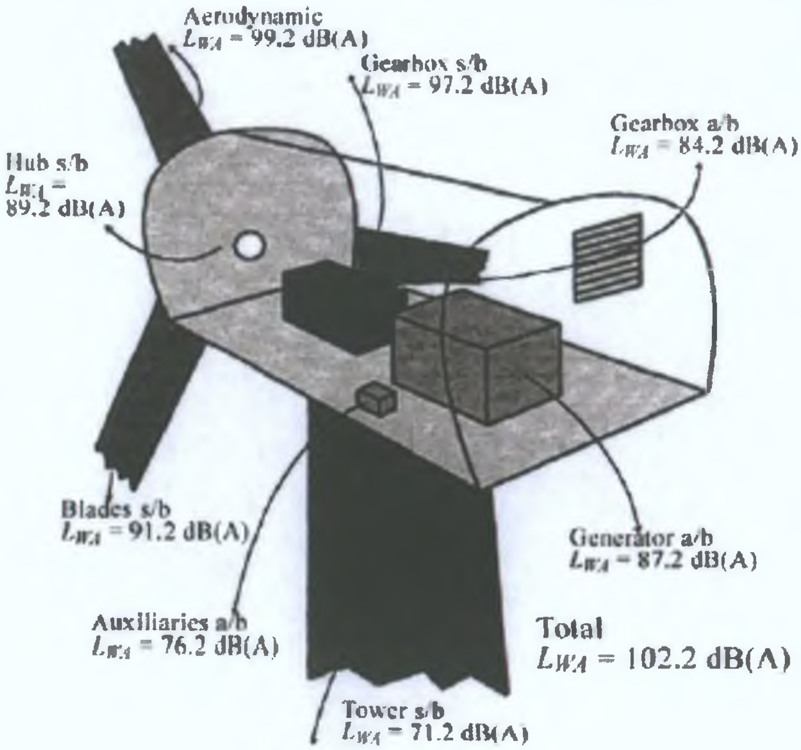
For the purpose of strategic noise mapping, Directive 2002/49/EC imposes the receiver point (or 'assessment point') height at 4 ± 0,2 m above the ground. As L_{den} is a compound indicator calculated from L_{day}, $L_{evening}$, L_{night}, this height is also mandatory for these indicators.

2.4 WIND TURBINE NOISE

2.4.1 Noise Sources Characteristics

Wind turbine noise can be attributed to aerodynamic noise created by the motion of the blades through the air and to mechanical noise generated by and radiated by the components of the wind turbine and support tower. A typical wind turbine consists of a tower, which is generally 50 metres or more in height; a nacelle (housing) containing the gearbox and generator, mounted on top of the tower, and 3 blades which rotate around a horizontal hub protruding from the nacelle. [RERL, 2004], [Brüel & Kjær, 2001]. Figure 2.2 shows the major turbine noise sources type and transmission path for a 2 MW wind turbine. Sound power levels are given for the major components and noise transmission is either structure borne (s/b) or air borne (a/b). Source: [Wagner, Bareib, Guidati, 1996].

Figure 2.2 Wind Turbine Noise Sources



Noise is assessed in terms of the magnitude its broadband characteristics (over a wide frequency range) and its tonal components. The broadband aerodynamic noise will generally determine the overall A-weighted sound power output level of the wind turbine, with the tip speed being the dominant parameter controlling the radiated noise level. Research from various sources (including the US National Wind Technology Centre, Renewable Energy Research Laboratory [RERL, 2004]) indicates that the dominant source of broadband noise from wind turbines is the passage of the rotor blades through the air.

The operation of mechanical elements located within the nacelle of a wind turbine can result in tonal noise radiation to the environment. Low frequency noise, below 80Hz in particular, is generated when the rotating blade encounters localized flow deficiencies due to the flow around a tower, wind speed changes, or wakes shed from other blades. [RERL, 2004] Low frequency, infrasonic sound from turbines peaks in the the 8-12 Hz range for large wind turbines and for smaller turbines this peak can extend into the low-frequency "audible" range of 20-20kHz [Kelly, NREL 1998]. This is due to the slower rotational speeds of the larger turbines and the higher rotational speeds and multiple blades for the smaller machines.. Generally there is little energy above 4000Hz so ultrasound is not a problem.

Low frequency noise often cannot be heard out of doors but within homes the waves can cause resonance, creating vibrations as well as redistributing the energy into the audible frequency region. This is evident if the noise source is impulsive or of a particular periodic nature. Impulsive noise is most prevalent in cases where the rotor is downwind of the support tower. Wake vortices being shed from the tower interact with the aerodynamic lift created on the rotor blades to generate impulses. Rare but similar impulses occur with turbines pointing in the opposite direction with random atmospheric turbulence in the wind interacting with the aerodynamic lift of the rotors.

In Europe, the majority of wind turbines have been installed with an upwind rotor design and thus low frequency noise is les of an issue. Here the primary concern is the higher frequency broadband and discrete frequency noise associated with the unsteady aerodynamic forces on the blades.

An audible tone in an otherwise broad band noise spectrum can significantly increase the perception of the noise and cause it to be perceived as more annoying than the broad band noise would on its own, even though the tone may not significantly increase the overall noise level. In some circumstances the situation with regard to tonal noise is that are they are subjectively inaudible or only just audible at the wind farm but become clearly audible at sheltered locations some distance from the wind farm.

2.4.2 Turbine Specification

Most of the older turbines in use rotate at a constant speed, usually between 25 and 50 rpm, irrespective of wind speed. However, newer turbine designs have dual speed or multi- speed machines which optimise power output while minimising noise generation. Significant reduction of noise may be achieved by up to 10 dB(A) in some cases. Examples of turbine noise specification for two different turbines are given in Table 2.4.

Table 2.4 Turbine Noise Data

Wind Speed m/s (V_{10})	Dual Speed L_W, dB(A)	Multi- Speed L_W dB(A)
3	93	90.2
4	95.5	94.5
5	98	99.5
6	100.5	103
7	103	104.2
8	104	105
9	104	105
10	104	103.8

Source: [Vestas 2005]

The Sound Power Level (L_W) from the dual speed turbine gradually increases up to a maximum (in this case) of 104dB(A) and beyond this noise levels remain steady up to cut-out point. Lower noise levels are observed at lower wind speed for the Multi-speed turbine, noise levels reach a maximum at 8m/s but reduce again at elevated wind speeds.

2.5 METEOROLOGY

Ambient noise levels are significantly affected by meteorological conditions both in terms of noise generation and propagation. Background noise will largely be a function of wind speed, other meteorological conditions that will influence noise propagation include wind direction, temperature, atmospheric pressure, humidity and atmospheric stability. The effects of each of these will depend on the source noise (magnitude and frequency) and other factors such as ground effects, reflection and screening must also be considered.

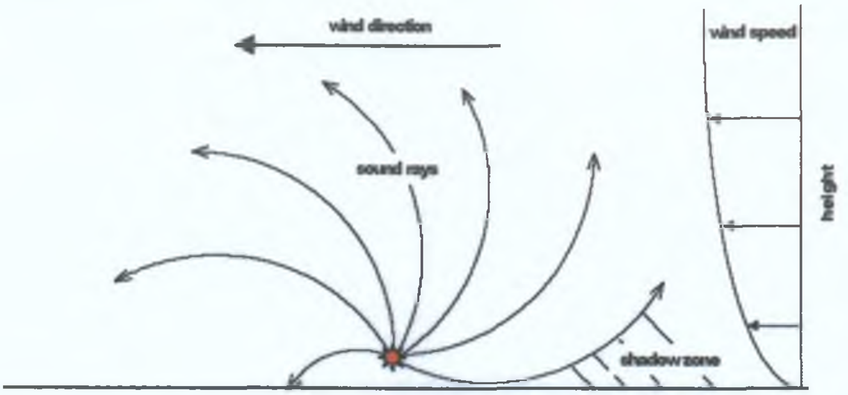
The influence of weather is most obvious for high frequency noise (>2kHz), effects are not very noticeable over short distances under 100m but effects can be significant over longer distances [Craven, Kerry, 2001]. Wind effects are particularly important for wind turbine noise because not only does wind affect the propagation of noise but it is also directly related to the generation of noise.. Wind speed typically will have the greatest effect on noise levels but research shows that L_{90} variations of up to 8dB may be attributed largely to temperature variations between day and night or over seasonal meteorological variations [EPA 2003b].

2.5.1 Wind

Wind speed is the principal factor determining the power output from a wind turbine. Wind speed determines whether a turbine is in operation or not and thus can be directly related to noise produced by the turbine. Wind will also generate background noise from other sources such as the rustling of trees and grasses, other factors like noise across the windshield also contribute.

Wind direction is important, with downwind locations receiving the most noise influence. Wind speed increases with altitude, thus higher winds in the upper levels have the effect of bending or refracting sound waves downwards on the downwind side of the source resulting in increased noise levels. At upwind locations, sound waves are refracted upwards and away from the receiver, resulting in reduced noise levels.

Figure 2.3 Wind Effects on Noise

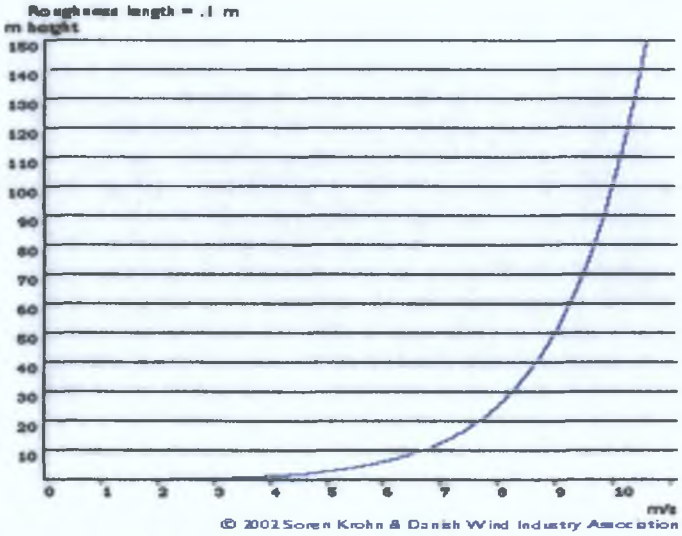


The variation of wind with height has a wide number of variables depending on factors such as the actual wind speed, temperature, type of ground cover, topography, cloud cover, atmospheric pressure and other atmospheric conditions.

2.5.2 Wind Shear

In the lower levels of the atmosphere wind speeds are much reduced by friction against the ground surface, this effect is described as wind shear. Ground effects on wind speed are most evident in the first few meters above ground level, these effects diminish exponentially up to a height of about 1km where ground effects are minimal.

Figure 2.4 Wind Shear Graph



(Source: www.windpower.org)

The wind speed at a certain height above ground level is given by:

$$V = V_{ref} \ln(Z / Z_o) / \ln(Z_{ref} / Z_o)$$

Where

V = wind speed at height Z above ground level

V_{ref} = reference wind speed, measured at height Z_{ref}

Z_o = roughness length in the particular wind direction

The "roughness" of the terrain is dependent on ground cover characteristics; long grasses and forests slow the wind down by a much higher degree than concrete surfaces or water surfaces. To evaluate wind conditions in a landscape the terms "roughness class" or "roughness length" are used. The roughness class is defined on the basis of the roughness length (Z_o) in meters which is the height above ground level where the wind speed is theoretically zero. Typical roughness classes and roughness lengths for various landscapes are listed in Table 2.4.

Table 2.5 Roughness Classes and Roughness Lengths

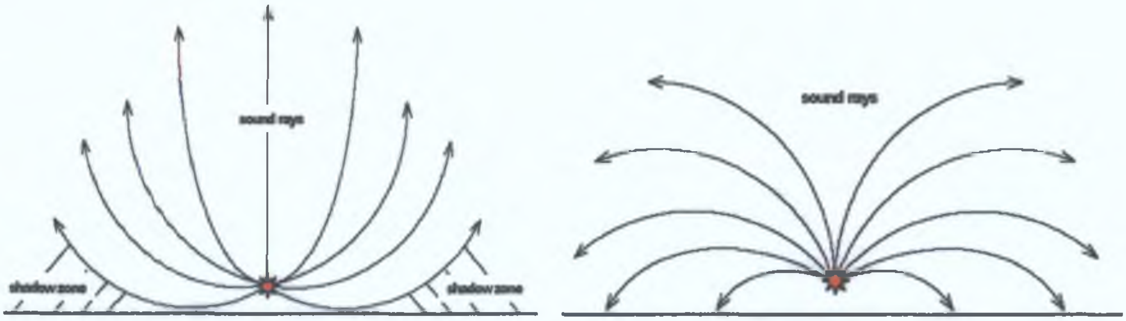
Roughness Class	Roughness Length, m	Landscape Type
0	0.0002	**Water Surface**
0.5	0.0024	Open terrain with smooth surface, eg concrete runway, mowed grass.
1	0.03	Open agricultural area without fences and hedgerows, scattered buildings, softly rounded hills.
1.5	0.055	Agricultural land with some houses, 8m tall sheltering hedgerows with separation distance of approximately 1250m.
2.0	0.1	Agricultural land with some houses and 8m tall sheltering hedgerows with a distance of approximately 500 metres.
2.5	0.2	Agricultural land with many houses, shrubs and plants or 8m tall sheltering hedgerows with a distance of approximately 250 metres.
3	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	Large cities with tall buildings
4	1.6	Very large cities with tall buildings and skyscrapers

2.5.3 Temperature

On a cold night noise is much clearer than on a warm day at the same location, this can largely be explained by air density characteristics and temperature gradients between the ground and upper levels. The speed of sound varies with temperature, being approximately 331 m/s at 0°C and 343 m/s at 20°C.

Temperature gradients produce similar effects as wind gradients except they are uniform in all directions from the source. In general, temperature decreases with increasing altitude with resultant increased flow of sound in an upward direction away from the source. In the case of a temperature inversion, where the ground is colder than the upper warmer layers, sound will be refracted downwards resulting in increased noise levels. Strong winds will reduce temperature gradients by mixing the upper and lower layers.

Figure 2.5 Temperature Effects



Normal Lapse Conditions

Inverse Conditions

2.5.4 Weather Considerations

Standard neutral atmospheric conditions exhibit a temperature profile with an approximate 1°C decrease per 100m increase in altitude. Atmospheric stability will vary however according to weather conditions primarily governed by wind speed, cloud cover and temperature variation. Wind profiles can change drastically depending on atmospheric stability [Holtslag, 1984] and can result in altered noise propagation with refraction of noise towards the receiver due to wind and temperature gradients.

Wind turbulence, another factor, can be caused by the presence of obstacles in the wind path or by convection currents caused by ground surface heating. Turbulence causes the scattering of sound into regions which otherwise may be acoustic shadows.

Atmospheric absorption of sound will depend on the environmental conditions and effects will vary according to the particular frequency. This is examined more closely in the next section on noise prediction.

2.6 NOISE PROPAGATION & PREDICTION

2.6.1 Source Noise & Propagation

In order to predict the wind turbine noise that will be experienced at a particular receiver position, calculation will be based on either:

(a) information on the sound power level (L_W) of the source, or
(b) measurements of sound pressure level (SPL) close to the source.

Calculations for noise propagation away from the source can be summarised as follows:

$$SPL_{receiver} = SPL_{measured} + D - A$$

where

D = the directivity correction to account for a variation in SPL in different directions away from a point source (D = 0 for omnidirectional acoustic spreading).

A = Attenuation factors along the propagation path. The degree of attenuation will depend on the particular frequency and atmospheric conditions. Factors that need to be considered for attenuation along the propagation path include:

- Geometric Divergence (different for line and point sources);
- Atmospheric Absorption;
- Ground Effects (reflection, absorption etc)
- Screening by obstacles
- Meteorological Correction

2.6.2 Geometric Divergence

Calculation of SPL at the receiver based on SPL measurement close to the source uses the relations below. For a point source noise the inverse square law states that sound intensity will drop with the square of the distance to the sound source. This results in a noise level drop of 6dB per doubling of the distance based on spherical spreading of sound. Equation 1 applies.

Equation 1 (Point Source): $$L_{p2} = L_{p1} - 20\log(r_2/r_1)$$

where

L_{p2} = sound pressure level in dB at distance r_2 in metres

L_{p1} = sound pressure level in dB at distance r_1 in metres

For a line source only a 3dB drop is observed due to hemi-spherical spreading of sound. Equation 2 applies.

Equation 2 (Line Source): $$L_{p2} = L_{p1} - 10\log(r_2/r_1)$$

A line source has to be at least three times as long as the distance between the source and receiver, otherwise it behaves as a point [Environment Agency (UK) 2002].

Calculation of SPL based on sound power data uses the following relation:

Equation 3: $$L_p = L_w - 20\mathrm{Log}\, r - 11$$

where

L_{p1} is the sound pressure level at a distance of r metres from the source

L_w is the sound power of the source

The correction value of 11 is based on spherical attenuation. If the ground between the source and the receiver is hard, a correction of 8 is used instead (hemispherical).

2.6.3 Atmospheric Absorption

Geometric divergence as outlined above accounts for the majority of noise attenuation over distance. Atmospheric absorption will cause further reduction and is described in ISO 9613 in terms of temperature, humidity, atmospheric pressure and frequency of the sound particularly at high frequencies. Table 2.5 gives an excerpt from ISO 9613 at two separate values of relative humidity for attenuation of separate octave bands at varying temperature.

Table 2.6 Atmospheric Absorption (ISO 9613-1:1993)

RH, %	**Temp, °C**	**Pure-tone atmospheric-absorption coefficients, dB/km**							
		63Hz	**125Hz**	**250Hz**	**50Hz**	**1kHz**	**2kHz**	**4kHz**	**8kHz**
50	**0**	0.2	0.4	0.8	2.1	6.8	23.8	71.0	147
	10	0.2	0.5	1.1	1.9	4.3	13.2	46.7	155
	20	0.1	0.4	1.3	2.7	4.7	9.9	29.4	104
80	**0**	0.1	0.4	0.8	1.5	4.1	13.8	48.8	147
	10	0.1	0.4	1.0	2.0	3.6	8.8	28.7	103
	20	0.1	0.3	1.0	2.8	5.2	9.0	21.3	68.6

Notes:

Figures refer to 1 atm pressure (101.325kPa)

RH = Relative Humidity

For broadband noise, a general atmospheric attenuation coefficient of 4 to 5 dB per kilometer is often used based on a normalised distribution noise curve about 1kHz.

2.6.4 Other Influences

Dense foliage offers some degree of noise attenuation, predominantly evident at higher frequency ranges. Table 2.6 summarises expected noise attenuation across a range of frequency bands according to International Standard ISO9613-2. A propagation distance (d_f) is defined based on a curved downwind propagation path approximated by an arc of a circle of radius 5km between the receiver and the source. Propagation distance, d_f is calculated from the sum of the distances (for both the source and receiver) away from a direct line of sight between the two points.

Table 2.7 Attenuation of octave band noise through dense foliage

Propagation distance d_f, m	**Nominal midband frequency, Hz**							
	63	125	250	500	1,000	2,000	4,000	8,000
Attenuation, dB, $10 \leq d_f \leq 20$	0	0	1	1	1	1	2	3
Attenuation, dB/m $20 \leq d_f \leq 200$	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.12

Ground effects influence the propagation of noise between a noise source and a receiver position. When dealing with wind farm noise, this will essentially only become a factor near the receiver position as in general the major source of noise will be from elevated positions with little ground influence (turbine hub and blades). Factors such as reflection effects, the presence of barriers and meteorological correction in practice are difficult to accurately quantify over the distances relevant for wind farm developments (commonly between a few hundred metres and 1 km).

2.6.5 *Calculation of Specific Noise and Background Noise*

Measuring noise levels in the proximity of a wind farm will be a combination of noise both from the wind farm and also background noise from other sources. In order to differentiate between the two the following equation is used:

In order to differentiate between the different components of the noise the following relation is used:

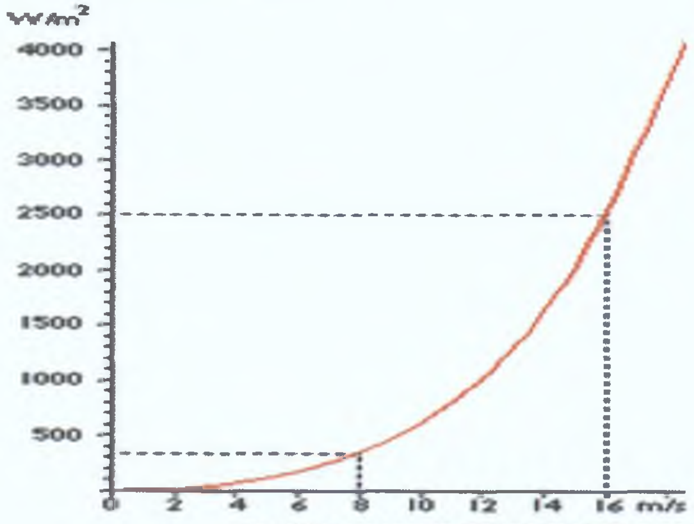
$$SPL_{Total} = 10Log_{10}(10^{(SPL1)/10} + 10^{(SPL2)/10})$$

Where SPL_{Total} is the total ambient noise and SPL1 and SPL2 are the two components (ie specific wind farm noise and background noise)

2.6 WIND POWER AND NOISE CONTROL

The power generated by the wind is related to the cube of the average wind speed, [www.windpower.org 1997-2003)] as illustrated in Figure 2.6.

Figure 2.6 Wind Power Curve



© 1998 www.WINDPOWER.org

The power generated by a particular wind turbine is determined by the relationship:

$P = \frac{1}{2} \rho v^3 \pi r^2$

where

P = power due to the wind passing perpendicularly through a circular area

ρ = (rho), the density of dry air (1.225 kg/m^3 at average atmospheric pressure at 15°C)

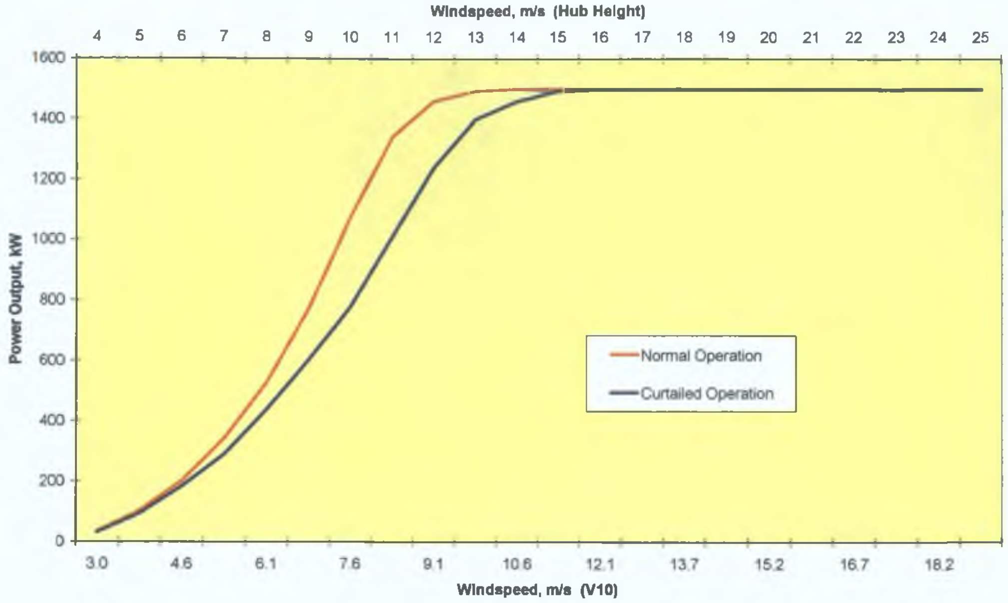
v = velocity of the wind in m/s

πr^2 = the area swept by a blade of radius r

Turbine manufacturers use these relationships together with specific turbine characteristics when determining the power output from an individual turbine type. Newer turbines have noise control systems whereby the sound output level can be adjusted by varying the turbine speed of revolution and pitch angle [Vestas 2005]. The speed of revolution will change to account for changes in wind speed and the pitch (rotation of the blade about its longitudinal axis) will adjust to achieve optimal power output. Operation of these turbines can be curtailed to achieve better noise controls but this will lead to a reduction in the energy generating capacity. Figure 2.7

presents a turbine power curve illustrating the power output over a range of wind speeds for normal operation and also at curtailed operation.

Figure 2.7 Turbine Power Output



In designing a wind farm, a turbine layout is chosen which will yield the maximum energy output for each turbine (and thus maximum income) within the available land area, with adjustments to minimise visual impact and noise disturbance. The energy yield can be accurately estimated through modelling based on turbine specification together with site topography and wind data.

Noise reduction measures may involve reducing the size of the wind farm or curtailing the operation of turbines in close proximity to neighbouring dwellings. With the high capital costs of a wind farm development, the profit margin is often quite small in the first few years of operation and any measures taken that will reduce the power output may make the project non-viable.

As a further measure, planting trees and shrubs provide a degree of noise attenuation (but only when they are tightly packed [ISO 9613]). Foliage eliminates visual intrusion and therefore has an added psychological benefit. Different foliage types e.g. evergreen and broadleaf trees generate their own noise and wind passing through foliage can cause an increase in background masking noise levels.

2.7 WINDFARM DEVELOPMENT AND NOISE LIMITS

In Ireland, there is no direct legislative control on noise from wind farms. Control is exercised indirectly under planning law or in cases where the noise is regarded as a statutory nuisance (see section 2.3 above). Ireland’s first commercial wind farm was at Bellacorick, Co. Mayo in 1992. A number of guideline documents have been published since then to assist wind farm developers to minimise associated environmental impacts. The Irish Wind Energy Association (IWEA) published best practice guidelines in 1994 stating that “typical noise levels from a windfarm 350 metres away are 35 to 45 decibels [IWEA, 1994]. Comprehensive guidance is available for wind farm development and associated noise issues in publications from Europe, the US, Australia and New Zealand. Similar approaches are observed internationally in setting noise limits for wind farm developments. A common approach involves setting base noise limits for lower wind speeds and limits for higher wind speeds are based on a margin exceeding background levels.

2.6.1 ETSU Report on Noise from Windfarms

This report was published in September 1996 for the Department of Trade and Industry (DTI) in the UK and presents the findings of a working group to provide information and advice to developers and planners on the environmental assessment of noise from wind farms [ETSU-R-97, 1996]. Contributions were made from research groups in the UK, Denmark, Holland and Germany to include the ETSU, the UK Department of Trade and Industry (UK DTI) and other research bodies. The following provides a summary of the recommendations for setting noise limits:

- Noise limits at noise sensitive dwellings relative to background levels are most appropriate in the majority of cases rather than absolute limits;
- Noise limits relating to wind speed are suitable only for wind speeds below 12m/s when measured at 10m height on the wind farm site;
- The $L_{A90,10min}$ descriptor is considered most appropriate for measurement and rating levels should apply to reflect the character of the noise;

- Separate noise limits should apply for day-time and night-time based on background data taken during quiet day-time and night-time measurements, in general, noise from the wind farm should be limited to 5dB(A) above background for day and night;
- In low noise environments, day-time absolute noise limits are recommended in the range of 35 to 40 dB(A);
- A night-time fixed limit of 43dB(A) $L_{A90,\ 10min}$ is recommended in order to achieve 35dB(A) L_{Aeq} levels against sleep disturbance (this assumes 10dB(A) attenuation through an open window and 2dB(A) correction for the use of L_{A90} rather than L_{Aeq}. This limit can be increased to 45 dB(A) if the occupier has some financial involvement in the wind farm;
- For installations of single turbines or wind farms with very large separation distances a general $L_{A90,\ 10min}$ limit of 35dB up to wind speeds of 10m/s at 10m height can apply thus negating the requirement for background noise surveys.

2.6.2 Planning Guidelines in Ireland

The Irish Planning Institute guidance published in 1995 [IPI, 1995] recommended noise limits of:
40 dB(A) L_{Aeq}, at a wind speed of 5 m/sec at hub height of nearest machine.
45 dB(A) L_{Aeq}, at a wind speed of 8 m/sec at hub height of nearest machine.

Guidance published by the Department of the Environment [DOE 1996] recommended that noise levels should not exceed 40 dB(A) at any dwelling house. The Department of the Environment Heritage and Local Government, published new draft planning guidelines for wind farm developments in 2004 [DoEHLG 2004 (a)]. These guidelines recommend using the $L_{A90\ 10min}$ noise descriptor for assessing both wind farm noise and background noise and recommend setting noise limits at the nearest noise sensitive location in the vicinity of the proposed wind farm development. Two approaches are suggested; set limits based on existing background noise levels or set absolute noise limits. A general approach based on the existing noise levels provides for a maximum increase of 5dB(A) above background noise at noise sensitive locations. In cases where existing noise levels are very low (less than 30dB(A)); absolute $L_{A90,\ 10min}$ levels between 35-40 dB(A) during the day and a fixed level of 43dB(A) at night or may be extended to 45dB(A) if the property is owned by a promoter of the development.

In another publication [DoEHLG, 2004(b)]DoEHLG the department suggests that "*noise impact should be assessed by reference to the nature and character of nearby surroundings and developments*" and "*generally, noise levels measured externally at any dwellinghouse should not exceed 40dB(A)* L_{eq} *and tonal or impulsive qualities in the noise should be avoided*"

These publications acknowledge many of the recommendations as outlined in the ETSU Report [ETSU-R-97 (1996)] but remain quite general and leave the application of guidelines open to interpretation.

2.6.3 Guidance and Best Practice Worldwide

Environmental Noise Guidance in Southern Australia [EPA SA 2003] recommends setting base noise limits typically 5 dB(A) lower than the level considered to reflect the amenity of the receiving environment. Recommendations also suggest setting noise limits to not exceed background levels by 5dB(A) at higher wind speeds or at higher existing ambient noise levels. Assessment criteria are based on the average $L_{A90,10min}$ noise descriptor measured in accordance with defined compliance checking procedures and determined by regression analysis from a graph of noise vs wind speed. Tonal adjustments are suggested and noise levels and should not exceed 35 dB(A), or the pre-existing background noise by more than 5 dB(A)whichever is the greater, at all relevant receivers for each integer wind speed from cut-in to rated power.

In New Zealand, [NZS 6808:1998] standards specify a predicted base level of 40dB(A) L_{Aeq} to be met at all receivers based on simple propagation modelling. In Denmark [MfE Denmark, 1991], specific legislation controls noise from wind farm developments. A limit of of 45 dB L_{Aeq} is set for all neighbouring properties and 40 dB L_{Aeq} in residential areas and other noise sensitive locations. Only fixed (base) noise levels are set and none relating to background noise levels. The noise limit does however consider wind speed, setting a base noise level L_{Aeq} of 40dB(A) for wind speeds of 8m/s. at a reeference height (V_{10}) of 10 metres. Germany and the Netherlands have similar advisory or recommended levels but have different values for day and night, in recognition of the lower background levels at night.

3.0 METHODOLOGY

The information gathering for this study can be summarised as follows:

- Literature review;
- A review of the quality of EIS noise studies conducted in Ireland with reference to appropriate standard methods;
- A review of planning conditions imposed - historically and current practice, the basis of how they are set and how attainable they are;
- Noise measurement at a selected number of sites to provide information on wind farm noise characteristics.

Consultation was made with wind farm developers, with communities adjacent to wind farms and with planning authorities. Data was gathered from historical reports and new measurement was conducted and compared. A full assessment all findings was then used to address noise assessment methodologies, control measures and the setting or attainment of noise limits.

3.1 REVIEW OF EIS FILES

A comprehensive review was conducted of 22 EIS files relating to wind farm developments in Ireland. Most of the files relate to proposed developments in Cork but in order to ensure a good cross-section, a wide number of different developers were chosen over a time scale of 14 years for varied development sizes. The files were sourced through the planning office in Cork, the ENFO offices in Dublin and were also viewed (where available) on the e-plan websites of planning authorities throughout the country.

Each file was examined based on common criteria relating to:

- Baseline survey,
- Prediction techniques and,
- Assessment basis.

Files were examined in terms of accuracy, explanation of results, comparability of studies and consistency with other studies and with referenced guidance. A summary of findings is given in Chapter 4.5. This report then offers a number of recommendations in order to ensure accuracy in the future and a standardisation of procedures used.

3.2 REVIEW OF PLANNING CONDITIONS AND NOISE LIMITS

A review was conducted of planning conditions relating to wind farm throughout Ireland. Conditions from 33 specific sites are listed and compared. Most of the conditions are those set by the relevant Planning Authority, some were amended by decisions of An Bord Pleanála and these where included where information was available. In some cases, the final decided conditions were not available (some are still in the planning process) but these serve to point out the differences between planning authority and An Bord Pleanála decisions, the types of noise conditions being applied and their consistency (or lack of) throughout the country.

Planning conditions reviewed include applications for developments throughout Ireland; in Cork, Kerry, Limerick, Clare, Galway Mayo, Sligo, Roscommon, Donegal, Wicklow and Wexford. The majority of the conditions were obtained directly from correspondence with the relevant planning authorities. In some cases, information was also available through the websites of local planning authority and An Bord Pleanála.

A critique of the findings was undertaken with reference to measurement data and available planning guidance available nationally and internationally. A detailed summary of findings is given in of Chapter 4.6.

3.3 NOISE ASSESSMENT

When monitoring wind farm noise, one of the major challenges is differentiating between naturally generated background noise and the specific wind turbine noise. Monitoring was conducted at sites before any turbines were installed in order to investigate typical baseline or background noise levels, noise measurement was then conducted at operational wind farm sites to examine typical noise levels and characteristics.

The primary objective of this study is to highlight the measurement and assessment issues that need to be addressed in order to conduct accurate baseline surveys and operational wind farm surveys. In Chapter 4, baseline and operational surveys are addressed separately for discussion.

3.3.1 Noise Monitoring

Noise measurement was conducted at 5 sites. Three of these were operational sites and two were not yet operational. Baseline monitoring and operational monitoring could not be conducted on the same sites for practical reasons (as there may be a period of 12 months or more before wind farm construction is complete). The original baseline EIS data of two of the operational sites was however referenced for comparison. A summary of the measured (and referenced) data is given in Table 3.1.

Table 3.1 Summary of Measurement Data

Site Reference	Location	Survey Type
Site 1	Mayo	Baseline (referenced)
		Operational (measured)
Site 2	Clare	Baseline (measured)
Site 3	Limerick	Baseline (measured)
Site 4	Cork (Milane Hill)	Baseline (referenced)
		Operational (measured)
Site 5	Cork (Curabwee)	Operational (measured)
EIS data for up to 14 additional sites in Ireland.		Baseline (referenced)

Noise monitoring was conducted over a number of days, together with continuous wind monitoring where possible. A control (or reference) monitor was set up at a central location on site for both baseline and operational surveys. This was set up to allow synchronised noise and wind speed/wind direction monitoring. Further short term monitoring was conducted at relevant locations in the environs of the wind farm site. The details of all specific measurement locations and measurement parameters are given in Chapter 4 Results and Discussion.

Noise Measurement was conducted at a height of between 1.5 to 2m above ground. Some standards recommend using a ground plane microphone set-up for direct turbine noise measurement but this was not used as it is generally only applicable to the determination of sound power level.

Standard parameters recorded during the noise survey were the equivalent continuous sound level (L_{eq}), the 10% (L_{10}), and 90% (L_{90}) percentile levels. Various measurement intervals and settings were used depending on the particular application, but for standard monitoring, the measurement time interval was set at 15 minutes, the history period was one minute and history period units was one second for all monitoring locations. The sound level meters were set to frequency weighting “A” and detector response to “Fast”. Standard monitoring was undertaken in accordance with international noise standards in particular ISO 1996: 1982 to 1987 “Description and measurement of environmental noise”.

L_{90} values were chosen to best represent wind turbine noise and forms the basis of the majority of noise measurement calculations in this study. Noise from a wind farm is continuous within operational wind speed ranges, typically 4 to 25m/s at hub height. L_{90} figures give an accurate indication of continuous noise, excluding the influence of short-term external influences such as a passing aircraft anthropogenic activity or animal sounds. The use of L_{90} has been recommended under previous work [ETSU-R-97] [Byrne 2001] [DOEHLG 2004 (a)] and its use is further illustrated in the results of this study.

Frequency monitoring was conducted at all sites and A-weighted and Linear weighted measurements were compared. This was done to investigate for the presence of tones and also to investigate the applicability of A-weighted measurement in light of work indicating that it is unsuitable for low frequency noise measurement. [Zwicker E 1990], [Bite, Flindell, 2004]. Low frequency noise has been identified as a particular concern in wind turbine noise [RERL, 2004].

Tonal noise assessment was conducted at all of the operational sites as listed in Table 3.1. For comparison, tonal assessment was also conducted at baseline sites where tonal noise is not expected to be present. Noise monitors were left overnight where possible and tonal measurements were conducted over 15minute intervals.

Frequency monitoring was conducted using 1/3 octave band analysis and the presence of tones investigated according to [BS 7445:1991 /ISO 1996] which recommends that if the level in one 1/3rd octave band is 5dB or more higher than the level in the two adjacent bands, then an audible tone is likely to be perceived.

Tonal noise was assessed over a range of wind speeds to account for:

- Higher mechanical noise expected at higher wind; this has been associated with the generation of low frequency noise.
- Measurement locations with low wind are expected to have less background noise and thus have less ability to “mask” or hide any tones that may be present.

Meteorological monitoring in most cases involved continuous wind monitoring at a height of between 1.5 to 2m at a control location on site. Spot measurements of temperature and wind speed were taken at some locations together with general observations on weather conditions. Supplementary weather data was also referenced from nearby meteorological stations where possible.

The GPS Coordinates of all monitoring points and turbines were recorded as well as houses in some cases. The coordinates were then plotted and used when determining separation distances for noise calculations.

Instrumentation

- Larson Davis 870 precision sound level meter with integrated wind speed monitor and direction sensor. Used as an on-site control for determining noise to wind relationships,
- Larson Davis 824 with Frequency Analyser. Used for medium to long term measurements and frequency analysis,
- Larson Davis 812: Used for short to medium term noise monitoring,
- Wind Shields Type: Larson Davis 2120 Windscreen,
- Calibration Type: Larson Davis Precision Acoustic Calibrator Model CA250,
- Elite Skywatch Handheld Wind omni-directional wind meter.
- Trimble portable GPS system

Noise measurement equipment used was Type 1 in accordance with the standards: IEC 651 Type 1, IEC 804-1985, Type 1, Directive 86/188/EEC, Directive IEC/TC-29, ANSI SI.4-1983 Type 1 and ANSI SI.25-1991 Type 1.

The minimum recordable noise level was estimated at between 15 to 20dB(A) based noise floor specifications data for each instrument.

3.3.2 Data Analysis

Measured noise level varies according to wind speed. Natural background noise levels increase with increasing wind speed and separate from this, wind turbine noise will vary according to wind speed. For baseline studies, noise level (primarily L_{90}) was plotted over a range of wind speed to show the variation in dB per m/s. For operational wind farm monitoring similar plots were conducted. Noise prediction was also conducted based on sound power levels at different wind speeds as per turbine noise specification data.

Different wind speeds are evident at different heights and thus whenever a wind speed is mentioned it is referenced to a particular height. In order to relate wind speeds at different heights, wind shear calculations were conducted on all measurements. For assessment purposes, all wind speed data was related to a reference height of 10m. This was chosen for a number of reasons:

- Turbine specifications which are used for noise modelling are typically standardised to 10m height;
- Wind speed at 10m height will provide a good relationship between wind speed at ground level (below 2m height) and also speeds measured at turbine hub height (nowadays typically greater than 50m);
- Wind measurements can from a practical point of view can be measured at 10m height without the requirement to install large wind masts;
- Denmark, one of the primary drivers of wind energy in Europe, and elsewhere have recognised 10m as a suitable height and specific legislation relating to wind turbine noise [MfE Denmark 1991].

Wind measurement during this project was taken at a reference height of 1.8m above ground (at a similar height to noise monitoring which was conducted with the microphone at 1.5 to 2m above ground). This was primarily done for ease of measurement but also so that all measurement data could be directly compared with historical surveys where wind monitoring was conducted at this height. For assessment, all wind speed measurements were then related to a 10m height.

The wind speed at a certain height above ground level is given by:

$$V = V_{ref} \ln(Z / Z_o) / \ln(Z_{ref} / Z_o)$$

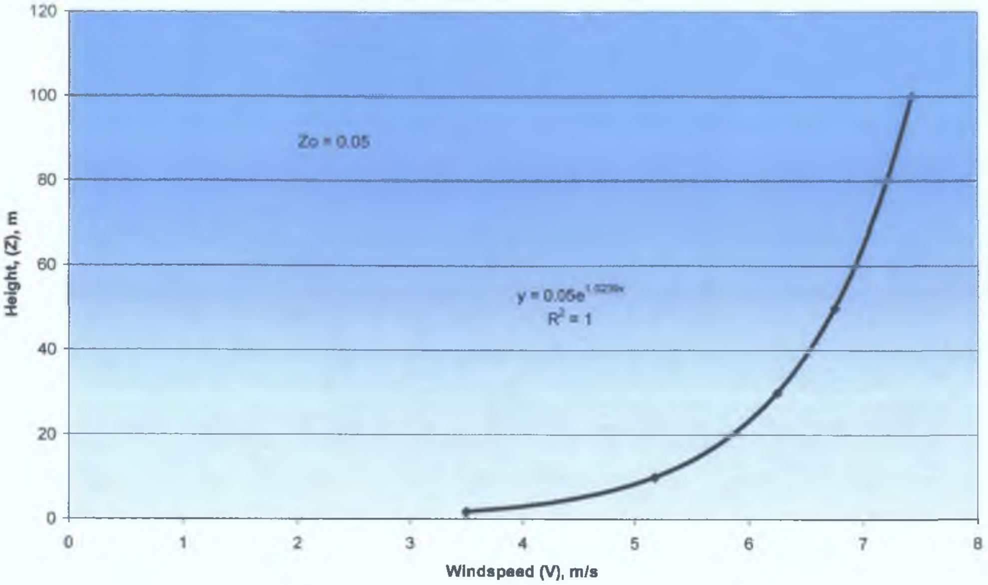
Where

V = wind speed at height Z above ground level

V_{ref} = reference wind speed, measured at height Z_{ref}

Z_o = roughness length in the particular wind direction

Figure 3.1 Wind Shear Graph



Wind measurement was conducted at 1.8m height, therefore Zref = 1.8m and Vref is the measured wind speed at 1.8m height.

Roughness length, Zo = 0.05m. This roughness length was chosen as it is suggested to represent farmland with some vegetation [IEC 61400-11:1998]. This was used as default value for all sites with similar terrain characteristics. Chapter 2 Section 2.5.2 describes various roughness lengths (eg 0.055 to approximate "*agricultural land with some houses, 8m tall sheltering hedgerows with separation distance of approximately 1250m*").

Table 3.2 shows calculated wind speeds expected at varying heights based on roughness length 0.05.

Table 3.2 Wind Shear Calculations

Ref Ht (Z):	1.8m	10m	50m	100m
WIND SPEEDS AT RELATED HEIGHTS	1	1.48	1.93	2.12
	2	2.96	3.86	4.24
	3	4.44	5.78	6.36
	4	5.91	7.71	8.48
	5	7.39	9.64	10.6
	6	8.87	11.6	12.7
	7	10.4	13.5	14.9
	8	11.8	15.4	17.0
	9	13.3	17.6	19.1
	10	14.8	19.3	21.2

The term V_{10} is used for wind speeds measured at a reference height of 10m. Noise-to-wind speed relationships were made for all measurement surveys with all wind speed measurements converted to their particular V_{10} wind speeds as above.

Long – term, synchronised, averaged (over 15minute intervals) noise and wind speed measurements were taken for each site. Noise level (L_{90} in particular) was plotted against wind speed (converted to a 10m reference height). Regression analysis was then conducted on the data to achieve a best-fit relationship. In each case, a linear regression plot was conducted but in some cases, particularly over wide wind speed ranges, non linear relationships were observed and thus polynomial regression analysis was more appropriate. This is supported by similar work conducted in Australia [EPA SA 2003] and the UK [ETSU-R-97].

3.3.3 Noise Calculation & Modelling

When dealing with wind farms the term "background noise" refers to the noise level in the absence of the wind farm. As the operation is continuous, the change in background noise with wind is determined from baseline L_{90} results.

The reduction in noise level with distance from wind farm sites was investigated by two methods: (i) by direct measurement of noise levels at varying distances away from the wind farm site and (ii) by prediction modelling.

Noise reduction with distance was investigated by direct measurement at two operational wind farm sites. A number of locations at varying distances from the wind farm site were monitored and GPS coordinates provided the information on separation distances.

Continuous noise and wind monitoring was conducted at one reference location while short-term monitoring was conducted at each of the other locations. Averaged noise levels at each location were then related back to the corresponding noise levels at the reference location in order to yield a value for noise reduction at each point. This was required to ensure that comparisons were only being made under he same conditions in each case. Measured L_{90} values were plotted against the distances from the wind farm site (nearest turbine) to examine noise reduction with distance.

Noise modelling was conducted for one example to illustrate the issues that need to be addressed in determining predicted noise impacts and calculating incremental noise increase above background noise. To do this, all noise data relating to baseline noise measurements and specific turbine noise was first related to each relevant wind speed (V_{10}) using the wind shear calculations. The components making up the total noise were then calculated using L_{90} values and the following relation:

$$SPL_{Total} = 10\text{Log}_{10}(10^{\text{Background Noise}/10} + 10^{\text{Specific Noise}/10}).$$

A scenario was modelled based on three turbines in a triangular layout with separation distances of 150m between each, noise levels were predicted at intervals up to 1km from the nearest turbine. The noise model used was based on "Description Of Noise Propagation Model" specified by the Danish Ministry Of The Environment [MfE, 1991] where the noise level at a receiver (house) at 1.5m above ground level from each turbine is obtained using the following equation :

$$Lp = Lwa - 10\log_{10}\{2\pi r^2\} - a\,r$$

where :

the source (a wind turbine) is broadcasting noise at Lwa dB(A);

Lp is the sound pressure level at the receiver in dB(A) ;

r is the line of sight distance between source and receiver in metres.

a is the attenuation coefficient in dB/m,

The model outputs were determined based on geometrical divergence or the spherical spreading over distance (including terrain height) with each turbine treated as a point source. Atmospheric attenuation was taken as 0.005 dB/m, assuming broadband sound power level. Ground effects, screening of barriers, foliage, buildings and reflection were not taken into account in this noise prediction calculation.

Noise modelling was based on noise specification for a GE 1.5MW turbine [GE 2005]

Table 3.3 Turbine Specification Data

Hub Height	50m
Cut-In Wind Speed (HH)	4 m/s
Cut-Out Wind Speed (HH)	25 m/s
Nominal Power Output	1.5 MW
Nominal Rated Speed (HH)	14 m/s
Sound Power Level at 5 m/s (V_{10})	98 dB
Sound Power Level at 10 m/s (V_{10})	104 dB

- The operating range is between 4 to 25 m/s measured at hub height (HH). Based on wind shear calculations (see section 4.5), this corresponds to wind speeds at 10m (V_{10}) between 3.1 to 19.2 approx.
- The Nominal Rated Wind speed is the windspeed at which the maximum power output is achieved. In this case a wind speed of 14 m/s (measured at hub height) is required for maximum output. The corresponding wind speed at 10m height will be approximately 10.8 m/s

Noise levels were modelled at wind speeds of 5m/s and 10m/s based on turbine specification data. Predicted noise levels were compared against background noise for 2 scenarios:

(a) for non-sheltered locations where wind speeds are the same as those experienced on the wind farm site

(b) for sheltered locations where wind speeds may be half those experienced on the wind farm site

The wind farm sites visited tended to be in upland locations with on-site wind speeds tending to be much higher than those experienced at nearby dwellings. The two scenarios examined here are not based on two particular reference locations but rather are meant to represent extreme but likely conditions.

In summary, information gathered from the EIS files provide information on what should be addressed in a wind farm development. The review of planning conditions gives an indication of the noise standards that need to be complied with. The noise measurement conducted allows a full critique of the files reviewed together with examining the nature of wind turbine noise.

The full process involved in the development of a wind farm is discussed from the EIS and planning phase to the operational phase and compliance assessment. Guidance is then offered for the accurate assessment of noise associated with wind farms, the costs associated with noise control and recommendations relating to the setting of noise limits.

4.0 RESULTS & DISCUSSION

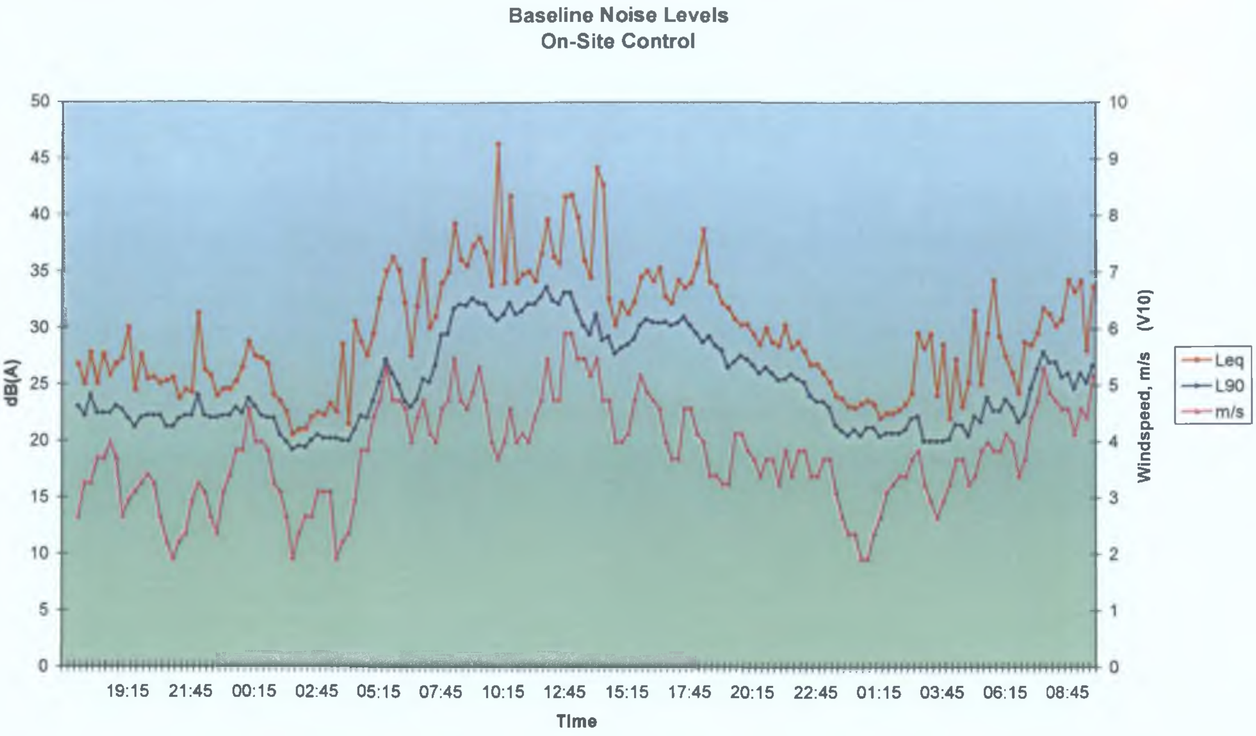
4.1 BASELINE NOISE RESULTS

Measured background baseline noise data was examined for a number of rural locations chosen as potential wind farm sites. The primary focus here is to examine the natural variation of noise levels over a range of wind speeds, to examine potential noise impacts and to assist in the process of setting suitable noise limits based on existing background noise levels. Wind measurements were conducted at 1.8m height and results were related to 10 m height using wind shear calculation (therefore multiplied by a factor of 1.48 to approximate wind speed at 10m height).

4.1.1 Site 1 -Mayo

Historical data for this site was referenced, averaged and corrected for wind speed reference height according to the methodologies in Chapter 3. Continuous synchronised monitoring of wind speed and noise levels was conducted over approximately a 40 hour period at this site. Figure 4.1 summarises the average variation of recorded values averaged over 15 minute intervals.

Figure 4.1 Site 1 - Natural Variation of Noise Levels and Wind speed



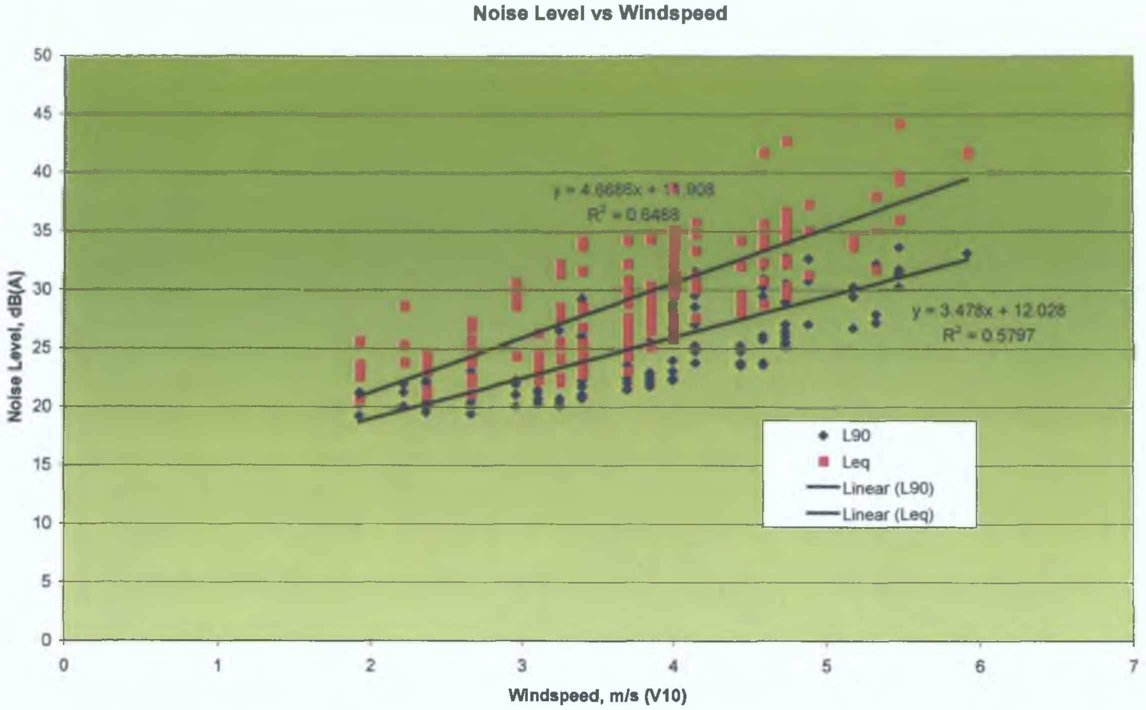
Measured noise levels (L_{eq} and L_{90}) change according to variations in wind speed. As expected, L_{eq} values show a wider variation than L_{90} values and noise levels generally are seen to be strongly dependant on wind speed.

Higher noise levels (L_{eq} and L_{90}) were observed during the day – this may be attributed to the corresponding measured increased wind speeds observed for the same period but also due to increased day-time noise coming from traffic on distant roads and increased anthropogenic activity within the surrounding hinterland.

The influence of weather was considered minimal during the survey (apart from wind speed). Conditions were dry, temperatures were estimated in the range of 2 to 7°C, colder at night and an average of approximately 5 °C during the day. based on weather station data.

Synchronised noise measurement data and wind speed averaged over 15 minute averaged intervals were plotted in Figure 4.2 and linear regression analysis was applied.

Figure 4.2 Site 1 - Regression Plot Noise Level vs Wind Speed



The L_{90} noise descriptor was used to represent operational wind turbine noise (as discussed in Chapter 3 Methodology). From the graph, L_{eq} values are seen to be more erratic and, in this case, tend to be on average 5dB higher than L_{90} measurements.

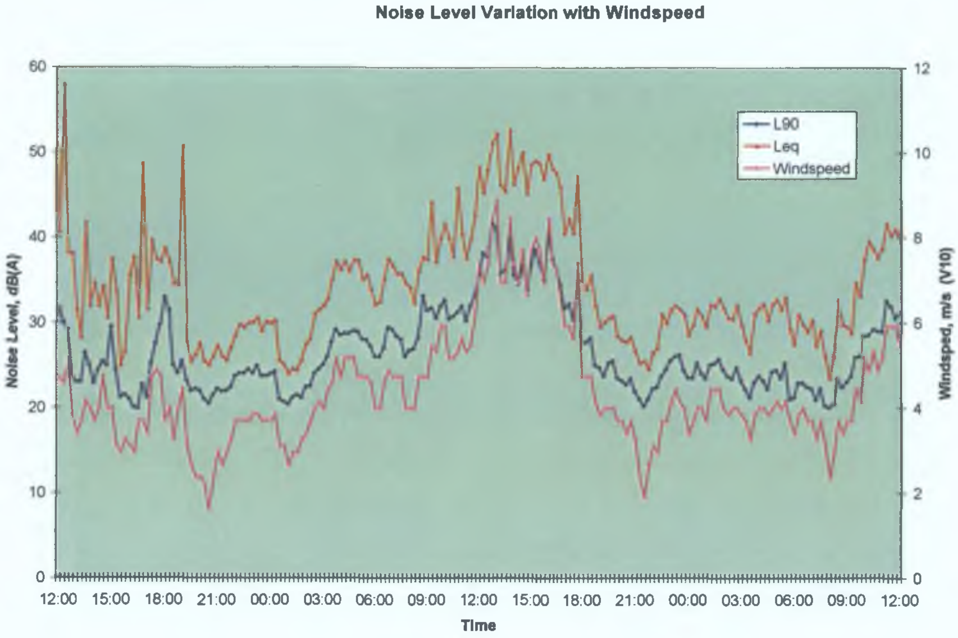
The equation of the L_{90} regression line is given as $y = 3.478x + 12.028$. The slope of the regression line (by differentiation), indicates that the rate at which L_{90} background noise levels increase with wind speed is **3.478 dB per m/s.**

A poor regression relationship is observed for this example, and measurement deviations of more than 5dB from the best fit line are common. The wind speed range is not very wide when considering the operational wind speeds for wind turbines. The results obtained here are not expected to give an accurate representation of background noise levels against which noise measurements at the operational site may be compared.

4.1.2 Site 2 - Clare

Continuous, unattended monitoring was conducted at this site over 4 days between the 7th to 11th October 2004. For presentation purposes only data between the 10th to 12th is illustrated in Figure 4.3 but all calculations are based over 4 days data.

Figure 4.3 Site 2 - Natural Variation of Noise Levels and Wind speed

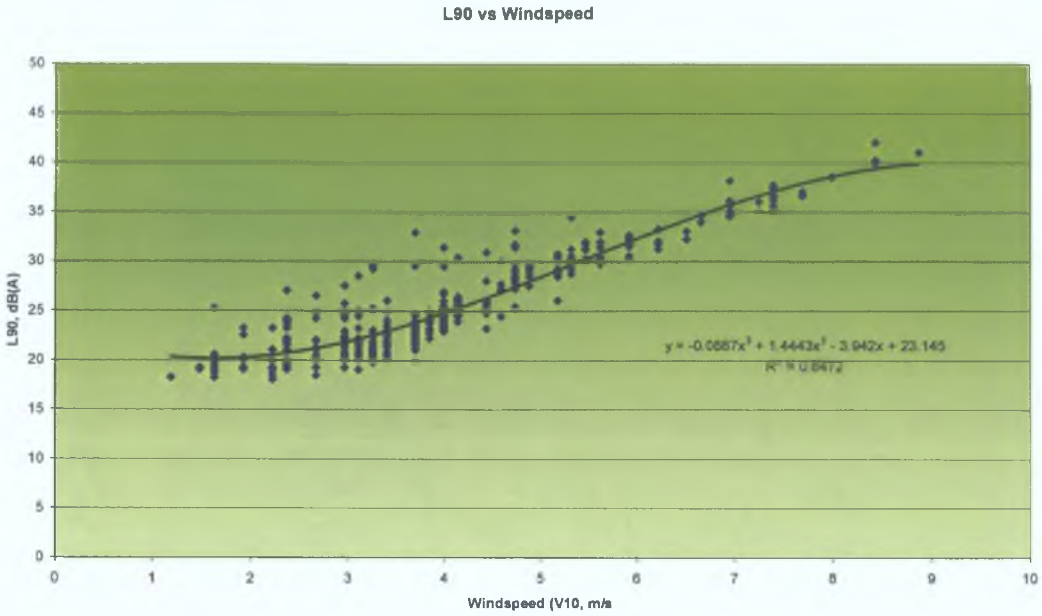


This graph shows the natural variation of noise with wind speed. There is a good correlation between noise level (L_{eq} and L_{90}) and results show it is both noisier and windier during the day.

No rain was recorded over the four days and weather conditions were quite stable, showing temperature increases during the day but all measurements between 7 to 13 degrees Celsius. Weather conditions during the survey are summarised in Appendix I, Section 1, Table 1 and Figure 1.

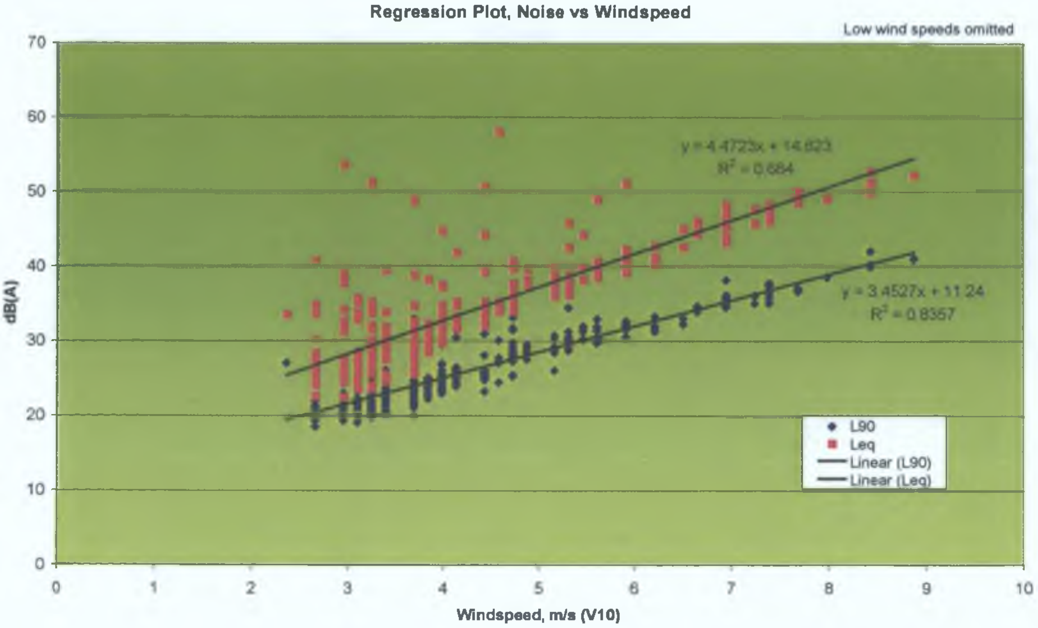
A regression plot of L_{90} vs wind speed is illustrated in Figure 4.4(a). A polynomial – type trendline was chosen instead of a linear type as it was shown to better represent the noise to wind relationship over wide ranges (as is the case here).

Figure 4.4 (a) Site 2 - Regression Plot L_{90} vs Wind speed



In order to get a more workable relationship, the same original data was plotted but the lower wind speed (below 2.5 m/s) values were omitted. Noise – to wind relationships tend to be poor at low wind speeds. Also for assessment purposes afterwards, only wind speeds above 3 to 4 m/s are relevant as this will correspond to the cut-in point for most turbines. Figure 4.4 (b) presents the resultant linear regression plot. Leq measurement data is also included.

Figure 4.4 (b) Site 2 - Regression Plot Noise Level vs Wind speed



L_{eq} data for Plot (b) shows the influence some random short-term noise. Both Plot (a) and Plot (b) illustrate how noise levels (L_{eq} and L_{90}) are quite random at low wind speed, measured noise then increases steadily between 3 to 7 m/s and beyond this point further effects of wind speed become less pronounced as noise levels approach their maximum.

The slope of the graph indicates that L_{90} increases at a rate of **3.45 dB per m/s**. Average measured L_{eq} are seen values in this case tend to be 5dB or so above L_{90} values and approximately 10dB higher at wind speeds in the range of 8m/s as conditions get gusty. This highlights the implications of choosing L_{90} rather than L_{eq} as the measurement parameter when setting noise limits.

In order to demonstrate the difference between day and night – time levels, the measurement data (in terms of L_{90}) was subdivided as follows:

Daytime hours: 08:00 to 20:00
Quiet Evening and Night time 20:00 to 08:00

Regression analysis was conducted separately for daytime and quiet evening and these are plotted in Figures 4.5 (a) and (b).

Figure 4.5(a) Site 2 - Regression Plot L_{90} vs Wind speed (Daytime)

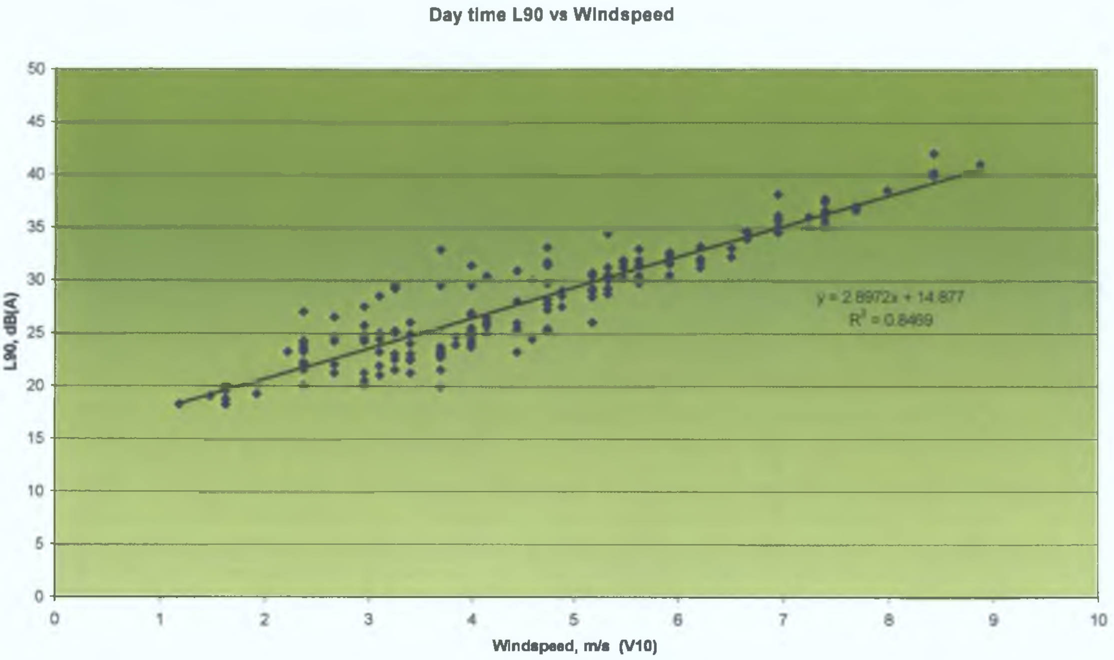
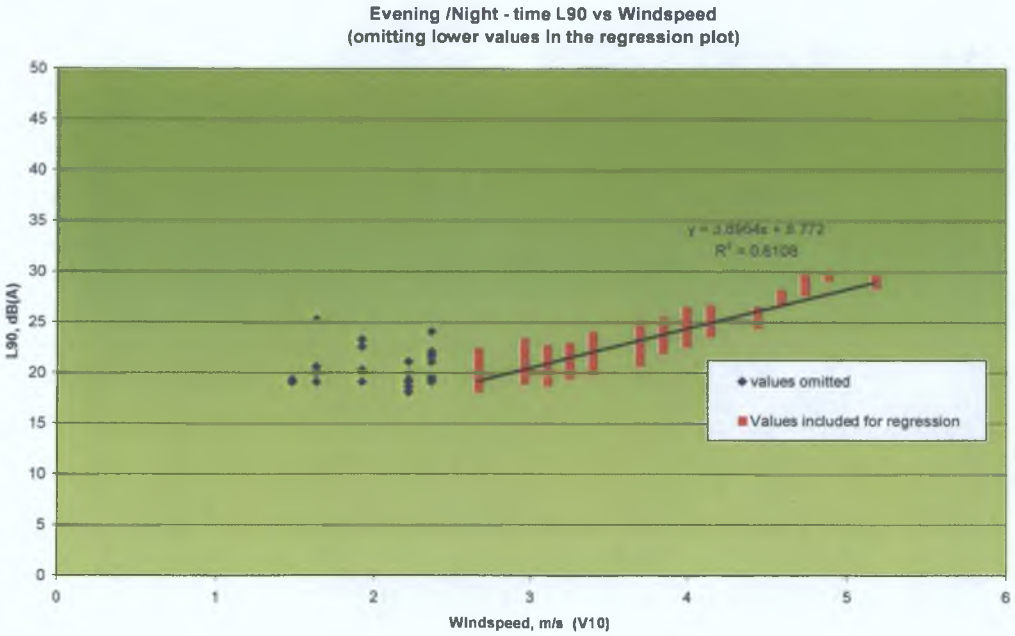


Figure 4.5(b) Site 2 - Regression Plot L_{90} vs Wind speed (Evening -Night)



A number of observations of note regarding the above plots include:

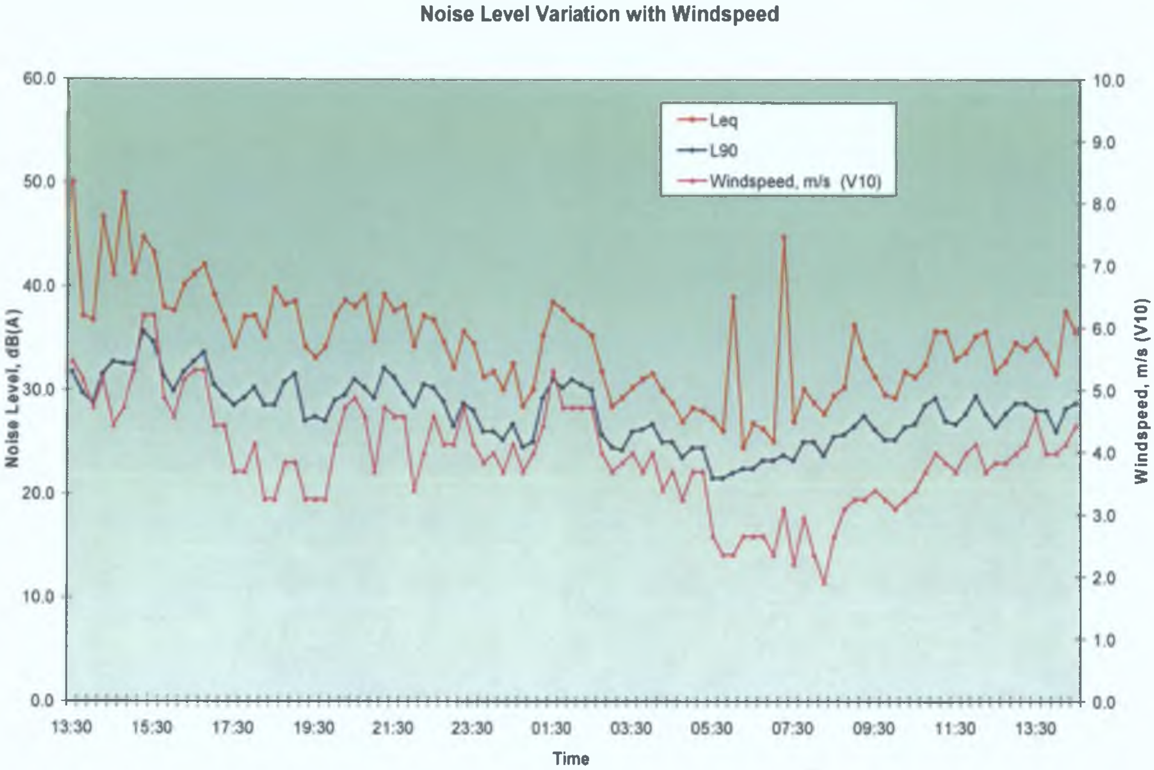
- Much lower background noise levels were observed during evening/night time periods (up to 10dB lower based on L_{90} figures);
- At low wind speeds (below 2 m/s) there is poor correlation with measured noise levels;
- Background L_{90} noise levels increase at a rate of 2.9 dB per m/s during day – time measurements and 3.9 dB per m/s (based on the slope of the regression line). This can be attributed to the lower wind speeds measured at night and the corresponding lower noise levels. At moderate to high wind speeds both plots agree for example at 5m/s both predict a corresponding L_{90} of approximately 29dB(A).

The above series of plots emphasise the requirement that noise levels must be measured over a wide range of wind speeds in order to achieve a good statistical data set. At moderate wind speeds (circa 2 to 7 m/s at 10m reference height), L_{90} noise levels tend to increase quite linearly at a rate of approximately 3.3 dB per m/s. At lower or higher wind speeds a different rate will be observed. Polynomial regression plots are useful to show the change in rate of this increase and will allow more accuracy when including wind speeds less than 2m/s and greater than 8m/s.

4.1.3 Site 3 - Limerick

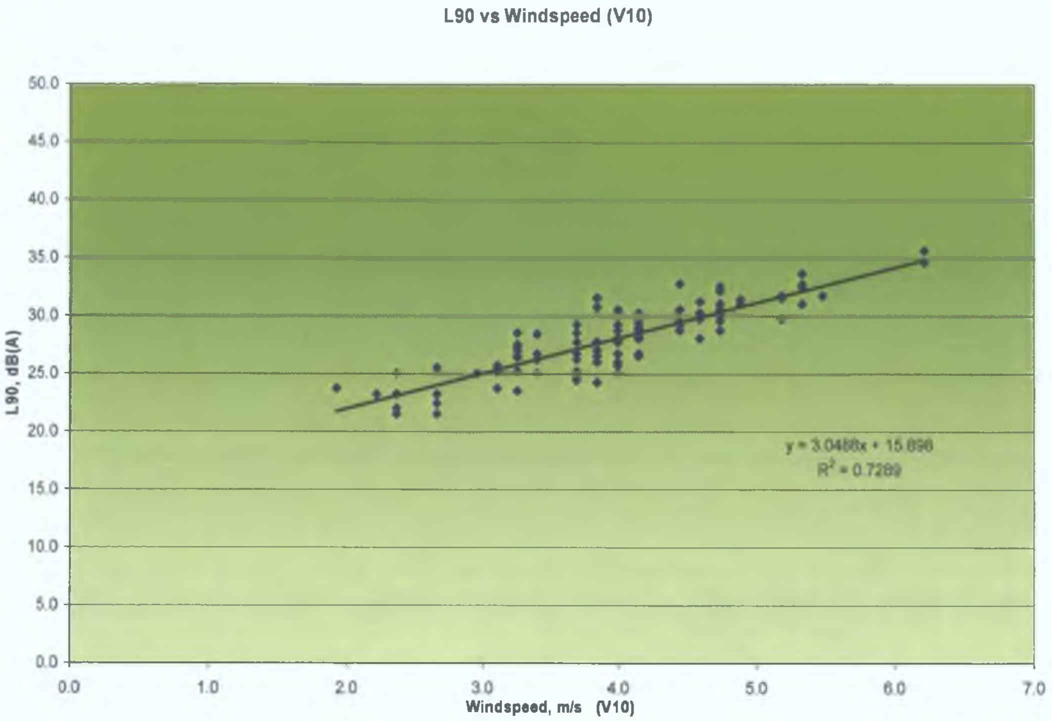
Continuous wind speed, wind direction and noise (L_{eq} & L_{90}) direction was measured in synchronised averaged intervals over 24 hours. A summary of results is presented in Figure 4.6.

Figure 4.6 Site 3 Natural Variation of Noise Levels and Wind speed



L_{eq} values show the effects of short term noise peaks but in general L_{90} and L_{eq} vary according to wind speed. Average wind speed measurements of approximately 4m/s were recorded and temperatures remained quite steady even throughout the night. More detailed weather information is summarised in Appendix I, Section 1, Table 2 and Figure 2.

Figure 4.7 Site 3 - Regression Plot L_{90} vs Wind speed



In this case, monitoring data was only collected over 24 hours but good wind conditions prevailed throughout the monitoring in the range of 2 to 7m/s. In practice, this wind speed range provides the best correlation with measured noise levels. Noise Levels (as L_{90}) in this case increase at a rate of **3.05 dB per m/s**.

4.1.4 Summary of Main Points

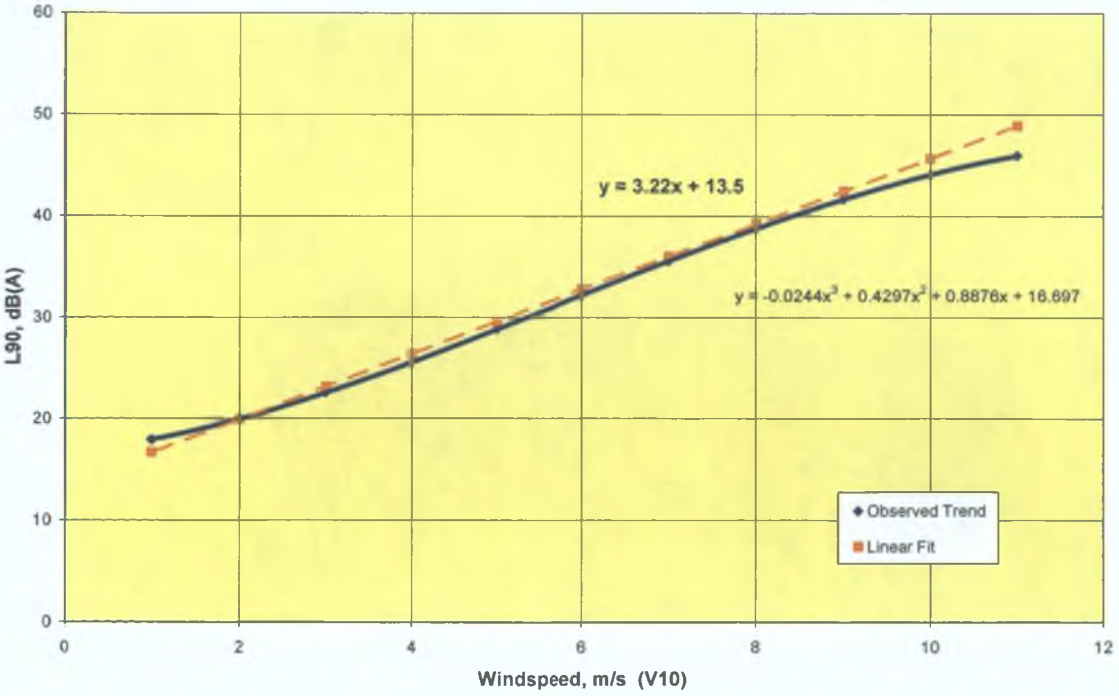
From the above examples, a number of points can be made in relation to baseline noise measurement:

- Noise level varies with wind speed, L_{90} varied within the range of 2.9 to 3.9 dB per m/s. Wind speed is the most important factor in determining noise levels in a baseline survey where there is an absence of noise outside natural background sources,
- Atmospheric conditions at night tend to be colder than the day time with lower wind speeds and thus lower background noise levels,

- Varying atmospheric conditions (as exhibited between day and night) can significantly affect background noise levels. Changes in atmospheric stability with altered temperature and wind gradients can be significant between day and night and therefore the measurement interval needs to suitably long to get an accurate representative results.
- Noise measurement (in particular L_{90}) needs to be gathered over a wide range of wind speeds in order that good statistical correlations can be made.

In order to illustrate the variation of L_{90} over a wide range of wind speeds, data from sites 1 to 3 was averaged at each integer wind speed. The collated data was then plotted on the one graph and a both a linear regression and 3rd order polynomial regression trendline was added, as presented in Figure 4.8. Although the raw data is from a variety of conditions and different sources the summary data is expected to offer a good overall indication of average background (L_{90}) noise levels that may be expected in upland rural locations similar to those monitored in this study.

Figure 4.8 Indicative Average Regression Plot L_{90} vs Windspeed



4.2 OPERATIONAL NOISE RESULTS

Noise measurement was conducted at 3 operational sites: Site 1, Site 4 and Site 5 as listed in Table 3.1. For all the wind farm sites visited, horizontal axis turbine type were present and blades were upwind of the tower. The vast majority of turbines used in Ireland and Europe are of this design.

4.2.1 Site 1 - Mayo

Noise Monitoring

Monitoring was conducted at the Mayo site after construction of the windfarm was completed. Measurement locations were chosen to coincide with the baseline monitoring locations as presented in the previous Section 4.1.1. GPS Coordinates of all monitoring points, turbines and nearby houses were plotted. These are illustrated in Appendix I, Section 1, Figure 3.

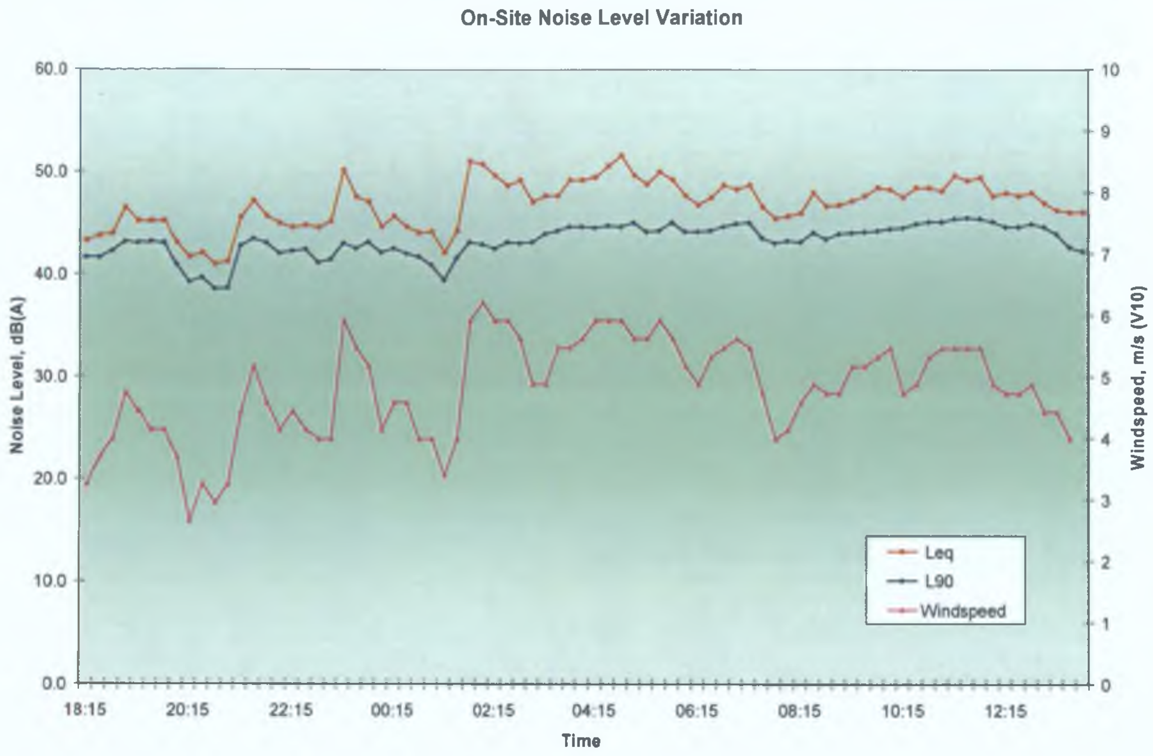
Table 4.1 Monitoring Point Details

Noise Monitoring Point	Distance to Nearest Turbine, m	Details
NM1	141	On Site
NM2	432	Southern Boundary
NM3	666	Off Site (Northwest)
NM4	728	Off Site (East)

(GPS accuracy to 5m)

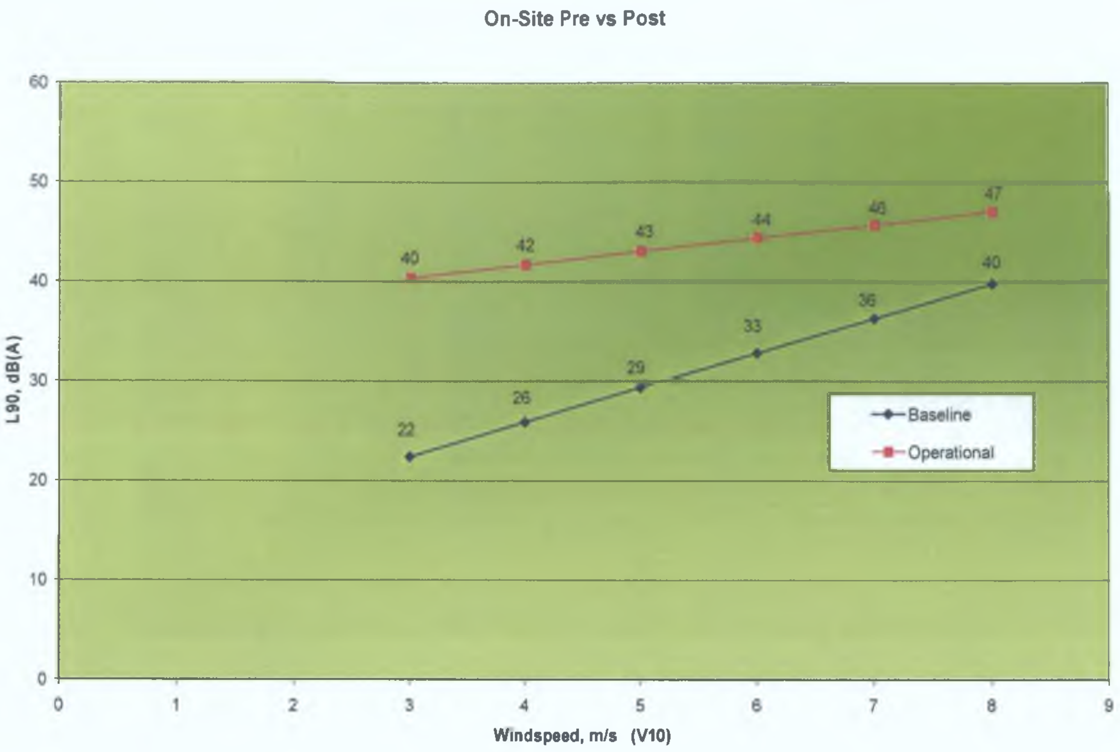
Simultaneous Noise and Wind speed monitoring was set up at NM1 which is located on the wind farm site at a distance of 141m from the nearest turbine. Figure 4.9 presents a summary of noise variation over approximately 19 hours on January 13th 2005. Poor weather conditions made it difficult to get suitable data at all locations and thus only short term measurements were only possible in some cases. Summary weather conditions are given in Appendix I, Section 1.

Figure 4.9 Site 1 Operational Noise Level Variation (NM1)



A regression plot of L_{90} vs wind speed is presented in Figure 4.10 for the operational wind farm noise survey and baseline L_{90} noise data from section 4.1.1 is illustrated on the same plot for comparison.

Figure 4.10 Comparison of Baseline and Operational Plots (NM1)



Comparing measured L_{90} values over a range of wind speeds for both operational and baseline surveys, a number of important observations can be made:

- The difference between background and operational noise is greatest around turbine cut-in point (approx 3m/s at 10m).
- Background noise increases at a higher rate than turbine noise. At this location, background and operational noise increases at a rate of approximately 3.5 and 1.3 dB/m/s respectively.

Change in Noise Level due to Turbine Operation

Noise Levels were measured at 4 locations; NM1, NM2, NM3 and NM4 at various distances from the wind farm site and situated side-wind of the prevailing wind. Details of monitoring points are given in Table 4.7 and illustrated in Appendix I, Section 1, Figure 3. Monitoring results were averaged and separated into Day, Evening and Night Time Intervals:

Day time:	07:00 to 19:00
Evening:	19:00 to 23:00
Night time:	23:00 to 07:00

Average results at each monitoring location are summarised for Baseline and Operational surveys in Tables 4.8 and 4.9.

Table 4.2 Summary of Baseline Monitoring

Measurement Period	Avgerage L_{eq}, dB(A)	Average L_{10}, dB(A)	Average L_{90}, dB(A)	Wind speed, (V_{10}) m/s
NM1				
Day	36	37	31	4.43
Evening	28	30	24	3.19
Night	26	28	22	3.48
NM2				
Day	41	37	31	-
Evening	31	32	27	-
Night	29	30	24	-
NM3				
Day	33	34	28	-
Evening	30	31	26	-
Night	29	30	25	-
NM4				
Day	36	37	27	-
Evening	31	32	29	-
Night	27	29	24	-

Table 4.3 Summary of Operational Monitoring

Measurement Period	Average L_{eq}, dB(A)	Average L_{10}, dB(A)	Average L_{90}, dB(A)	Wind speed, (V_{10}) m/s
NM1				
Day	47	49	44	4.74
Evening	45	46	42	3.96
Night	48	50	43	5.08
NM2				
Day	45	46	39	-
Evening	45	46	38	-
Night	49	51	39	-
NM3				
Day	38	39	36	-
NM4				
Day	46	49	40	-

Daytime monitoring contained a larger data set of noise measurements with simultaneous wind speed data for all monitoring points and therefore formed the basis for determination of Turbine Noise (at each wind speed). L_{90} values were used in calculation to examine the particular component of the total noise that could be attributed to background noise and that related to the wind farm:

$$\text{Total Noise} = \text{Background Noise} + \text{Specific (wind farm) Noise}$$

In order to differentiate between the different components of the noise the following relation is used:

$$SPL_{Total} = 10\text{Log}_{10}(10^{\text{Background Noise}/10} + 10^{\text{Specific Noise}/10})$$

Table 4.4 presents a summary of the calculated results.

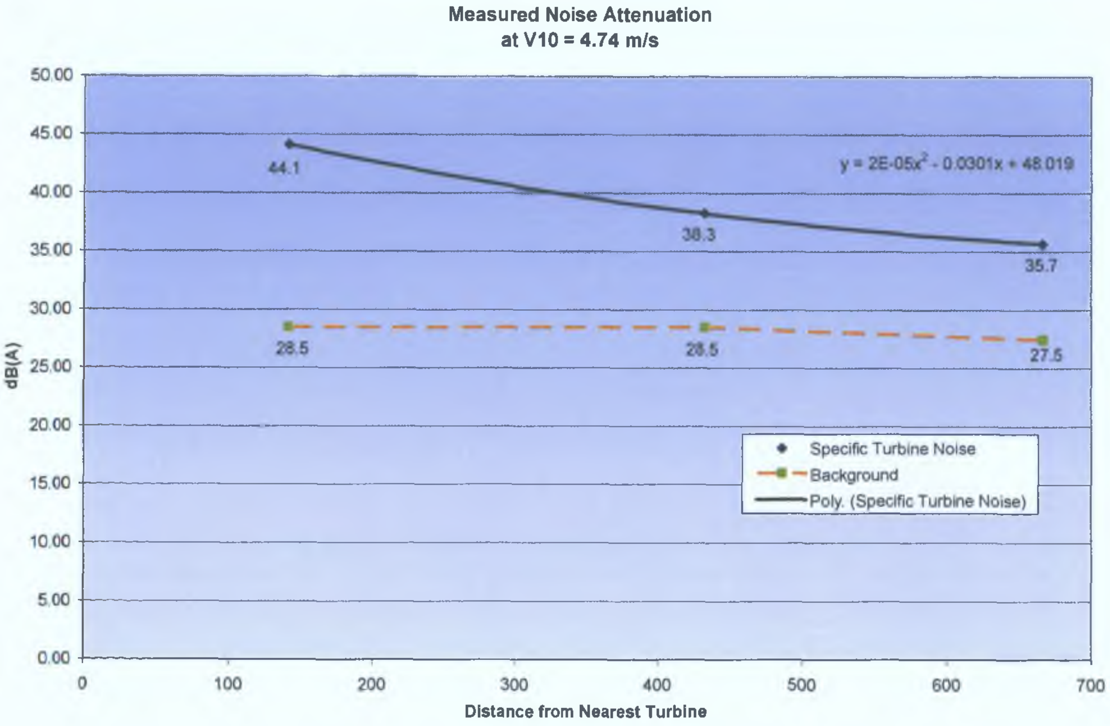
Table 4.4 Calculation of Specific (Turbine) Noise

Noise Monitoring Point	Distance to Nearest Turbine, m	Turbine Noise, dB(A)	Background Noise, dB(A)	Total Noise, dB(A)
NM1	141	**44.1**	28.5	**44.2**
NM2	432	**38.3**	28.5	**38.7**
NM3	666	**35.7**	27.5	**36.3**
NM4	728	**40.1**	27.5	**40.3**

- Noise levels were related to a wind speed of 4.74 m/s as this was the average windspeed measured at NM1 during the relevant measurement interval. The "Total Noise" in each case was taken from measured values at each point;
- The "Background Noise" was taken from baseline results. These were corrected for wind speed (to 4.74 m/s on site) and for localised conditions based on noise-wind speed regression relationships at each location;
- The Specific (Turbine) Noise was calculated using relations outlined in the previous page.

In Figure 4.11 the Specific Noise Levels for NM1, NM2 and NM3 were plotted against their corresponding distances from nearest turbine. NM4 was omitted from the plot as measured values show that it does not agree with projected trends. This point is very near a cluster of houses and adjacent to a minor road and thus exhibits external influences.

Figure 4.11 Specific Noise Level Reduction with Distance



The total contribution of Total + Specific Noise was not included on the plot as Background Noise will have little or no effect, initially adding less than 1dB at 666m. A good rule of thumb applied here is where there is a difference of 10dB or more between two noise sources, the lower noise level will have a negligible effect on overall noise levels.

Measurement results indicate that turbine noise dominates up 700m but the overall noise level is below 40dB after 350m distance and thus would approaching typical acceptable noise criteria eg the Department of the Environment Heritage and Local Government [DoEHLG 2004] recommends $L_{A90,\ 10min}$ levels between 35-40 dB at nearby properties.

4.2.2 Site 4 – Cork (Milane Hill)

Noise Monitoring

Monitoring consisted of a control noise and wind monitor was set up in the centre of the site and further short term monitoring at a range of points downwind of the site. Noise monitoring locations are summarised in Appendix I, Section 1, Figure 4 together with weather conditions during the survey. Average measurement results at the reference location on site are summarised in Table 4.5.

Table 4.5 Average Monitoring Results at the On-Site Reference Location

	Windspeed, m/s (V_{10})	**L_{90}, dB(A)**
Maximum	5.3	52.1
Minimum	3.2	45.7
Average	**4.0**	**48.1**

Note:
Wind Direction: S/SE
Statistical maximum, minimum and average results were calculated on the full data set of 15minute averaged intervals.

Calculation of Turbine Noise

Noise reduction with distance was investigated for four downwind locations using the methodologies described in Chapter 3.3.3. Chosen measurement points were directly downwind from the reference location on soft ground and at least 100m from trees or any other external influences. Table 4.6 summarises the measured noise reduction at each location.

Table 4.6 Measured Noise Reduction

Distance from nearest turbine, m	Noise Reduction, dB
123	- 3.5
181	-6.6
282	-9.0
619	-12.5

These values were then applied to average conditions of 48.1 dB (L_{90}) at 4.0m/s as calculated earlier in Table 4.5.

Table 4.7 Calculation of Specific (Turbine) Noise

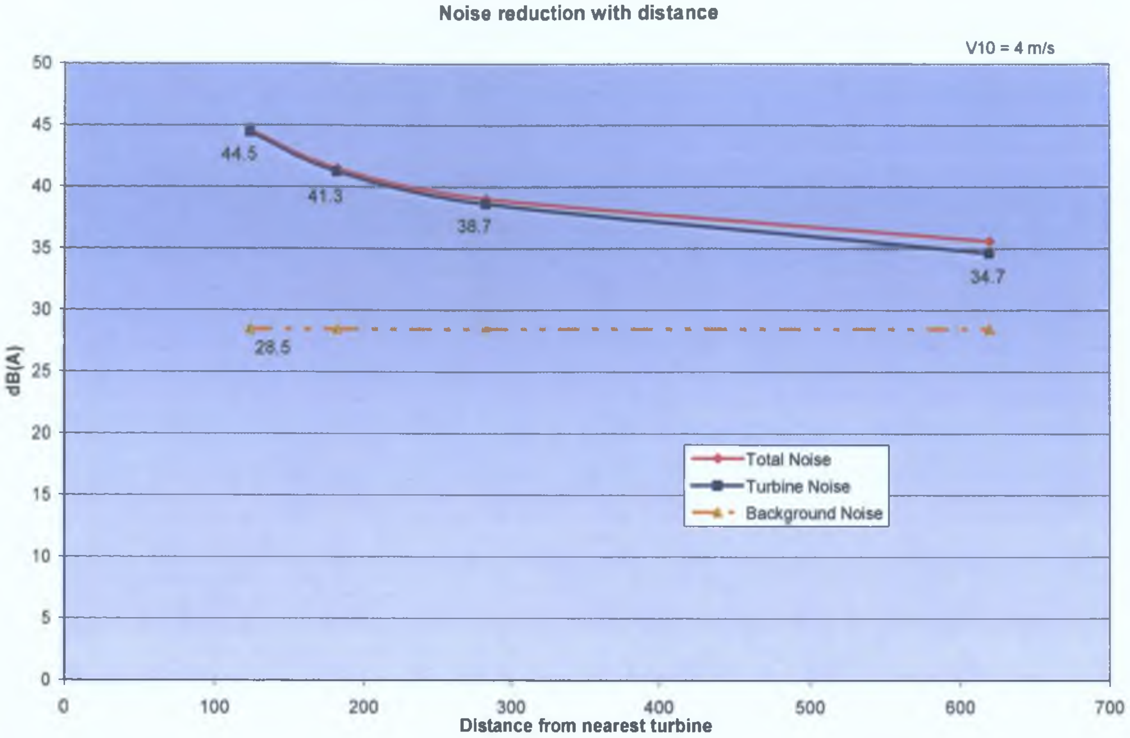
Noise Monitoring Point	Distance to Nearest Turbine, m	Turbine Noise, dB(A)	Background Noise, dB(A)	Total Noise, dB(A)
NM1	123	44.5	28.5	44.6
NM2	181	41.3	28.5	41.5
NM3	282	38.7	28.5	39.1
NM4	619	34.7	28.5	35.6

Wind speed, $V_{10} = 4.0$ m/s

The total noise represents the measured noise level. Background noise in the absence of wind turbine noise was taken to be 28.5dB(A) based on measurements at a similar location, referenced to a windspeed of 4.0m/s. The contribution of turbine noise was calculated as in the previous example using the formula:

$$SPL_{Total} = 10Log_{10}(10^{Background\ Noise/10} + 10^{Specific\ Noise/10})$$

Figure 4.12 Specific Noise Level Reduction with Distance



Wind turbine noise is seen to dominate the noise climate beyond a 600m distance but overall noise levels are below 40dB after approximately 200m and thus approaching acceptable noise limits (as described in the previous example).

Monitoring in this case was conducted at low wind speeds averaging 4m/s (V_{10}). As shown in the earlier example in Figure 4.10, at low wind speeds near the cut-in point, noise from the turbines themselves are not excessively high but as but the difference between background noise and turbine noise is at a maximum. Turbines will start operating at 4m/s at hub height (corresponding to approximately 3m/s at V_{10}) and as there is low background noise at these wind speeds there is little potential for masking. Background noise will increase steadily and eventually exceed turbine noise at a point dependent on how far away from the source one is located.

Turbine noise will increase steadily with wind speed until it reaches its nominal wind speed (wind speed at which the maximum power output is achieved). Beyond this point noise levels tend to remain quite constant at their maximum level (based on turbine specification data).

4.2.3 Site 5 – Cork (Currabwee)

Noise Monitoring

A control noise and wind monitor was set up in the centre of the site and synchronised measurements were recorded over approximately 21 hours. Extensive monitoring was conducted at a number of locations on site and off site to examine turbine noise levels over varying wind speeds. Wind was from the North West for the duration of the monitoring with only minor deviations in wind direction observed. Average daytime temperatures were approximately 5°C, reducing by 2 to 3°C at night-time. Skies were clear and no precipitation was observed throughout the monitoring period. Weather data at the neaest weather station at Ballinascarthy was referenced. A summary of weather variation throughout the monitoring period is summarised in Appendix I, Section 1, Figure 6.

Figure 4.13 Noise Level Variation - On Site Control

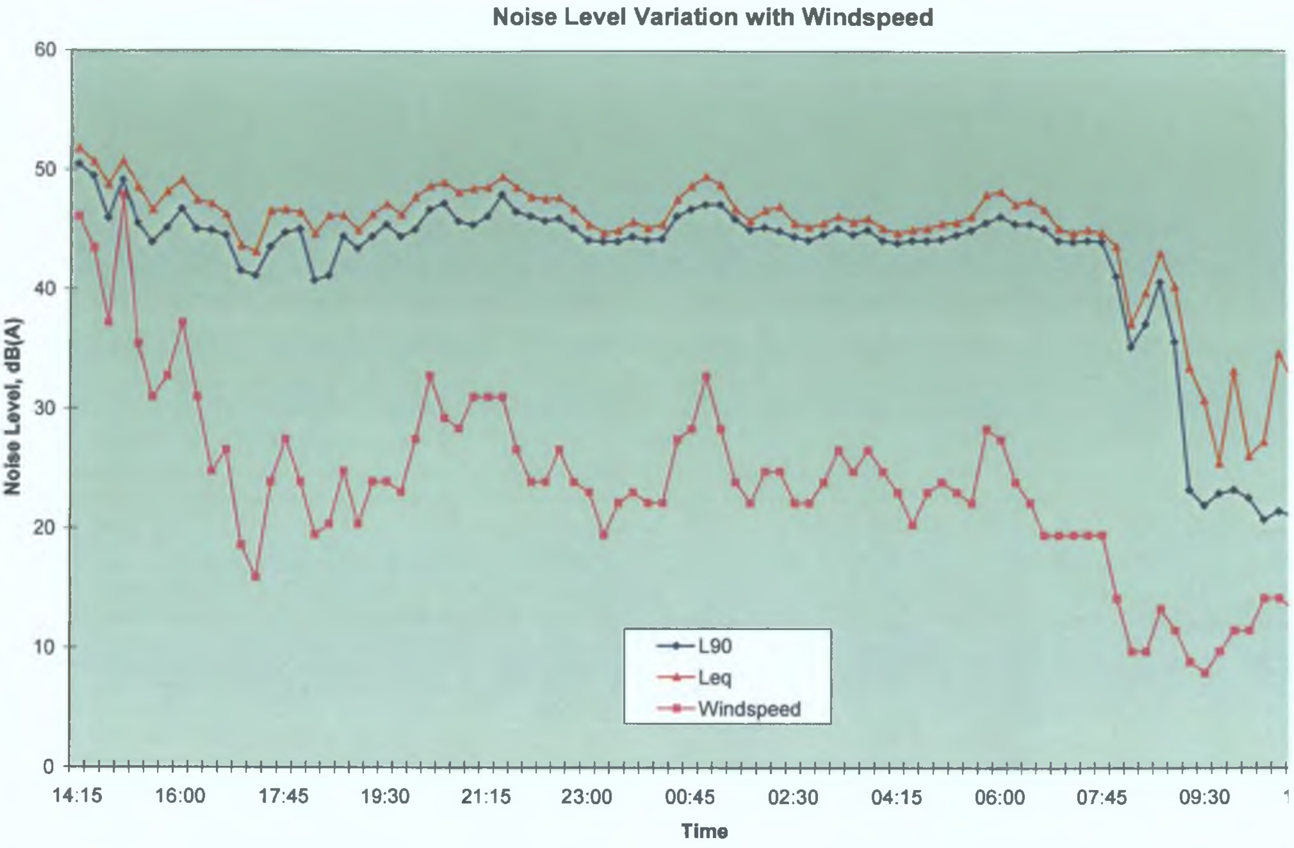


Table 4.8 Summary of on-site measurement

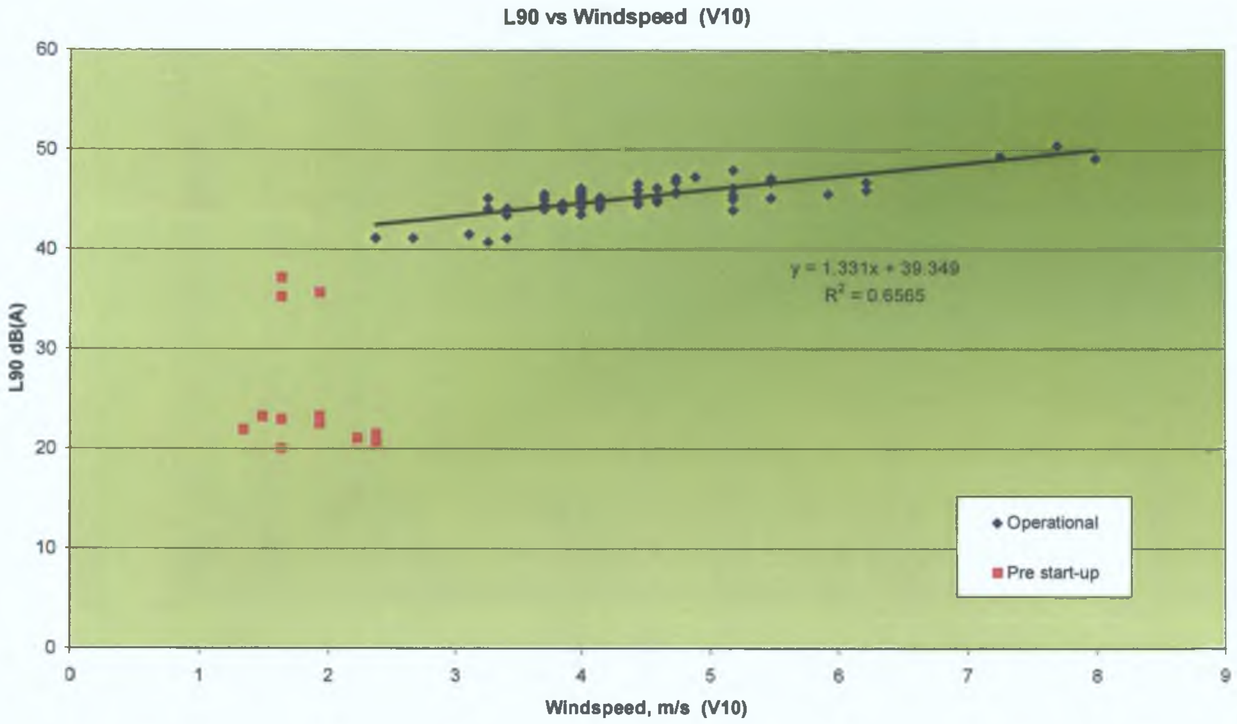
	Windspeed, m/s (V_{10})	L_{eq}, dB(A)	L_{10}, dB(A)	L_{90}, dB(A)
Max	7.98	51.8	52.8	50.5
Min	1.33	25.5	25.8	20.1
Avg	3.89	44.4	45.7	41.6

Summary data refers to the statistical maximum, minimum and average values from data gathered at 15minute measurement intervals over 21 hours.

The control (or reference) site was located in the middle of the wind farm at a distance of 82m from the nearest turbine. Noise levels (L_{90}) were quite steady at around 45dB(A) throughout the monitoring period but towards the end of the survey wind levels dropped below V_{10} of 3m/s (4m/s at Hub Ht. approx) and turbines shut down. A significant noise reduction in the range of 20dB was observed on site as a result.

A regression analysis of L_{90} vs wind speed was completed and plotted in Figure 4.14. Noise levels for low windspeeds (below V_{10} of 2.5m/s) were omitted from regression calculations but are illustrated on the graph.

Figure 4.14 Regression Analysis - On Site Control



The slope of the graph indicates that turbine noise will increase at **1.3 dB per m/s** on site. Background noise is not expected to contribute to noise levels on site to any significant degree at this location at moderate wind speeds and thus the measured noise level may be directly attributed to turbine noise. The rationale behind this is explained by similar methods used in BS4142:1990 or formulae described earlier for the calculation of specific noise. If specific noise from the wind turbine is 10dB or more than the background or residual noise (in the absence of the turbine noise),

No baseline data is available for this site but the influence of background noise is expected to become evident above 7 or 8 m/s based on data for a similar setting.

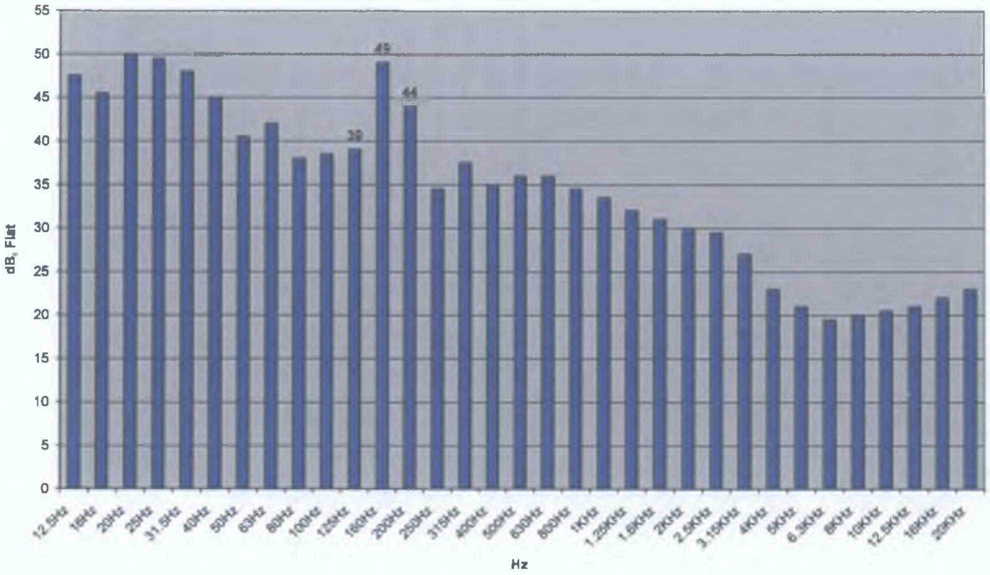
Information available at the site indicated that the turbines were of dual speed type. This is important when.3 examining increase in turbine noise with wind speed. For example, in Figure 4.14, noise increased at a rate of approximately 1.3 dB per m/s, this may so for the particular measured wind speed range but this rate will change depending on the wind speed. Based on this, it can be said that general guidance relating to positioning of wind farms is not very useful and that noise modelling should be a requirement in all cases.

In practice and based on discussions with residents near wind farms, noise is often only a problem when the wind is blowing in the direction of the house but is normally most evident under relatively calm conditions. Noise problems here are thus a combination of wind direction influences and the absence of sufficient background noise at low wind speeds to mask the specific noise from the wind farm.

4.3 TONAL NOISE

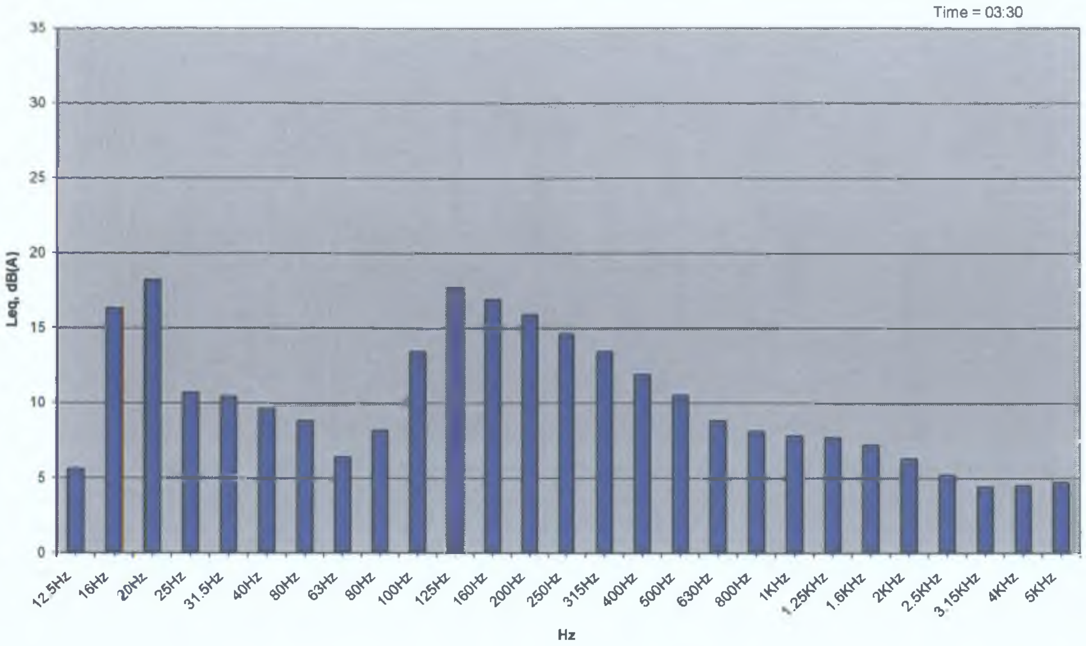
Frequency analysis was conducted at operational wind farm sites over a range of wind speeds, during day and night at various distances from the site based on rationale described in Chapter 3.3.1. No significant tonal noise was observed for measured sites. The majority of measurement spectra are contained in Appendix I, Section 2 and a number of observations are made in this section.

Figure 4.15 Site 5 - On-Site Location, Flat weighting L_{90}



In Figure 4.15, flat- weighting was used and also the noise level was based on L_{90} rather than L_{eq}. Monitoring in this case was at a wind speed of 4.8m/s and the flat-weighted peak of 49dB(flat) corresponds to an equivalent A-weighted level of 35.6 (a difference of -13.4dB) [ISO 3744:1994]. In general flat/linear weighting allows a clearer view of low frequency noise.

Figure 4.16 Baseline Spectrum – Night time

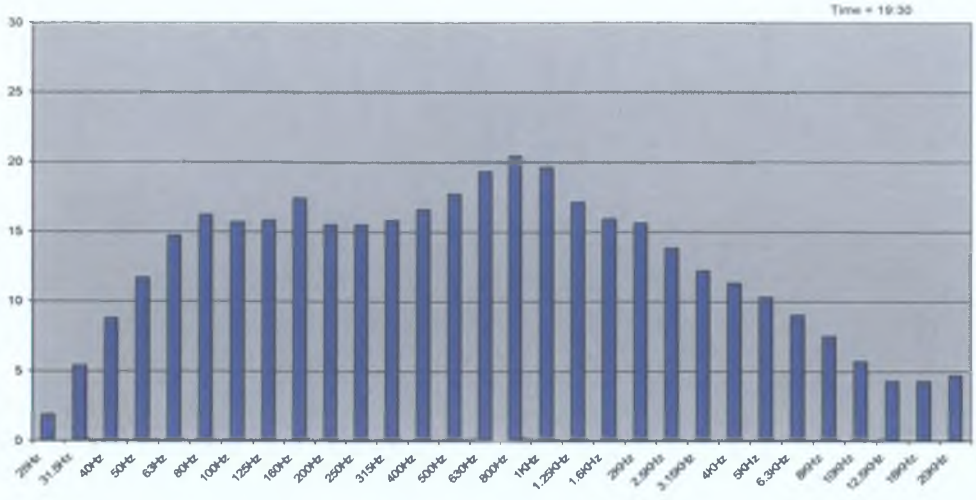


For contrast, Figure 4.16 shows a baseline noise spectrum measured at low wind speeds during the night and also using A –weighting. The observed spectrum is shown to be particularly vulnerable should any particular tone be introduced.

The above spectra are intended to illustrate the requirement to examine tonal qualities over a range of wind speeds, particularly in sheltered locations with limited noise masking potential.

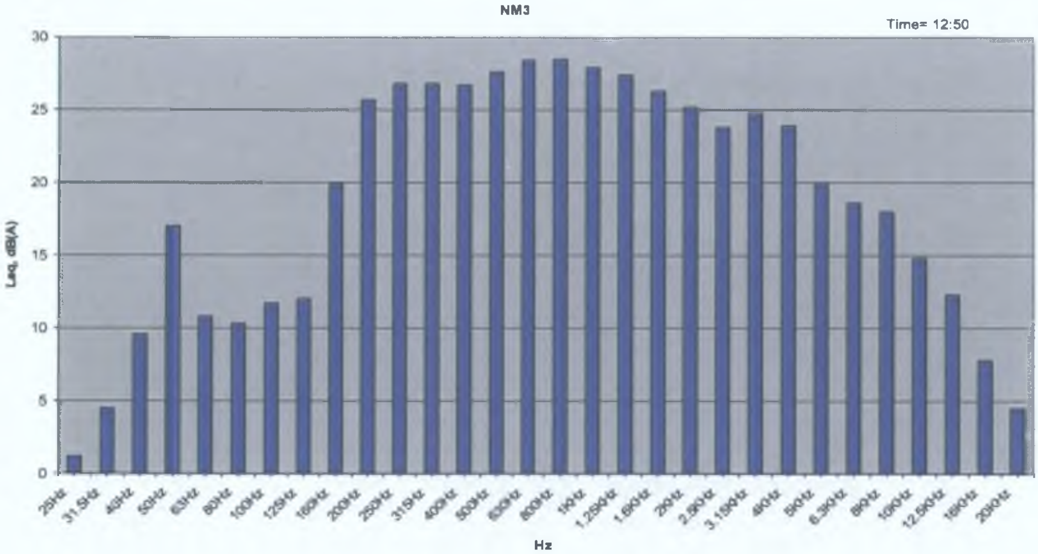
Frequency analysis was conducted at a second site under baseline conditions and again during wind farm operation. Frequency spectra for both are shown in Figures 4.17 and **4.18**. Baseline results were obtained from historical files and had been conducted using A- weighting measurement and thus measurements for the operational study were conducted in the same manner.

Figure 4.17 Baseline Frequency Spectrum



L_{90} = 26.3
Control site wind = 4.1m/s SE

Figure 4.18 Operational Frequency Spectrum



Distance of 666m from nearest turbine N/E of site (see NM1 in Fig 4.14)
L_{90} = 36.3
Control site wind = 4.78 m/s S/SE

Figure 4.17 and 4.18 show the baseline and operational noise spectra for the same location. Frequency bands below 50 Hz are shown to be poorly represented by the A-weighted measurement system. A typical full frequency spectrum will provide information on frequency bands down to 12.5 Hz but the use of A-weighted measurement has resulted in incomplete measurement at lower frequencies.

The measurement location represented in Figures 4.17 and 4.18 is in a sheltered woodland area with little background noise and little influence from wind. The surrounding trees will have the effect of lowering localised wind speed and thus lowering background noise. Trees will also attenuate noise to a certain degree but typically this is more effective for higher frequency noise (ISO 9613-2). Wind passing through leaves and other plant life will however generate its own localised noise of a broadband nature.

A low “hum” was heard from the wind farm and the periodic beats of the blades turning. There was heavy cloud cover during the time of monitoring and rain showers had occurred both before and after the measurement time. 50Hz is the frequency at which A/C current operates but no power lines were seen in the near environs although some were present towards the wind farm site at a distance of over 600m.

The tone measured is only approximately 17dB in magnitude and therefore is unlikely to cause any major nuisance effects. In other acoustic surroundings, in less sheltered areas, noise of a wider broadband nature would generally mask peaks of this magnitude.

Tonal noise is wind-speed dependent; as the wind speed increases the likelihood of tonal noise would appear to increase. This is different for example with multi-speed gear boxes, where a series of noise peak “ramps” will exist as the turbine moves through its series of operational speeds. Wind speed is also a major factor in generating increased background noise to mask the audibility of tones, and will determine the distance from the wind farm at which the turbines are unlikely to cause nuisance.

4.4 NOISE MODELLING

Dual speed or Multi-speed turbines may have complicated noise curves over a range of wind speeds and thus noise modelling will be very specific to turbine type and the wind speed in question.

Noise modelling was conducted according the methods outlined in Chapter 3.3.3 based on scenarios of sheltered and non-sheltered locations at different wind speeds. Results for each are summarised in Figures 4.19 (a/b) and Figures 4.20 (a/b). For ease of reading, values for total noise and background noise have been indicated on the graphs, 5dB marker bars have also been included on two of the graphs in order to assist in showing the difference between background noise and turbine noise. 5dB was chosen as this is regularly used to indicate a significant change in noise level and noise limit values are often based on turbine noise not exceeding 5dB above background noise levels.

Figure 4.19(a) Predicted noise at 5m/s (non-sheltered locations)

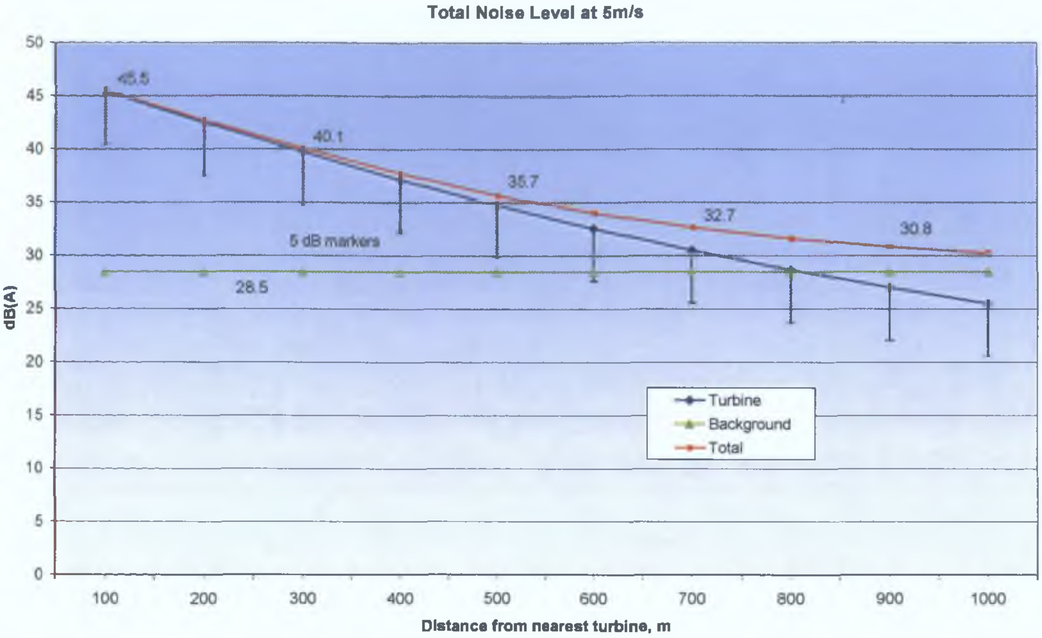


Figure 4.19(b) Predicted noise at 5m/s (sheltered locations)

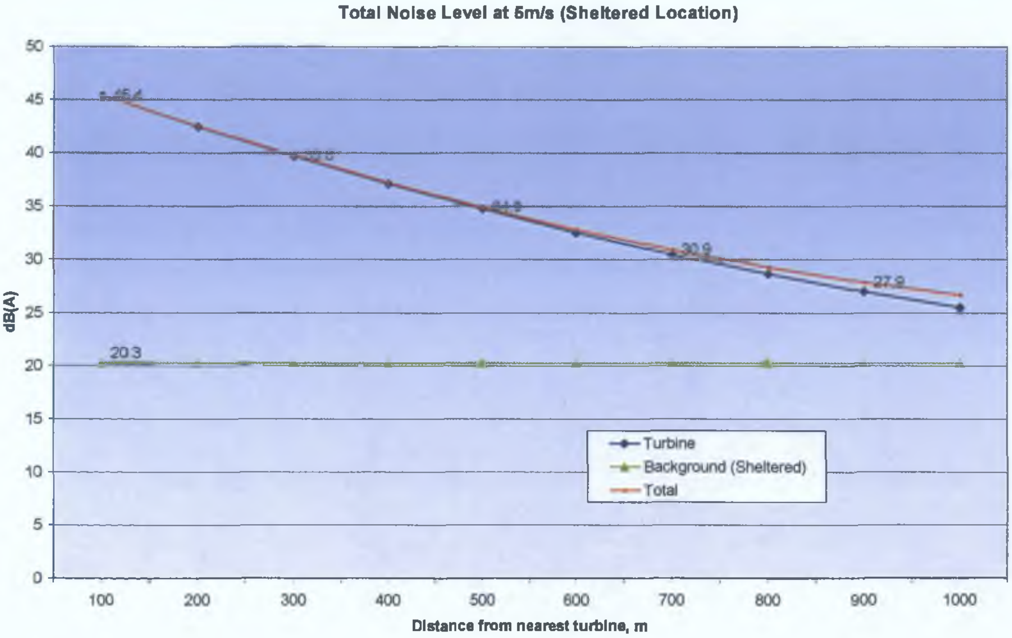


Table 4.9 Predicted Noise Levels at 5m/s

Distance From Nearest Turbine	Turbine Noise, dB(A)	+ Background Noise of 28.5 dB(A)	+ Background Noise 20.3 dB(A)
100	45.4	45.5	45.5
200	42.5	42.7	42.5
300	39.8	40.1	39.8
400	37.2	37.7	37.3
500	34.8	35.7	34.9
600	32.6	34.0	32.8
700	30.6	32.7	30.9
800	28.7	31.6	29.3
900	27.0	30.8	27.9
1000	25.5	30.3	26.7

A comparison of predicted noise levels against common noise limits is made:

At 5 m/s wind speed, turbine noise is less than 40dB(A) at distances greater than 300m. The difference between turbine noise and background noise will however give a better indication as to whether noise nuisance is likely. For exposed areas at a distance of 500m or greater there is at least a 5dB difference between turbine and background noise thus sufficient masking of noise is anticipated (see Figure 4.19(a)). For sheltered areas however, there may be insufficient masking at distances of 1km (as shown in Figure 4.19(b)).

Figure 4.20(a) Predicted noise at 10m/s (non-sheltered locations)

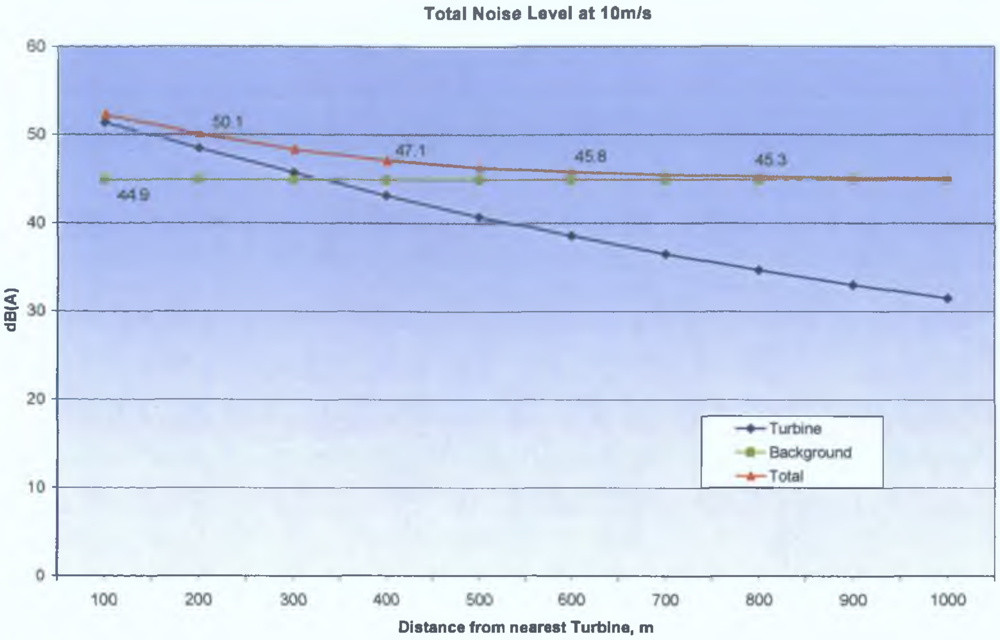


Figure 4.20(b) Predicted noise at 10m/s (sheltered locations)

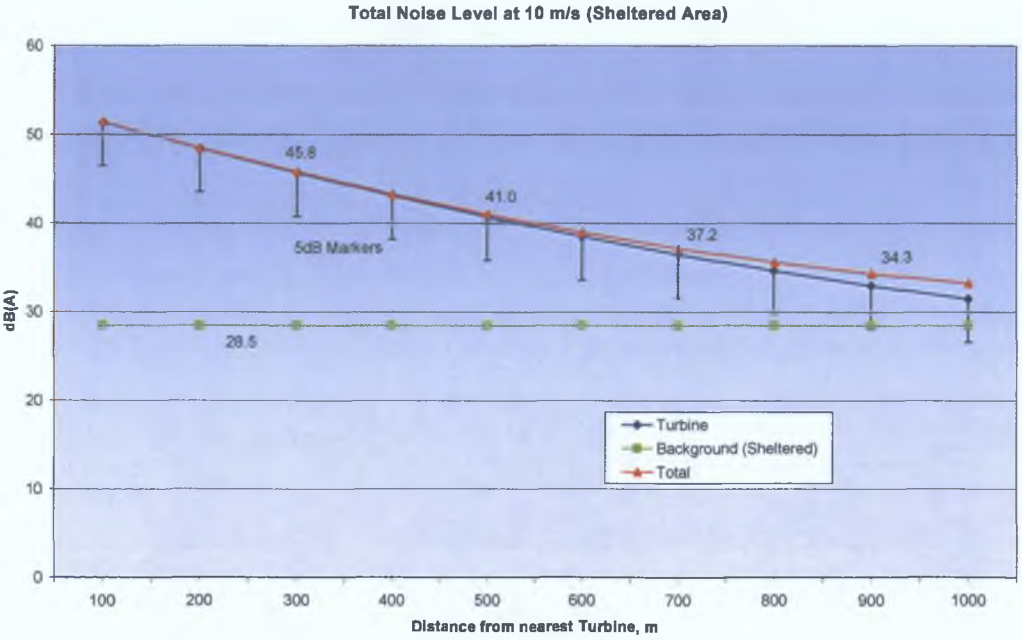


Table 4.10 Predicted Noise Levels at 10m/s

Distance From Nearest Turbine, m	Turbine Noise, dB(A)	+ Background Noise of 44.9 dB(A)	+ Background Noise 28.5 dB(A)
100	51.4	52.3	51.5
200	48.5	50.1	48.6
300	45.8	48.4	45.8
400	43.2	47.1	43.3
500	40.8	46.3	41.0
600	38.6	45.8	39.0
700	36.6	45.5	37.2
800	34.7	45.3	35.6
900	33.0	45.2	34.3
1000	31.5	45.1	33.3

At 10m/s wind speed, turbine noise is less than 40dB(A) at distances greater than 550m. For exposed areas, as shown in Figure 4.20(a), a 5dB difference between turbine and background noise will be achieved at distances of only 150 to 200m. In sheltered locations, this margin may be exceeded at up to 900m distance but in general, it is expected that background noise levels will be higher than 28.5 dB as chosen in this example and therefore it is unlikely that distances above 900m between dwellings will be required.

To summarise, noise levels are generally expected to be within acceptable range at distances of 550m or less, but in sheltered locations, the absence of sufficient background noise may lead to noise nuisance at up to 1km distance. Tonal noise (as dealt with in Section 4.4) is also more likely in sheltered locations especially for tonal components at low frequencies which exhibit less atmospheric attenuation. The presence of trees or barriers may be responsible for low wind speed at sheltered downwind locations and thus low background noise levels. Although trees may provide some attenuation of turbine noise this will generally be observed at higher frequencies and thus lower frequency noise is likely to dominate.

In practice, to accurately assess noise levels in sheltered locations, simultaneous measurement of noise (L_{90}) and wind speed should be conducted at the wind farm site and also at the sheltered site. This should be done for baseline studies to allow a full impact assessment and for studies when the wind farm is operational.

4.4.2 Current Practice and Future Trends

In planning applications for a wind farm development, noise modelling to predict the potential noise impact is typically conducted at two wind speeds (similar to the above example). This is normally only suitable however, for single speed or dual speed turbines as noise generally increases quite linearly with wind speed up to a maximum point, beyond which noise levels are relatively constant. Multi-speed turbines can have much more complicated noise profiles and often have non-linear noise to wind relationships. In order to assess the impacts of these turbine types, noise modelling needs to be conducted over a much wider range of wind speeds normally from the cut-in point up to the maximum noise generating wind speed.

Turbine hub height is another important factor to consider when predicting noise impact. Increasing hub height will place the turbine in areas of much higher wind speeds (less influenced by ground shear) whereby the cut in point of 4m/s at the elevated hub height will correspond with much lower ground level wind speeds. This will lead to turbine start – up in situations where there is very little background noise at ground level to mask the effects.

Predicted noise level is thus dependent on a wide number of variables depending on turbine type, height and site-specific factors such as roughness, topography and meteorological influences. Nowadays, with the wide range of turbine types and specifications it will be necessary for more detailed prediction modelling under clearly defined conditions for a potential development.

Multi-speed turbines do not have a linear noise-to-wind speed relationship and thus modelling will need to be done at all relevant wind speeds. It is essential, particularly for higher hub heights, that a clear distinction is made between the reference heights to which wind speed and noise specification data relate. Wind shear calculations will allow all data to be referenced to a single reference height. A 10m reference height is considered suitable in that it can easily be related to both hub height and ground level conditions when dealing with wind speed and noise level data.

Different noise modelling software packages can vary quite significantly in their noise level predictions. A number of relevant standards that are referenced in varying degrees include ISO 9613, ISO 3744, ISO 3746 and ISO 8297. Much work has been done in Europe to harmonise noise prediction methods as driven by the environmental noise directive 2002/49/EC. Wind turbine noise prediction is quite individual and requires standardisation in itself. Normally noise monitoring and modelling calculations are based on low to moderate wind speeds but for wind turbine noise modelling, much higher wind speeds will be relevant. Meteorological correction for downwind propagation is accounted for in ISO 9613 but only for "*wind speed between approximately 1m/s and 5m/s at a height of 3m to 11m above ground.*" Wind directional noise gradients that are observed at higher wind speeds (as for wind farms) are not well accounted for and this may lead to large deviations from predicted noise levels using standard noise modelling prediction methods.

Wind shear calculations used in earlier examples to calculate wind speeds at different heights, only relate to average conditions based on a roughness length of 0.05. Roughness lengths vary from site to site and must be adjusted accordingly to suit specific conditions(see Chapter 2 Section 5.

Standard wind shear formulae only hold true under neutral atmospheric conditions, with lapse rate defined by an approximate 1^{o}C drop per 100m increase in altitude. Conditions can be very variable in practice depending on day/night or time of year; on a cool clear night, temperature gradients may be reversed due to radiative surface cooling leading to stable conditions, extreme cases of which cause inversions. This can lead to much higher wind speeds at hub height (and thus increased sound power level) with lower relative winds at ground level and thus lower masking noise at the receiver. The effects can become very significant for high hub heights as the atmospheric conditions between the source (hub height) and the receiver can be very changeable. Refraction of sound waves due to wind and temperature gradients can cause very significant increase in noise towards the receiver and these phenomena are poorly accounted for in prediction models.

4.5 REVIEW OF EIS FILES

4.5.1 Summary Tables

Under Irish legislation, an EIS is required for wind farm development having more than 5 turbines or an output greater than 5MW. An EIS is often also required for sub-threshold developments in the vicinity of an existing wind farm due to cumulative impacts [EIA 1999].

Results of the file review are summarised in Table 4.11 (a) and (b) and a brief description of assessment criteria and acronyms are described below.

Measurement Interval and Measurement Duration: Measurement interval is usually between 5 minutes and 1 hour, it is the time taken for each unit measurement. Measurement duration refers to the time, generally in hours or days, over which measurements were taken.

NSR = Noise Sensitive Receptor, generally refers to an occupied dwelling, the boundary of a neighbouring site or community building or amenity area.

Noise at Site / at NSR: Noise measurement may be conducted either on the (proposed) wind farm site or in the vicinity of an NSR.

Wind at Site / at NSR: Wind measurement may be conducted at the same points as noise measurement. Wind speeds may vary considerably between upland locations on site and sheltered locations in the vicinity of an NSR.

Model: Indicates whether or not noise modelling was conducted.

Wind and Reference Height: The specific wind speed and corresponding reference measurement height. Wind speeds will vary considerably between ground level and hub height and therefore a clear distinction should be made between the two.

Noise vs Wind: In order to determine the change in noise level over a range of wind speeds, both are plotted against each other and regression analysis is used to calculate an average relationship between the two. The slope of the line will give information on the noise increase in dB per m/s wind speed.

Assessment Basis: Assessment of baseline results and prediction modelling is normally based on published guidance documents or reference standards. The major ones are included below:

IPI = Irish Planning Institute
DoE = Department of the Environment
EPA criteria = standard noise limit criteria of 45dB(A) for night time abd 55dB(A) for day time
DTI/ETSU = Department of Trade and Industry/Energy Technology Support Unit Working Group

NS = Not Specified
NM = Not Measured
HH = Hub Height
Gen & Ref (when referring to windspeed):
    Gen = General wind speed observations (eg windy, calm)
    Ref = Reference weather data from nearby meteorological stations

Table 4.11 (a) EIS Review Summary

Site and Planning Ref. No	BASELINE SURVEY						PREDICTION METHODS			ASSESSMENT BASIS
	Meas. interval	Meas. duration	Noise at site	Noise at NSR	Wind at site	Wind at NSR	Model	Wind and Reference Height	Noise vs Wind	
Barraboy, Cork, 99/5076	NM	NM	NM	NM	NM	NM	Yes	8m/s at HH	No	DoE 1996
Coomleagh, Cork, 99/5557	NM	NM	NM	NM	NM	NM	Yes	5m/s & 8m/s at HH or 10m (used interchangeably)	No	IPI'95 & DoE '96
Milane Hill, Cork, 98/1482	10min	13 days	Yes	Yes	Yes	NS	Yes	3m/s at HH, 8m/s at 10m 10m/s at 10m	Yes	DTI / ETSU
Currabwee, Cork, 98/0680	NM	NM	NM	NM	NM	NM	Yes	NS	No	EPA Criteria
Gneeves, Cork, 99/0616	30min	2 x 24hr	Yes	Yes	Yes	Yes	Yes	5m/s, heights interchanged	Yes	DTI / ETSU
Coolea, Cork, 98/5456	Varied	2 x 24	NS	Yes	Yes	Yes	Yes	5m/s, heights interchanged	Yes	DTI / ETSU
Mullaghmesha, Cork, 98/1166	15min	Short term over 24hrs	NM	Yes	NS	NS	Yes	8m/s, heights interchanged	No	DTI / ETSU
Taurbeg, Cork, 98/1483	10min	2 weeks	Yes	Yes	Yes	NS	Yes	6,8,10m/s at 10m	NS	DTI / ETSU
Lahanaght, Drinagh, Cork 00/0805	NS	NS	NS	NS	NS	NS	Yes	8m/s, heights interchanged	No	EPA Criteria
Ballybane, Cork, 00/4594	NS	Short-term over 1 day	NS	Yes	Gen	Gen	Yes	8m/s at 10m	No	DTI / ETSU
Coomatalin, 00/6380	15min	Short-term over 1 day	Yes	Yes	Gen	Gen	Yes	8m/s at 10m	No	DTI / ETSU
Cappaboy Beg, Kealkill, Cork, 00/6590	15min	35hrs	Yes	Yes	Yes	NS	Calculation based	5m/s, heights interchanged	NS	NS

Table 4.11(b) EIS Review Summary

Site and Planning Ref. No	BASELINE SURVEY						PREDICTION METHODS			ASSESSMENT BASIS
	Meas. interval	Meas. Duration	Noise at site	Noise at NSR	Wind at site	Wind at NSR	Model	Wind and Reference Height	Noise vs Wind	
Boggeragh Mts, Inchamay N., Cork, 01/1248	30min	1 night	Yes	Yes	Gen	Gen	Yes	8m/s at 10m, heights interchanged	No	DoE '96, IPI '95, DTI/ETSU
Ballinagree East, Cork 02/3696	15min	8 days	Yes	Yes	Yes	NS	Yes	4m/s and 8m/s, heights interchanged	Yes	NS
Glanta Commons, Cork, 02/3281	30min day 15min night	24hrs short-term	NS	Yes	Gen	Gen	Yes	8m/s at 10m and various at 2m	General	DoE '96, IPI '95, DTI/ETSU and EPA
Coomacheo, Millstreet, Cork, 03/1997	30min	24hrs	Yes (24hr)	Yes (short-term)	NS	NS	Yes	5m/s & 8m/s at HH	No	IPI 1995
Meentinny, Knockacummer, Cork, 04/8354	15min on site 1hr off site	5 days	Yes	Yes	Yes	Yes	Yes	4m/s & 8m/s at 10m, heights interchanged but notes made to relate to HH	Yes	DoE 2004
Coom, Kerry, 3571/01	NM	NM	NM	NM	NM	NM	Yes	8m/s at HH and 10m. Calculations provided to relate heights.	NS	IPI 1995
Meenacloghspar, Donegal '03	NM	NM	NM	NM	NM	NM	NS	10m/s at 10m, heights interchanged	No	NS
Dunneill, Dromore, Sligo, 8-Aug-03	1hr	2 x 24hr	Yes	Yes	Yes	NS	Yes	8m/s at 10m, heights related by calculation	No	IPI 1995, DoE 1996
Carroward/ Cabragh, Sligo '03	1hr on site 15min at NSRs	6 days	Yes	Yes	Gen* & Ref	Gen & Ref	Yes	4m/s & 8m/s at 10m, heights interchanged	Yes	NS, adequate distance
Shannagh, Kilcar, Donegal, '03	NM	NM	NM	NM	NM	NM	Yes	8m/s, HH assumed		IPI, DoE, adequate distance

4.5.2 Discussion of Findings

A total of 22 EIS files were reviewed according to common comparison criteria in terms of baseline studies, noise prediction and assessment basis. The main points are summarised below.

Baseline Monitoring

- 14 files had baseline data, 6 sites did no monitoring, 2 were not specified;
- Measurement intervals varied between 5 minutes and 1 hour;
- Long term monitoring of 24 hours or greater was conducted at 10 sites, other cases relied on short – term monitoring during one visit to site;
- Wind speed was measured at 7 sites, for other sites no measurements were taken or only short-term and general observations were made.

Prediction and Assessment Basis

- All sites had some form of prediction or calculation;
- Noise vs wind speed correlations were calculated in 6 files;
- In most cases wind-speeds at hub-height were used interchangeably with wind speed at lower ground level. This becomes an issue when attempting to calculate the incremental noise due to wind farm operation. The combination of turbine noise and background noise can only be made when referring to the same wind speed at the same reference height;
- The assessment of impacts usually referred to standard guidance including the recommendations of ETSU, IPI or DoE guidelines.
- Noise modelling was often only conducted at one or two wind speeds and in many cases the height at which these wind speeds are measured is not specified. Modern turbine noise specifications can be complex due to multi speed and pitch control mechanisms and thus will require modelling across a wide range of wind speeds.

In general there was a high degree of inconsistency in the methodologies used. Baseline monitoring surveys tended to be incomplete and assessment methodologies in most cases did not provide useful information to allow accurate prediction of incremental noise impacts.

4.6 REVIEW OF PLANING CONDITIONS

4.6.1 Summary Tables

Details of the file review are summarised in Table 4.12 (a to d) and a brief description of assessment criteria and acronyms are described below.

Noise Limits Fixed or Background Based: Noise limits are usually defined in terms of an absolute fixed noise level which cannot be exceeded, for example 45dB(A), or may be defined in terms existing background noise levels for example a limit of a 5dB increase in background noise may be applied.

Where Limit Applies: A noise limit may be imposed at the boundary of the site or at the nearest sensitive receptor (NSR).

Indices: Noise limits are normally based on the L_{eq} (equivalent continuous noise level) or L_{90} (90th percentile noise level). Summary data as presented in the tables includes the time interval to which the measurement relates (where stated).

Separate Day/Night Limit: separate limits often apply to day and night time measurements. Day time limits are generally based on nuisance potential whereas night time limits tend to be based on sleep disturbance.

Wind speed Reference: Wind turbine noise is largely dependent on wind speed and thus sometimes limits are set at different windspeeds.

Tonal Reference: Penalties are sometimes applied for tonal noise using criteria described in ISO 1996 and BS4142. This normally involves a penalty of 5dB added onto the relevant noise for compliance assessment purposes.

Requirement for Noise Survey (Operational): The requirement for a noise survey is often specified in conditions to assess compliance with prescribed limits.

Basis of Conditions: Most of the conditions are (somewhat) based on published standards and guidance. Observations and comments were made where the source of the guidance was likely.

IPI = Irish Planning Institute "Planning Guidelines for Wind Energy", 1995
Recommended noise limits are 40 dB (A) and 45 dB(A) L_{Aeq}, at a wind speed of 5 and 8m/sec respectively at hub height of nearest machine.

EPA = Environmental Protection Agency.
A standard noise limit criteria of 45dB(A) for night time and 55dB(A) for day time noise level expressed as L_{Aeq}.

ETSU = [ETSU-R-97 (1996)] Recommends that noise from the wind farm should be limited to 5 dB(A) above background, with lower limits of 35–40dBA at the nearest dwellings and up to 45dBA at properties where the owners have an interest in the project. An upper fixed limit of 43 dB(A) for the night-time is also recommended.

Critical wind speed: Normally refers to the wind speed at which the noise from the wind farm is most in excess of ambient noise levels.

Table 4.12 (a) Assessment of Planning Conditions

Site and Planning Details	Noise Limit fixed or background –based		Where Limit Applies		Indices		Separate Day/Night Limit	Windspeed Reference	Tonal Ref	Requirement for Noise Survey (Operational)	Basis of Conditions and Comments
	Fixed	B'ground	Boundary	At NSR	Leq	L90					
CORK											
Milane Hill, 98/1482	Yes	-	-	Yes	15min	-	-	40dB at 5m/s 45dB above 10m/s	+5dB	Within 4 months or if excessive	Similar to IPI 1995
Currabwee, 98/0680	Yes	-	Yes	-	15min	-	-	As above	+ 5dB	Within 4 months	Similar to IPI 1995
Gneeves, 99/0616	Yes	-	Yes	-	15min	-	-	As above	+5dB	Within 1 yr, or if excessive	Similar to IPI 1995
Coomatallin, 00/6380	Yes	-	-	Yes	-	43dB	-	-	+ 5dB	Within 1 yr, or if excessive	ETSU, Tonal penalty unclear
	-	Yes +5dB	-	Yes	NS	NS					
Mileeny, Coolea, 02/2552	Yes	-	-	Yes	-	43dB	-	-	+ 5dB	Within 1 yr, or if excessive	ETSU, Tonal penalty unclear
	-	Yes +5dB	-	Yes	NS	NS					
Glentanemacelligott, 02/4283	-	-	-	-	-	-	-	-	-	Within 1 yr	No limits applied
Coomacheo, 03/1997	-	-	-	-	-	-	-	-	-	Within 1 yr or if excessive	Apply BATNEEC vs noise in turbine selection
Castlepook, 03/2263 (Pleanala PL04.205173)	Yes	-	-	Yes	15min	-	-	40dB at 5m/s 45dB above 10m/s	-	Within 1 yr	IPI 1995 (similar), An Bord Pleanala
Kneeves, Terelton, 03/2365 (Pleanala)	Yes	-	-	Yes	-	43dB	-	-	-	Yes	Excerpt from Pleanala report, ETSU reference
Meentinny, Knockacummer, 03/3220 (Pleanala PL04.205254)	Yes	-	Yes	-	15min	-	55dB, 8:00 to 20:00, 45dB at other times	-	+5dB	Within 1 yr, or if excessive	EPA, BS4142
	-	Yes +5dB	-	Yes	15min	-	-	-			

Note: NS = Not Specified, **HH** = Hub Height

Table 4.12 (b) Assessment of Planning Conditions

Site and Planning Details	Noise Limit fixed or background –based		Where Limit Applies		Indices		Separate Day/Night Limit	Windspeed Reference	Tonal Ref	Requirement for Noise Survey (Operational)	Basis of Conditions and Comments
	Fixed	B'ground	Boundary	At NSR	Leq	L90					
Rockhill – extension, 03/6946 (Pleanala 04.207910)	Yes	-	-	Yes	-	43dB	-	-	+5dB	Within 1 year	Varied, BS4142
		Yes +5dB	-	Yes	NS	NS					
Gneeves – extension, 04/188			Yes	-	15min		55dB, 8:00 to 20:00, 45dB at other times	-	-	-	Draft conditions. Background noise defined.*
		Yes +10dB		Yes							
KERRY											
01/390	Yes	-	-	Yes	40dB, 5min	-	-	Critical windspeed	-	Within 6 months	Critical windspeed defined **
Kilgarvan, 02/1241	-	-	-	-	-	-	-	-	-	-	No noise conditions
Coom, Glenowen, 03/3977	Yes	-	-	Yes	At least 15min	-	-	40dB when less than 8m/s or 45dB when above 8m/s (at Hub Ht)	-	-	Windspeed measured at hub height
Beale Hill extension 04/1065	-	-	-	-	-	-	-	-	-	-	No noise conditions added
LIMERICK											
Grouselodge, 02/1857 (Pleanala PL13.203575)	Yes	-	-	Yes	45dB, 5min	-	-	Critical windspeed	-	Within 6 months	Proposed condition (bord pleanala)
03/1343	-	-	-	-	-	-	-	-	-	-	No noise conditions
CLARE											
Booltiagh, 00/567 (Pleanala PL03.120616)	Yes	-	-	Yes	15min	-	-	40dB at 5m/s, 45dB above 10m/s	-	-	Pre operational survey at residences within 500m

Table 4.12 (c) Assessment of Planning Conditions

Site and Planning Details	Noise Limit fixed or background –based		Where Limit Applies		Indices		Separate Day/Night Limit	Windspeed Reference	Tonal Ref	Requirement for Noise Survey (Operational)	Basis of Conditions and Comments
	Fixed	B'ground	Boundary	At NSR	Leq	L90					
Carrawnaweelaun, Kilkee, 00/2417 (Pleanala PL03.131382)	Yes	-	-	Yes	40dB, 5min	-	-	Critical windspeed	-	Within 6 months	Critical windspeed defined **
Furroor, Liscasey, 03/80 (Pleanala PL03.204911)	Yes	-	-	Yes	45dB, 5min	-	-	Critical windspeed	-	Within 6 months	Critical windspeed defined **
Pleanala PL 03.120616	Yes	-	-	Yes	15min	-	-	40dB at 5m/s, 45dB above 10m/s	-	-	IPI 1995 (similar)
GALWAY											
Sonagh Old, 00/3234	Yes	-	-	Yes	45dB, down to 40dB	-	-	-	-	Yes, as agreed with Galway CoCo	45 or 40 dB obscure condition
Keelderry, 00/5248	Yes	-	-	Yes	15min	-	-	40dB at 5m/s, 45dB above 10m/s	-	Yes, as agreed with Galway CoCo	IPI 1995 (similar)
Leitir Gunaid, Na Forbacha, 03/4656	-	-	-	-	-	-	-	-	-	-	No noise conditions – adequate distance
MAYO											
Cuillalea, Kiltimagh, 98/1672	Yes	-	-	Yes	40dB	-	-	Critical windspeed	-	Within 12 months	Not stated if Leq and no time interval given
	-	+5dB for 50% of time		Yes	NS	NS		-			
Corvoderry, 01/2542	Yes				35 dB 1hr			Between 3 to 8m/s at 10m	no tonal/impulsive	-	Mayo CoCo proposed conditions
Corvoderry, (Pleanala decision)	Yes	-	-	Yes	40dB, 5min	-	-	Critical windspeed	-	Within 6 months	Critical windspeed defined **

Table 4.12 (d) Assessment of Planning Conditions

Site and Planning Ref. No	Noise Limit fixed or background –based		Where Limit Applies		Indices		Separate Day/Night Limit	Windspeed Reference	Tonal Ref.	Requirement for Noise Survey (Operational)	Basis of Conditions and Comments
	Fixed	B'ground	Boundary	At NSR	L_{eq}	L_{90}					
Raheen barr	Yes	-	-	Yes	NS	NS	-	40dB at critical w/speed	-	Within 1 yr	Not stated whether L90 or Leq
		+5dB at 50% of time	0	1	NS	NS	0	-			
SLIGO											
03/619	Yes	-	-	Yes	Yes, no interval	-	-	40dB at 5m/s 45dB at 8m/s at Hub Ht.	+5dB	Within 1 yr and every 5yrs over range of weather conds.	IPI 1995 (similar)
ROSCOMMON											
Skrine/Knockmeane 04/103 (Pleanala PL16.208733)	-	-	-	-	-	-	-	-	-	Within 1 yr	No limits imposed
DONEGAL											
03/103 (Pleanala PL05.202743)	Yes	-	-	Yes	40dB, 5min	-	-	Critical windspeed	-	Within 6 months	Critical windspeed defined **
WICKLOW											
01/4273 Cronlea, Upper Shilleagh (Pleanala PL27.125044)	Yes	-	-	Yes	15min	-	-	40dB at 5m/s, 45dB above 10m/s	-	Ongoing at residences within 600m	IPI 1995 (similar)
WEXFORD											
00/3983 Riesk, E.D. Kilmore (Pleanala PL26.124447	Yes	-	-	Yes	15min	-	-	40dB at 5m/s, 45dB above 10m/s	-	Pre- Noise survey and proposed mitigation report	IPI 1995 (similar)

4.6.2 Discussion of Findings

Planning conditions from 33 different sites throughout Ireland were reviewed during the course of this study. The primary observations include:

- When wind speeds are mentioned, the limit does not state at which height the wind speed is to be measured at;
- In some cases, wind speed at hub height is mentioned. This is unsuitable as a general condition as hub heights vary and thus wind speeds are not standardised;
- L_{eq} is often used as the measurement basis. This can be highly variable and influence by external sources and thus the L_{90} is considered more appropriate. L_{90} is also more suitable in determining the specific contribution of turbine noise against natural background noise.
- Tonal penalties of 5dB are commonly stated in conditions. These are derived from recommendations of BS4142 and ISO 1996 and may be somewhat severe in low noise environments.
- Noise limits seem to follow available published guidance and as understanding grows, the condition requirements seem to be improving.
- Conditions suggested by planning authorities seem to vary somewhat from region to region but conditions imposed by An Bord Pleanála tend to be more standardised.

In general, noise conditions seem to be quite “loosely” stated and were also found in places not to be very well enforced. Poorly stated noise conditions can be open to interpretation and therefore pose problems for all parties involved in that accurate compliance assessment is difficult and developers will be unsure as to what standard is acceptable.

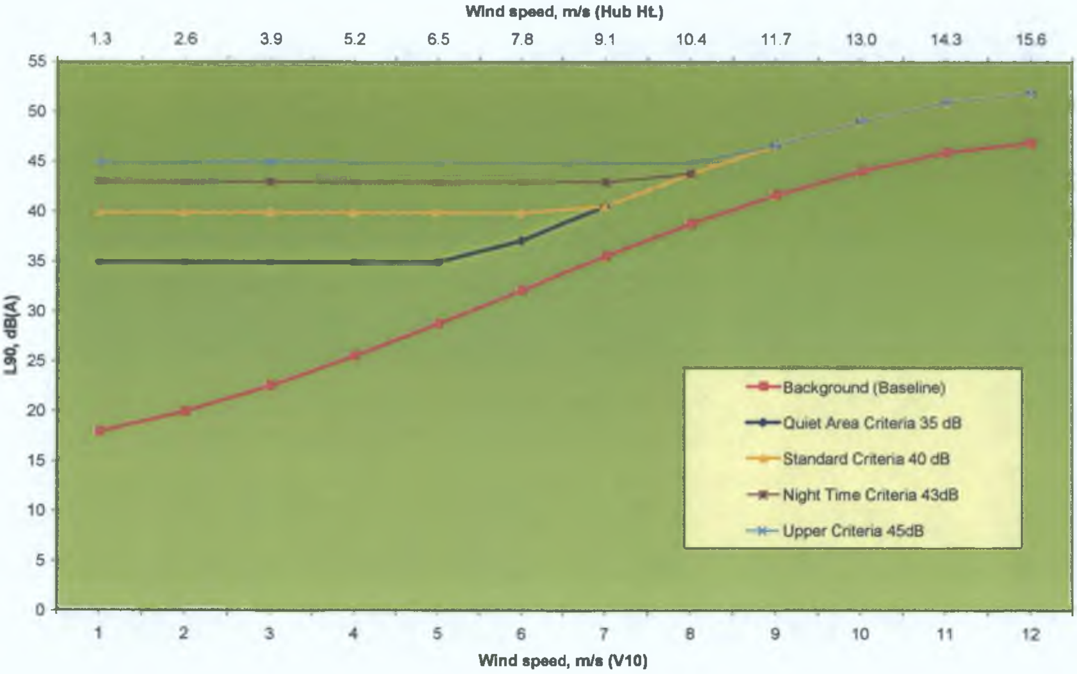
4.7 NOISE LIMITS

4.7.1 Standard Noise Limits

Noise limits are normally specified under the conditions of an approved development. This section examines typical noise limits that may be applied, with reference to published guidance and discusses a number of actual prescribed noise conditions for developments in Ireland. [IPI 1995], [DOE 1996], [ETSU-R-97 (1996)], [DoEHLG, 2004a]

Proposed noise limits as recommended by the ETSU report and the DoEHLG under various conditions are plotted in Figure 4.21. Limits are compared against indicative background noise levels as determined from average baseline L_{90} values Section 4.1. A noise limit of 5dB(A) above baseline levels is plotted together with common fixed limits of 35, 40 and 45dB. Reference heights for 10m and a hub height of 50m are both included on the graph.

Figure 4.21 Proposed Noise Limits



A general limit of 5dB above background is considered reasonable except at low wind speeds (with corresponding low background noise levels). A limit of 35dB is exceptional and is reserved only for very quiet areas. In any case, this limit may only be applicable when wind speeds (V_{10}) are less than 5m/s, the corresponding wind speed at Hub Height (HH) is approximately 6.5 m/s(based on roughness length 0.05m and HH = 50m). As seen from the graph, background noise is approaching 35dB at this wind speed and thus the criteria based on a 5dB noise increase will be more applicable at this point.

Using similar reasoning, the following can be stated:

40 dB limit – only appropriate when $V_{10} \leq 6.5$m/s (or $V_{HH} \leq 8.5$m/s).
43 dB limit – only appropriate when $V_{10} \leq 7.8$m/s (or $V_{HH} \leq 10$m/s).
45 dB limit – only appropriate when $V_{10} \leq 8.5$m/s (or $V_{HH} \leq 11$m/s).

Beyond the stated wind speeds, background noise will be sufficiently high and a noise limit based on a 5dB increase in background noise will be more appropriate. Note the wind speeds at hub height quoted refer to a hub height of 50m and a roughness length of 0.05m, these parameters will be site specific and therefore it is better to reference everything to a 10m standard height.

The Irish Planning Institute Limits are based on L_{eq} levels and referenced to wind speeds at hub height. L_{eq} noise levels are often highly variable and from earlier measurements tend to be greater than L_{90} figures by an average of approximately 5dB at moderate wind speeds, in the absence of any major external influences apart from wind induced noise. Hub heights vary from site to site, generally ranging between 45m to 80m or more and thus would be considered an unsuitable reference on which to base a general limit.

4.7.2 Noise Limit Examples

A comprehensive review of noise limits in Ireland was conducted and a summary of findings is contained in Table 4.12. A number of examples are selected and discussed.

Condition 1

"Noise levels emanating from the proposed development when measured at the nearest inhabited dwelling shall not exceed 40 dBA (15 minute L_{eq}) at a wind speed of 5 m/s and 45 dBA (15 minute L_{eq}) at a wind speed in excess of 10 m/s."

- This limit does not state at which height the wind speed is to be measured at therefore is open to interpretation;
- L_{eq} values can be highly variable and the use of L_{eq} instead of L_{90} makes it difficult to differentiate between wind farm noise and background noise when conducting a compliance survey;
- At wind speeds in excess of 10m/s the natural background L_{eq} noise level is anticipated to be in excess of 45dB even without a contribution from the wind farm.

Condition 2

"The noise level due to site operations measured at any occupied dwelling shall not exceed an L_{Aeq} of 35 dB (A) when measured over one hour. There shall be no tonal or impulsive qualities in the noise when measured in accordance with current Environment Protection Agency Guidelines for noise measurement. Measurements shall be taken at a wind speed of between 3m/s and 8m/s and at a height of 10 metres."

- This is extremely restrictive and not practical, background noise is anticipated to be substantially higher than the limit even at lower wind speeds. This condition was overturned by an Bord Pleanála and the following was prescribed:

Condition 3

"At the critical wind speed (that is, at the speed at which the noise of the wind turbines and blades is most in excess of ambient noise levels), the noise from the proposed development shall not, when measured externally at the nearest occupied house, exceed 40 dB(A) L_{eq} when measured over any five minute period."

- L_{eq} is considered unsuitable by the author for assessing noise levels as it is highly affected by short term noise from sources external to the wind farm. The use of a five minute measurement period makes it easier to conduct monitoring free of external influences but is not practical for compliance assessment over longer time intervals;
- The critical wind speed based on the above definition should, in general, be taken to coincide with turbine start –up cut point (based on earlier measurement results). The differences between L_{90} and L_{eq} were seen to not be as substantial at lower wind speed;
- This limit only relates to a single wind speed and doesn't specify controls over any other range of conditions.

Condition 4

"After the wind turbines are commissioned the developer shall arrange for a noise monitoring programme to determine the increase in ambient noise levels due to the turbines operation. The noise monitoring is to be carried out at the 2 nearest dwellings"..... "If at the end of the monitoring period, the conclusion is that the increase in noise levels due to the wind turbines causes an ambient noise level of 45dB(A) or more, then remedial measures shall be put in place to reduce the noise to a level of 40 dB(A) at these sites."

- Unclear whether limit refers to L_{eq} or L_{90};
- An increase in noise levels causing a noise level of 45dB as stated above would suggest a scenario whereby if background noise levels were 42dB, a turbine noise level of 42dB would be permitted (combining decibels 42dB + 42dB = 45dB);

- Another scenario for a low background noise level of 35dB, a turbine contribution in excess of 44dB would still result in an overall noise level less than 45dB (35dB + 44.5dB ≅ 45dB);
- The final sentence of the above condition is somewhat unusual whereby in the case where an ambient noise level exceeds 45dB is found, measures must be enforced to reduce noise level to 40dB. This could suggest that a noise level of 44.9 dB is acceptable but if 45dB is exceeded a tightening of the limit to 40dB would occur;
- No adequate provision is made for wind speeds or existing background noise. At higher wind speeds ambient noise will naturally be in the range of 45dB

Conditions are not applied in a consistent manner throughout the country. In many cases, conditions included the requirement for a noise compliance survey to be conducted, typically in the first year of operation. This does not appear to be strictly enforced in many of the cases studied. The vast majority of conditions reviewed were not clearly defined and were often open to interpretation.

4.7.3 Financial Issues relating to Noise Compliance

Control of the speed of rotation and blade pitch angle can assist in reducing noise levels but with corresponding power output loss and thus loss of revenue. Control measures are introduced in Chapter 2.6 and a practical example is given in Appendix II. In the example given, the total cost of curtailing noise levels by 3dB at two selected houses in the vicinity of a wind farm development may result in an overall loss of revenue in excess of €26,000 per annum. When viewed as a percentage of the total financial yield from the turbine (of nearly €250,000) the loss may be justified when balanced against the potential profit when all other factors have been considered.

A reduction in source sound power level of 3dB will lead to a reduction in measured sound pressure level at a receiver position close to the wind farm site. This is a significant noise reduction, on a logarithmic scale it corresponds to a halving of source noise and in rural areas with low background noise it will be particularly important. The cost of achieving this reduced noise level does however point to the importance of setting correct noise limits on a potential development. Unnecessarily stringent limits can impose unwarranted financial burden on a developer in cases where noise may not be a problem. The need for the correct assessment of noise is essential to promote a proper understanding of the issues involved and this will facilitate better judgements to be made by both planning authorities and developers.

5.0 RECOMMENDATIONS AND CONCLUSIONS

This thesis sets out to improve the understanding of wind turbine noise by examining shortfalls in current practice and offering recommendations for improvement. A review of planning files for developments across Ireland provides a good indication of current practice both in terms of impact assessment methodologies and planning conditions imposed. Noise measurement and modelling conducted at baseline and operational sites provides information on the nature of wind farm noise and the specific issues that need to be addressed.

5.1 EIS REVIEWS

The majority of EIS files examined during the course of this study were incomplete in their assessment of noise impacts. Common assessment criteria were based on standards more applicable to industrial applications or traffic. Baseline monitoring data was not adequately dealt with for prediction of likely impacts on the existing environment or for the investigation of suitable noise limits. Assessment criteria did however tend to be based on up to date guidance including the recommendations of ETSU, IPI or DoEHLG guidelines. The findings of this study indicates however that there is a general poor understanding of noise assessment issues relating to wind farm developments from developers to planning authorities and more concise guidance is required. Section 5.2 recommends the issues that need to be addressed for an accurate noise measurement and assessment based on shortfalls in current practice and findings during the course of this study.

5.2 NOISE MEASUREMENT AND ASSESSMENT PROTOCOL

Where low background noise levels exist, the noise climate is particularly vulnerable to influences of anthropogenic origin or meteorological conditions. A number of recommendations are made to ensure that information gathered is accurate and comparable.

5.2.1 Assessment Recommendations

- International standard ISO-1996 provides good general guidance on survey implementation. This standard is not suitable however for measurement at high wind speeds associated with a wind farm development and therefore additional precautions need to be taken.
- Wind (speed and direction) monitoring is essential for all noise measurements. Wind measurement at different reference heights above ground will allow accurate wind profile determination. For baseline monitoring, the L_{90} noise level has been shown to change at a rate of 3 dB/m/s or more. For operational monitoring, the wind speed will be directly related to the turbine sound power level.
- Other meteorological conditions need to be noted due to their influence on noise propagation, including temperature variation, cloud cover, precipitation.
- Observations regarding foliage, evergreens, long grass, blossom and distance from measurement locations need to be noted.
- Baseline and operational surveys ideally should be conducted at the same time of year or similar meteorological conditions in order to facilitate comparison. Conditions will need to be dry and monitoring needs to be conducted over a wide wind speed range above 2m/s and up to 10m/s or greater, if possible.
- L_{A90} measurement values are considered the most useful measurement parameter as they provide a good indication of average noise levels excluding short – term peaks. For operational surveys, wind turbine noise is continuous over the relevant wind speeds and thus can be directly related to L_{A90} values.
- Synchronised noise and wind monitoring should be conducted at an exposed location on site and averaged over approximately 15minute intervals. 10 minute intervals are suggested in the ETSU report on noise from wind farms and also adapted in Irish Draft Guidelines [DoEHLG 2004] and this is considered a suitable interval to allow noise to wind correlations to be made. Wind speeds on site can be used to approximate potential wind speeds at hub height which will be required in calculate potential noise generation.
- Noise monitoring should also be conducted in the vicinity or nearby dwellings or sensitive receptors. For a complete assessment, wind speed data should also be

recorded for these points. This will identify sheltered areas or will provide information on the noise masking potential at each point.

- Frequency monitoring will need to be done to investigate potential tonal noise in an operational survey. Baseline frequency data for the same location will be useful if any existing tonal components are already present.
- Frequency monitoring should be conducted over a range of wind speeds. Locations should be chosen close to the wind farm site and also in areas down wind of the site, particularly in sheltered locations due to low masking potential and vulnerability to tonal influence.
- Flat weighted frequency monitoring is recommended to fully investigate the presence of low frequency tones. A-weighted sound pressure level measurement has shown failings in accounting for low frequency noise. This may be particularly evident when background noise levels are low.
- All the recommendations as listed above apply to both baseline and operational surveys. Frequency monitoring and downwind measurement may not as entirely relevant in baseline studies as an operational study but this information will be necessary to allow all factors relating to noise to be compared afterwards.
- Noise assessment should be conducted up to a distance of 1km from the wind farm site and at noise sensitive locations

5.2.2 Data Handling, Prediction and Assessment

Synchronised baseline noise (L_{90}) data vs wind speed will provide a rate of change of noise level in dB per m/s. Wind speed data should relate to a 10m reference height. This can be determined from power output–to-wind relationships or direct measurement and use of wind shear calculations to relate varying heights to 10m.
Regression analysis of L_{90} vs wind speed is recommended for baseline studies and also for operational wind farm studies in order to differentiate between background noise and wind turbine noise over a range of wind speeds. From experience, 3rd order regression curves give a good representation of expected trends.

For noise prediction, modelling should be conducted based on turbine specification data relating to the change in sound power level with wind speed. The specific predicted noise level at each wind speed can then be assessed in relation to the background noise at each wind speed as determined from baseline measurement. It is essential that all noise data relates to wind speeds at the same reference height (i.e. 10m). Noise prediction modelling may also be done based on turbine specification frequency spectra (as determined by standard IEC 61400-11).

The specific noise prediction principles employed in the software should be clearly stated. Some prediction software only uses simple principles based on attenuation of noise with distance, other software makes a number of corrections including those for attenuation due to atmospheric absorption and ground type. All these corrections can be significant, for example average atmospheric absorption can result in 2dB attenuation over 500m.

Calculation of the influence of meteorological influences is normally only confined to criteria such as that stated in standard ISO 9613-2 relating to downwind propagation of noise. In this, downwind noise levels can be approximated accounting for the influence of moderate wind speeds. Downwind influences on noise levels can be quite complex and not adequately dealt with however in most noise modelling software that is based on ISO standard 9613 or simpler packages..

Atmospheric stability, as related to wind speed, cloud cover and temperature variation can explain altered propagation and refraction of noise towards the receiver due to wind and temperature gradients. For wind turbines, atmospheric stability has a further significance in that it also affects noise generation; on clear nights, lower ground temperatures can alter wind profiles which can lead to higher winds at hub height (thus high sound power level) but lower wind at ground level and thus less background masking effects.

Wind turbine noise has a modulating or beating sound which is produced in each revolution as the blade passes the tower. This makes it particularly discernable from background noise even at when the actual noise level is quite low. Tonal noise also, even though it may only be present in low levels, will cause more of an impact where existing noise is low. Wind farms in Ireland are typically located in upland rural sites with little noise attenuation due to barriers whether natural or man-made.

The average hub height of turbines is continually getting higher in order to be in a region of higher wind speed and therefore higher power output. This has serious implications on noise level in that the start- up point, (normally 4m/s at Hub Height) will correspond with much lower wind speeds at ground level and therefore the wind turbine noise will be imposing on much quieter background conditions (based on wind shear influences)

The Author recommends setting noise limits based on background. An accurate representation of background noise can only be achieved by long term monitoring over a range of weather conditions. Prediction modelling for noise normally doesn't consider an accurate "worst case scenario" as is required for example in air dispersion modelling. Noise limits generally only refer to average levels but in order to be useful, they should be reference to defined weather conditions. Further work needs to be done to examine the full implications of meteorological effects on turbine noise level beyond the methods currently used in noise prediction.

With a wide number of variables to consider, including turbine specification and local conditions, noise assessment is shown to be very individual to each case. This will need to be considered when deciding on appropriate noise limits.

5.3 PLANNING CONDITIONS & NOISE LIMITS

Setting of inappropriate noise limits can have severe financial implications on the developer if too stringent, or can be the cause for extreme annoyance for people living near a wind farm if too lenient. Current trends of higher hub heights and variable speed machines make wind turbine noise less predictable than before and thus general limits relating to noise level or separation distance from wind farms are not as useful as they may have been before.

From discussions with planning officers and developers there is a need for simple, clearly stated noise conditions that are consistent and accurate in their purpose. The following recommendations are thus made:

- L_{A90} is considered as a suitable descriptor on which to base compliance. The ETSU report recommends L_{A90} over a 10 minute interval. This interval is seen as useful to allow a large number of short-term compliance checks. Long term monitoring however is recommended for both baseline and operational surveys in order to gather sufficient statistical data and thus longer measurement intervals may be more appropriate for data handling purposes.
- A general noise limit maintaining a 5dB increase in background noise is considered suitable based on L_{A90} measurements. Wind turbines however, at start-up point, produce likely increases of 10 to 20 dB in background noise close to the site and thus a fixed limit of 40dB (or less) is necessary to account for lower wind speeds. Setting noise limits much lower than this are impractical as they will be very difficult to achieve and also, ambient noise levels in the absence of the wind farm (as per the baseline study) are very variable at low wind speeds and thus difficult to determine a true average. A lower fixed limit should be imposed to preserve very quiet areas and in time, may extend to all cases as turbine acoustic design improves.
- Different night and day time limits may seem impractical in that wind turbines will operate based on wind speed regardless of day and night. Night limits are important however to prevent sleep disturbance especially when turbine noise

generation can actually be higher at night time (due to atmospheric stability factors) as described earlier together with less masking noise.

The limits suggested agree quite well with guidance as provided for in ETSU-R-97 and the new DoEHLG guidelines but the manner in which compliance is assessed needs to be clarified:

- Limits need to address compliance over a range of individual wind speeds (common practice is to examine only one or two relevant wind speeds). This will be required to account for the changeable noise profiles of newer multi-speed turbines.
- Wind speed data will need to be directly related to noise measurements during the same measurement interval.
- Wind speeds should relate to a 10m reference height. The most accurate method of determining wind speed is from the measurement of the electric power output compared to specific turbine Power vs Wind speed curves (according to standard IEC 61400-12). Wind shear calculations can then be used to convert these to a 10m reference height which is more suitable for standardised reference.
- Wind speed should also be measured at ground level at each noise measurement location to observe localised wind speeds which may be much lower. Ground influences can cause high variation in wind speed.
- Tonal noise needs also to be addressed over a range of wind speeds. At lower wind speeds tonal noise may be less but more noticeable due to low masking background noise. At higher wind speeds the increase in mechanical noise may cause the generation of low frequency tones which may be evident at far distances from the site, especially in sheltered locations. Tonal assessment may need to include flat or linear weighted analysis to accurately determine low frequency noise.
- Standard tonal penalties were originally designed for relatively high noise environments and were also based on L_{eq} values (rather than L_{90} as used here). Varying tonal penalties based on narrow band frequency analysis may be applied but a workable tonal penalty of 2 to 3 dB may be more appropriate.

- Compliance should be measured over a minimum of 24 hours but a longer interval is recommended to account for meteorological variation.

5.4 FINAL COMMENTS

The complete process of noise measurement and assessment needs to be clearly defined and standardised in order that reliable and comparable information is available going forward. At the planning application stage, imposing the requirement for comprehensive studies under defined criteria will provide much of this data while also promoting good practice among developers to explore better noise control measures. A standardised process will also make it much easier for planning authorities to impose accurate and useful controls which will protect nearby dwellings from adverse affects and help preserve the natural soundscape of rural areas where wind farms are normally located.

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Further Reading:

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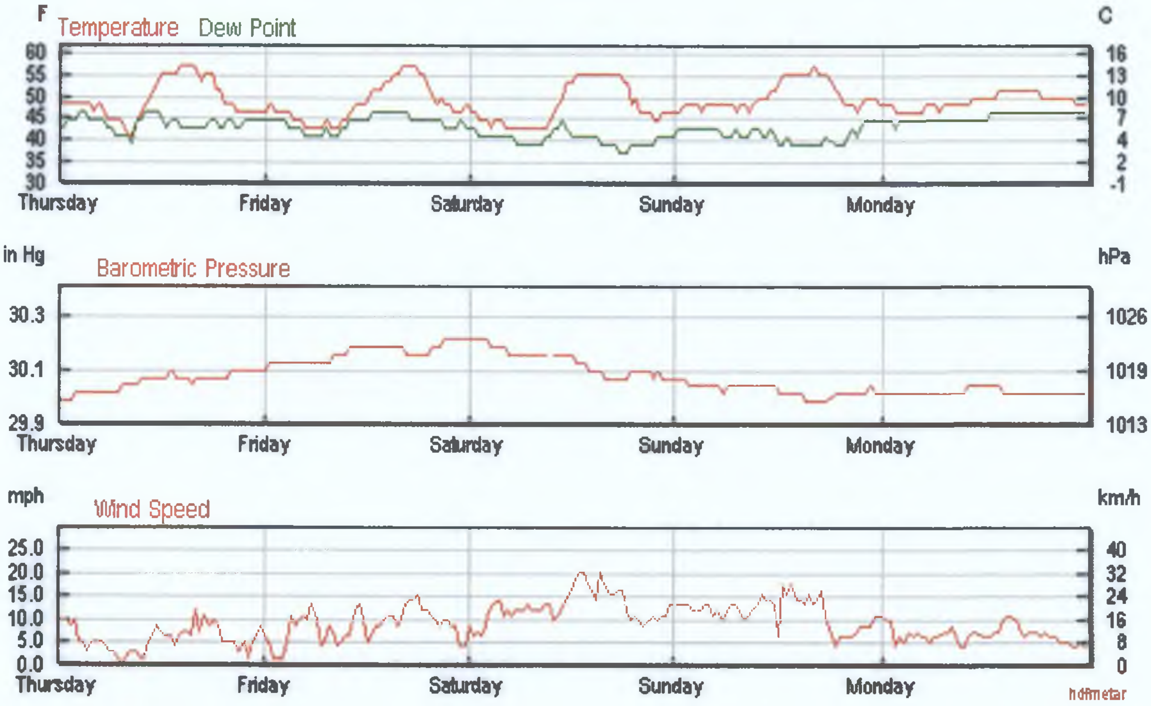
Appendix I Additional Information

Section 1 Additional Information for Monitoring Surveys

Table 1 **Site 2 Baseline Survey - Average Weather Data 7th to 11th October**

Parameter	**Average**
Temperature °C	9.0
Precipitation, cm	0.0
Wind, km/h, (m/s)	14.0, (3.9)
Pressure, hPa	1018

Figure 1 **Site 2 Baseline Survey - Variation in Weather 7th to 11th October**

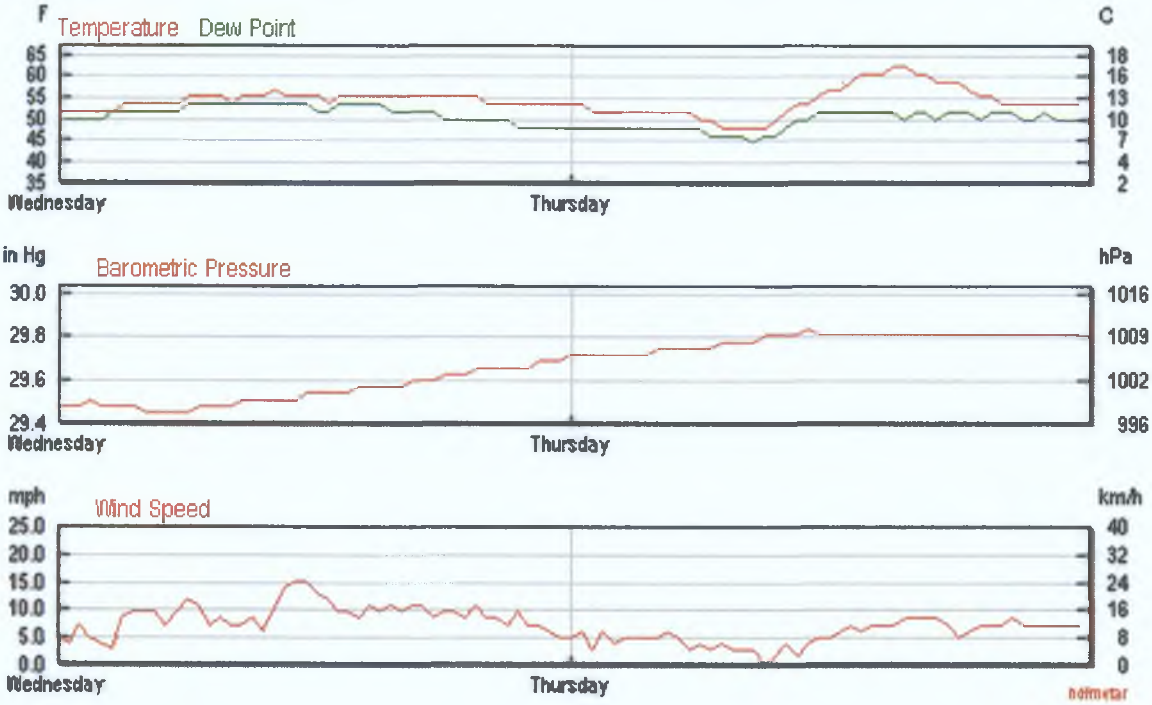


(Source www.wunderground.com)

Table 2 **Site 3 Baseline Survey - Average Weather Data 9th to 10th October**

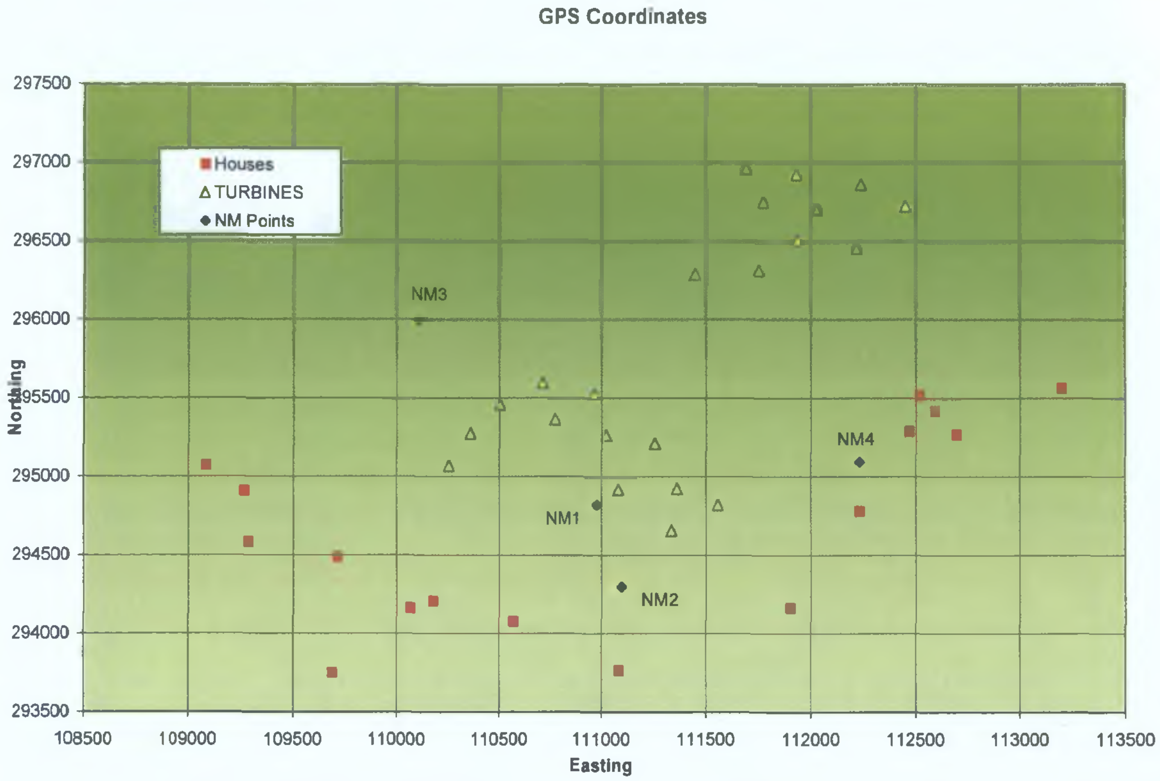
Parameter	Average
Temperature °C	12.0
Precipitation, cm	0.0
Pressure, hPa	1004

Figure 2 **Site 3 Baseline Survey - Weather Data 9th to 10th October**



(Source www.wunderground.com for Shanon Airport)

Figure 3 **Site 1 Operational Survey Layout**

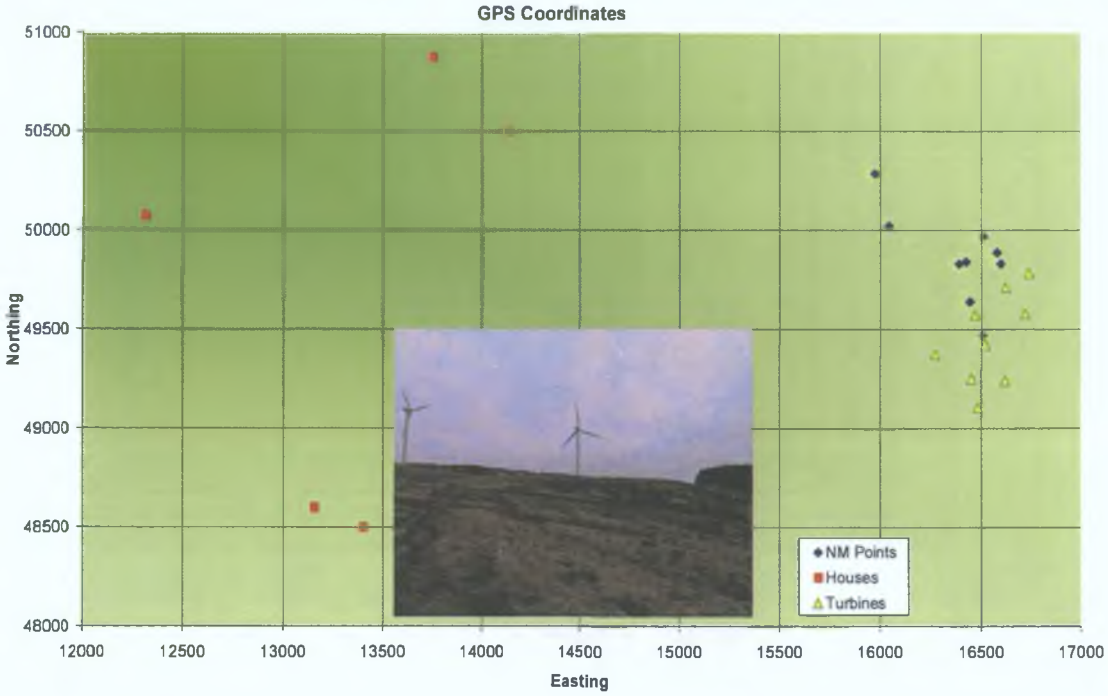


NM = Noise Monitoring Point

Site 1 Operational Survey – Weather conditions

Temperatures varied from a max of 10ºC (approx) during the day to a minimum of 3ºC (approx) at night. The nearest Met Éireann weather station at Belmullet recorded 30.9 mm of rain over 24 hours and 0 sunshine hours. Wind and noise monitoring was conducted over 19 hours on site at NM1.

Figure 4 Site 4 –Operational Survey Layout



Site 4 Operational Survey – Weather conditions

Monitoring was conducted over approximately a half day. The wind was blowing from the South West for the duration of the monitoring survey with only minor deviations in wind direction observed. Only minor variation in atmospheric conditions was observed during the monitoring survey. Average temperatures were approximately 5°C, conditions were cool and breezy with light cloud cover.

Fig 5 Site 5 Operational Survey Layout

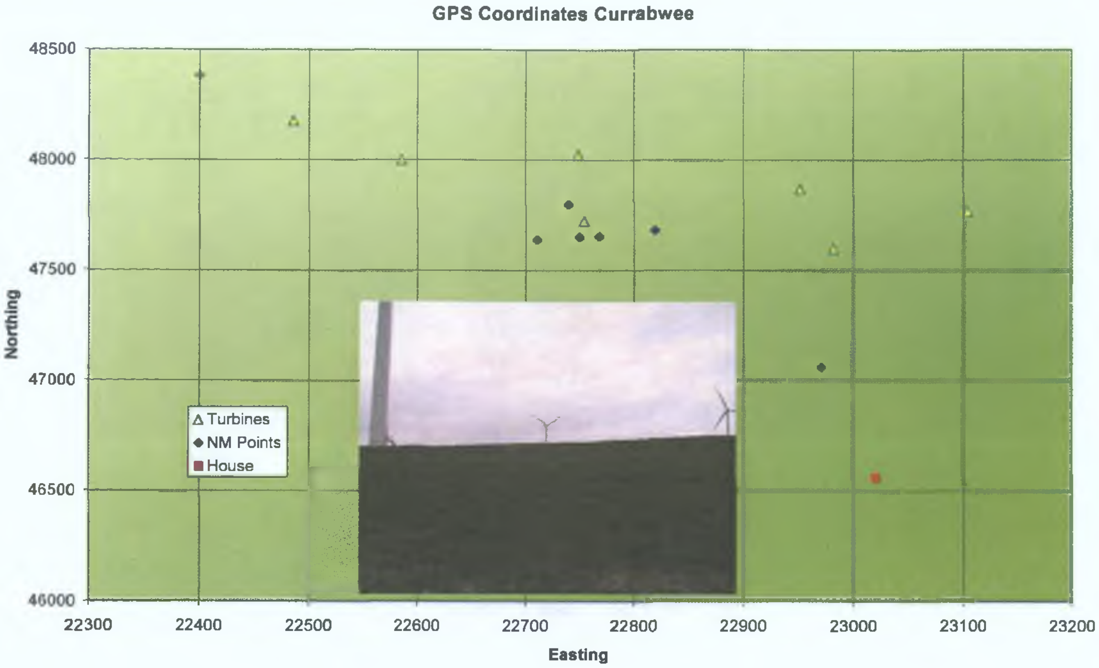
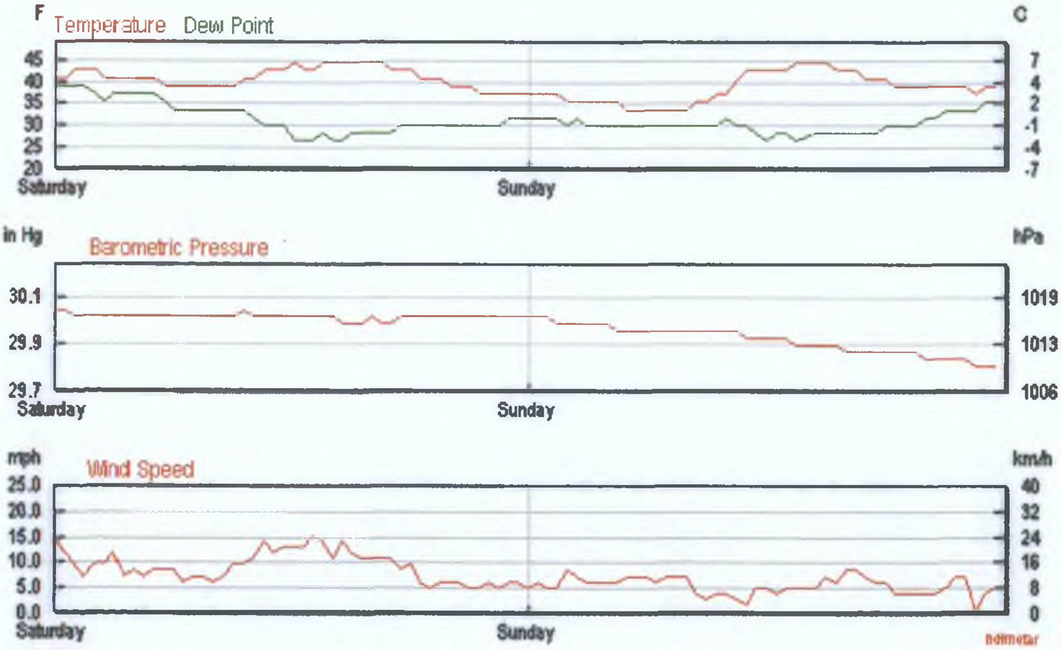


Figure 6 Site 5 Operational Survey - Weather Data



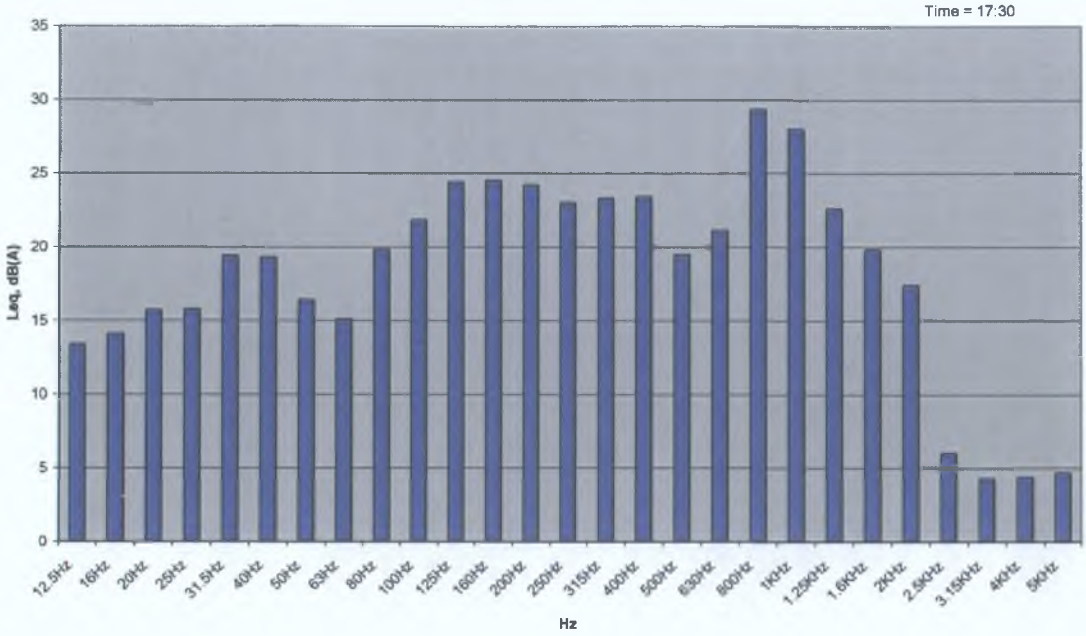
(Source www.wunderground.com for Ballinascarthy)

Section 2 Additional Information for Tonal Asessment

Site 1 Day and Night - Baseline

Figures 7 (a) and (b) show baseline spectra for the same location, but spectrum (a) was conducted at 17:30 during the day under breezy conditions whereas spectrum (b) was conducted at 03:30 during the night when conditions were calm.

Figure 7 (a) Baseline Spectrum –Day time



Site 4 (Milane Hill)

At this site, measurements were taken at a number of locations directly down-wind from the site. The GPS coordinates were recorded and plotted as shown earlier on Figure 4. Four particular locations were chosen for monitoring the change in noise character with distance. The first location was in the middle of the site at a distance of 50 m from the nearest turbine. The other locations are at distances of 123, 282 and 619 from the nearest turbine, all downwind.

Figure 8 **Site 4, Frequency Spectrum for On-Site Location**

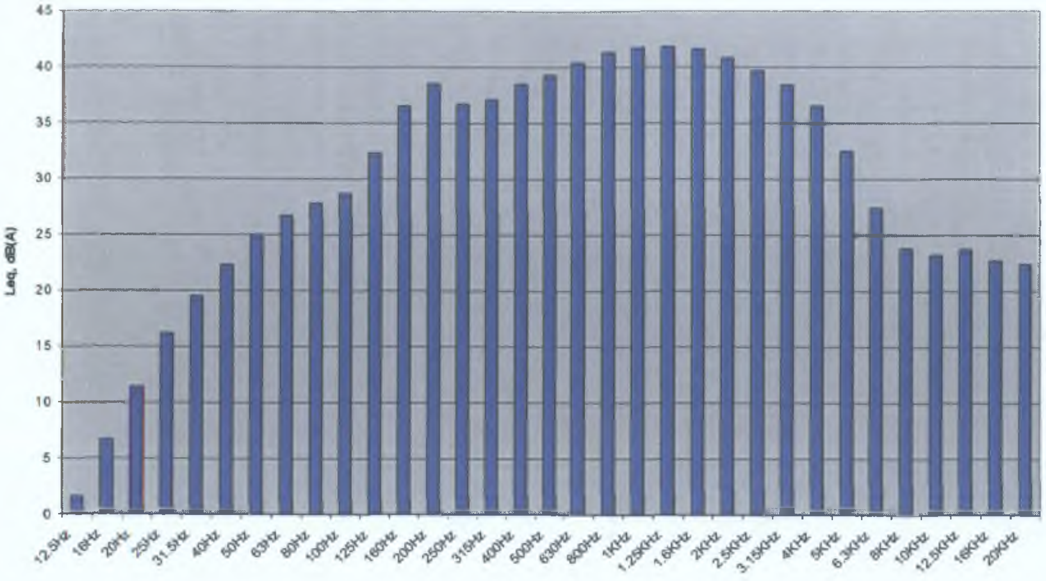
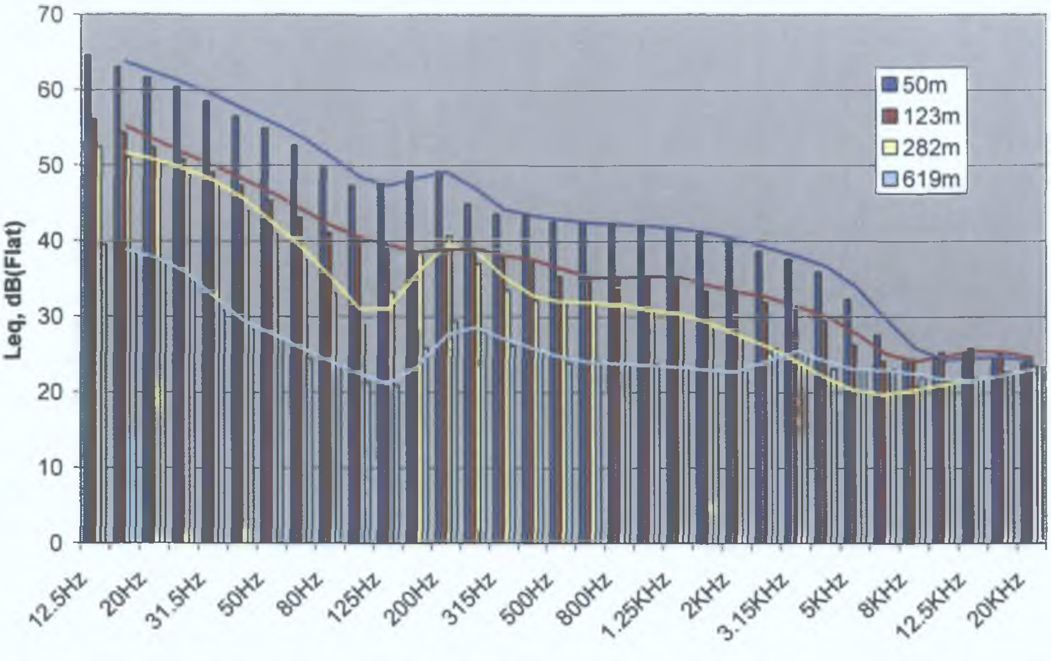


Figure 8 shown a frequency spectrum for measurement at 50 m from the nearest turbine. A broadband curve is observed with maximum values between 1kHz – 2kHz.

No tones are evident on this spectrum, nor were any observed on spectra at other locations. It was observed, at greater distances from the windfarm and at low noise levels that that frequency measurements below 100 Hz were quite erratic. In these low noise environments it was decided that Flat weighting frequency was more appropriate. Figure 9 shows the combined frequency spectra for the four locations on one graph. The bars on the plot show the magnitude of each band for the 4 distances and the trend line added in shown the average change at each distance.

Figure 9 Site 4 - Combined Frequency Spectra (Flat Weighted)



Minor peaks are observed at 160 Hz and 200Hz and it is seen that these are not very well attenuated with distance. A select number of frequencies were examined and plotted on Figures 10(a) and 10(b) for flat weighted and A-weighted spectral analysis.

It must be noted that for these graphs the point monitored in the control monitoring location at the centre of the site is 50m from the nearest turbine but is also highly influenced by all other turbines. Other monitoring locations were taken at defined distances from the nearest perimeter turbine and will have significantly less influence from other turbines. As a result the noise level at the on-site location is highly elevated and is not meant to be compared directly with other monitoring locations.

Figure 10(a) Site 4 - Octave band attenuation with distance (Flat Weighting)

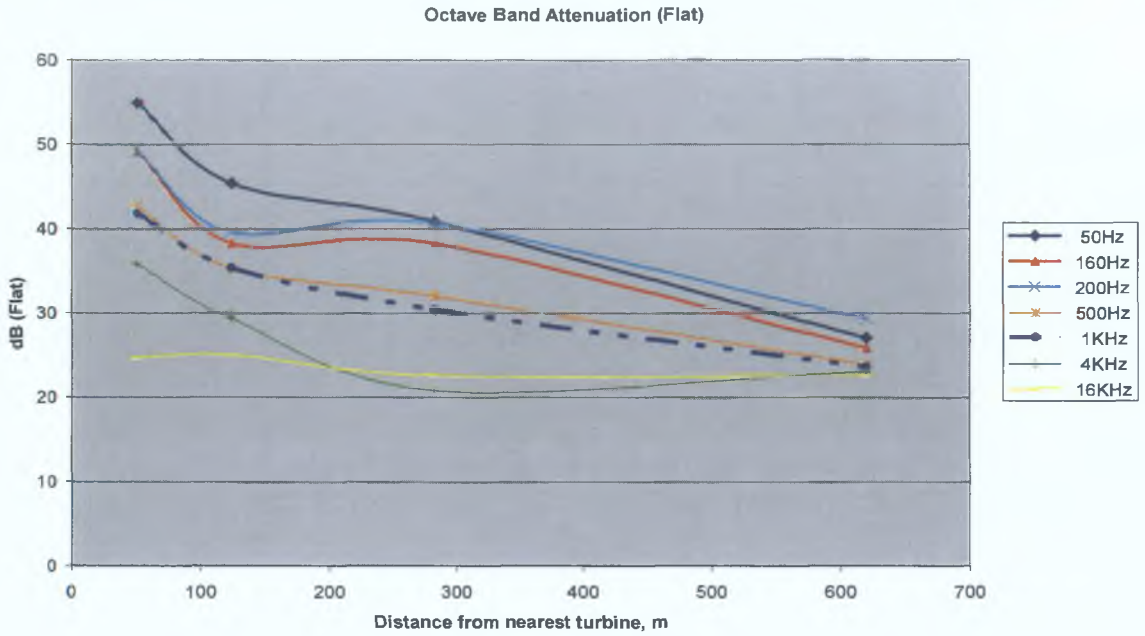
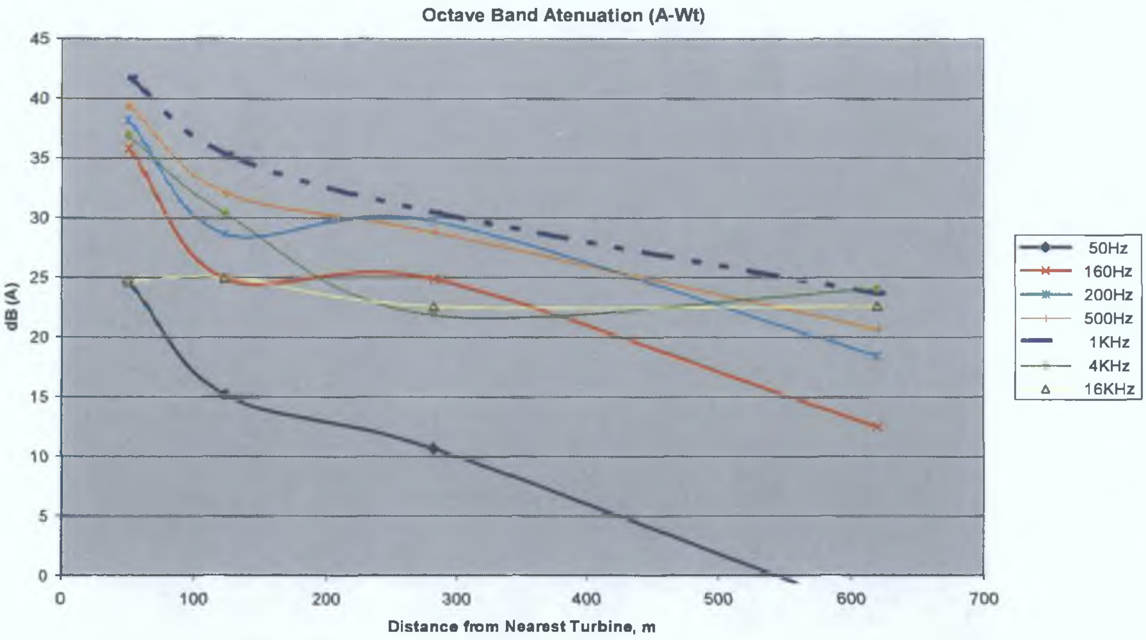


Figure 10(b) Octave band attenuation with distance (A- Weighting)

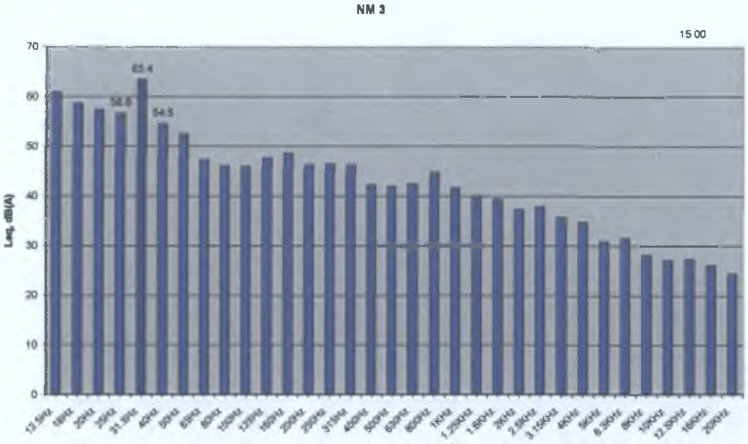


The correction factors to inter – convert between A weighted and Flat – weighted noise levels are given in Chapter 2 Table 2.1. From the graphs, noise peaks are somewhat elevated at 160Hz ad 200Hz and levels at most other frequency bands reduce quite steadily with distance. In the absence of any definite tones it is difficult to ascertain at longer distances what portion of the noise may be attributed directly to the wind farm. The 1kHz line (dotted line in each plot) shows a steady reduction with distance. The theoretical reduction of each frequency band can be calculated based on figures in ISO 9613-1, some are listed in Chapter 2 Table 2.5.

Calculation based on attenuation due to distance which will be approximately 6dB per doubling of distance. Theoretical atmospheric absorption is approximated at 3.6dB per kilometre from figures in ISO 1996-1 centering around 1kHz at 10°C and 80% relative humidity. Higher frequency bands are normally attenuated to a higher degree but in the above plots are not showing any significant reduction with distance. This may indicate that noise at these particular frequencies is not directly attributed to the wind farm. The frequency bands at 160 or 200Hz appear to be related to turbine noise and these may pose a tonal problem if present individually at different windspeeds. Atmospheric attenuation has less of an influence on lower frequency bands and thus they may become evident at longer distances downwind in locations where natural background noise is low.

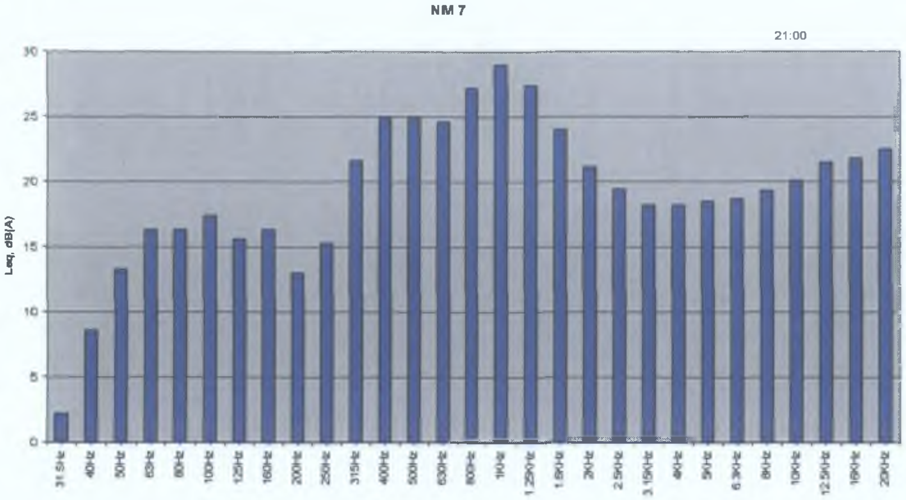
Site 5 (Currabwee)

Figure 11 **Site 5 On–Site Location, wind speed= 5.9 m/s**



At this location on site, a broad noise spectrum was observed. A high proportion of the noise is in the lower frequency ranges even when measured using A - weighted filters. A potential tone was observed at 31.5 Hz when the wind speed was at 5.9 m/s. but further monitoring at different wind speeds indicated that this was not always present.

Figure 12 Site 5 - Off–Site Location, wind speed = 5.2m/s



Off site monitoring (away from the noise source) showed a general noise reduction across all frequency bands but particularly in the lower frequency ranges below 200Hz.

Appendix II

Noise Control and Financial Implications

1.0 Noise Control Strategy

Noise control measures have been discussed in Chapter 2.6. Curtailing the operation of turbines at certain wind speeds is a noise control strategy but may lead to significant reduction energy output, with resultant financial implications. In order that efficient curtailment will be undertaken the following methodology is proposed:

Examination of Options

A proposed turbine layout for a new development was mapped in order to yield the maximum power yield. Noise modelling was conducted and it was found that a number of houses would potentially be affected by noise. A number of solutions are explored:

(a) Change the layout of the individual turbines so to allow better separation distance between neighbouring properties. A suitable location must minimise the energy yield loss, must not interfere with wind paths of other turbines and also must not transfer the noise problem to a different location.

(b) Change the turbine type. Some turbines are noisier than others; multi-speed turbines are often not as noisy (at certain wind speeds) as single – speed or dual speed turbines. The choice of turbine must consider the additional costs and suitability based on the particular wind characteristics of the site.

(c) Remove the offending turbine(s) from the layout. In some cases this may make more financial sense, balancing the loss of low energy yield (and revenue) at a new turbine location, the increased capital cost of a “low noise” turbine together with the installation costs of an extra turbine.

1.1 WORKED EXAMPLE

1.1.1 Energy Yield and Noise Reduction

In this example, the turbine layout was slightly changed, limited by land space availability and positioning relative to other turbines. Turbine power output was not significantly changed. Noise modelling results showed that there still remained the possibility of further minor noise disturbance but closer examination suggested that curtailing the operation of the relevant turbines at the relevant wind direction and speed would eliminate the problem.

Newer, variable speed turbines can make it possible to program the turbine to curtail its operation under defined conditions specifically for the chosen location. Altering the pitch of the blades and inducing operation at lower rotor speed will result in lower sound power levels. The energy yield will however also drop however and a 3dB reduction in sound power level may result in an energy drop of 20%, depending on the turbine and the wind speed.

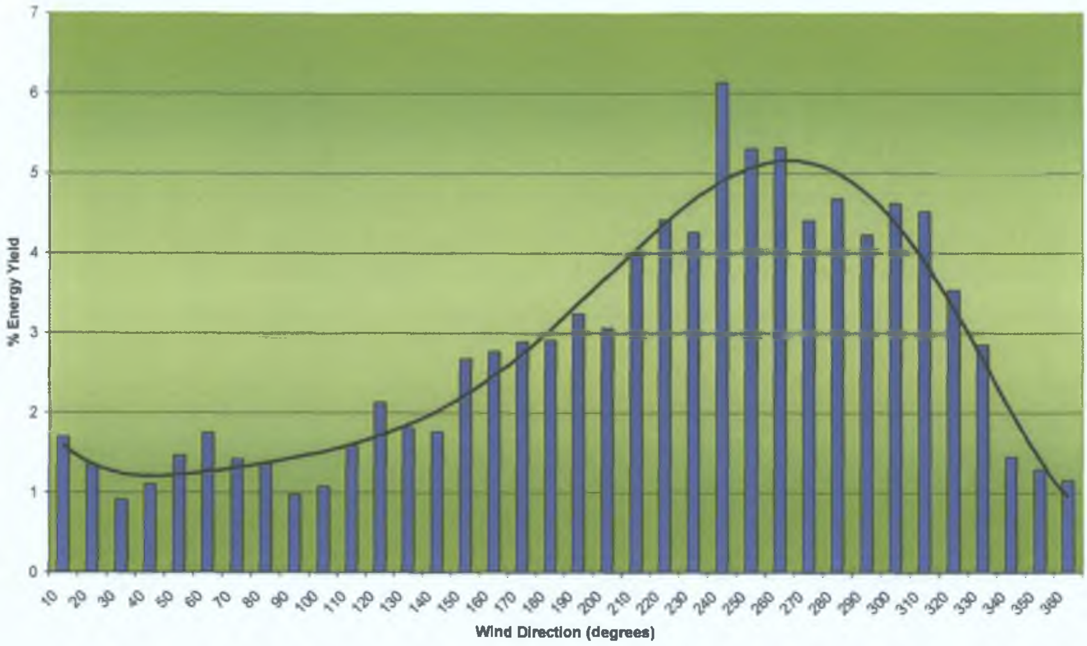
The complete model was run again using the lower sound power levels for the curtailed turbines and the financial implications were calculated. To illustrate the process the following scenario was chosen where two houses were identified with the potential for noise disturbance:

House 1 – situated to the North-East of the site. This will be affected by noise when winds in blowing from the South West.

House 2 – situated to the North West of the site. This will be most affected by winds from the South East.

Wind conditions for the site were recorded over a 12-month period and the potential energy yield for each 10 degree segment was determined.

Figure 1 Energy yield from all wind directions



North = 0°/360° East = 90° South = 180° West = 270°

Figure 1 shows that the predominant wind direction responsible for the maximum energy yield is between 240° to 260°.

Downwind noise propagation is mentioned in ISO 9613 and ISO 1996 relating to wind direction effects within an angle of ± 45° from the centre of the dominant sound source and from the centre of the specified receiver position. Using this sector as the area of most downwind noise influence it was decided that to minimise noise disturbance at House 1 and House 2, as mentioned above, turbines would be curtailed as follows:

House 1 - the nearest turbine to be curtailed when wind is from a SW direction, ± 45° on either side (i.e. within quadrant 180° to 270°),

House 2 - the nearest turbine to be curtailed when wind is from a SE direction, ± 45° on either side (i.e. within quadrant 90° to 180°).

The percentage yield attributed to each 45° section was calculated and is summarised on the pie chart below.

Figure 2 Energy yield in 45° sections

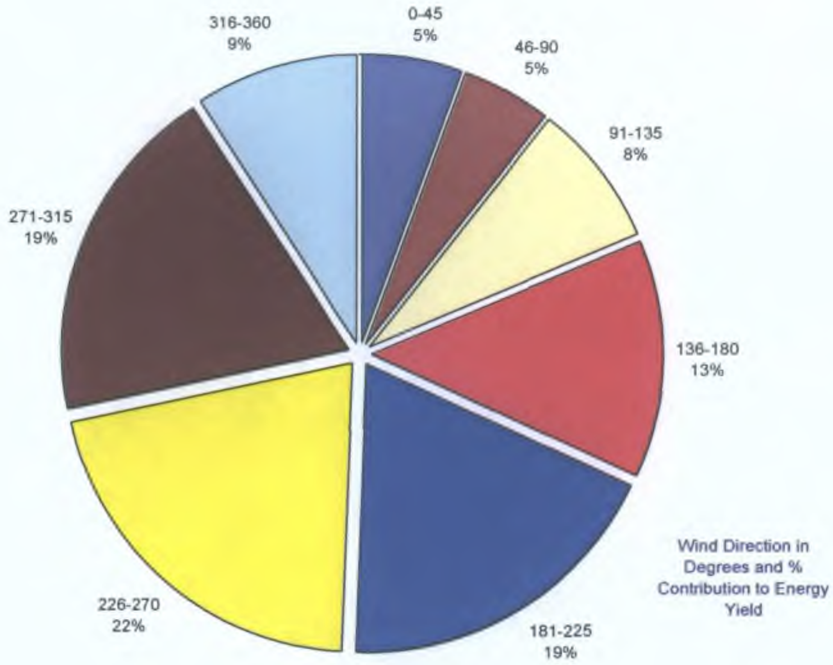


Table 1 summarises the energy yield at the relevant directions that will need to be curtailed to prevent noise disturbance at Houses 1 and 2.

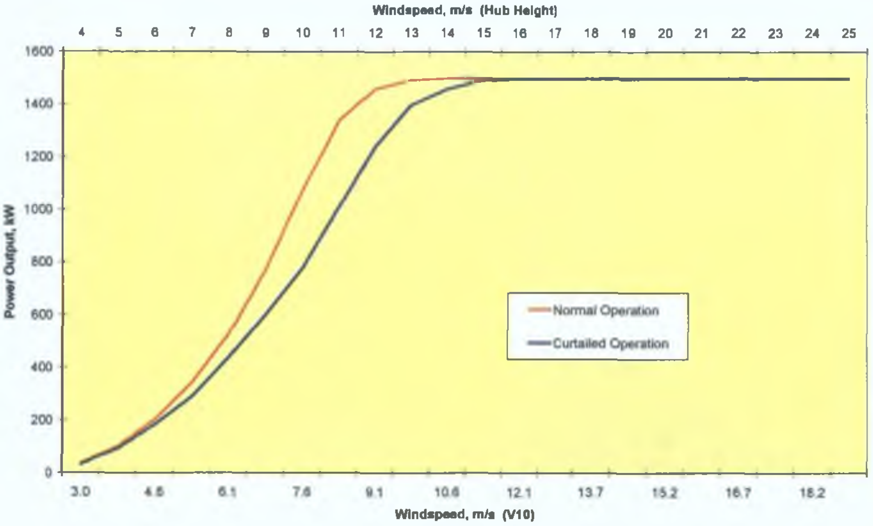
Table 1 Energy Yield in Relevant Wind Directions

House ID	Relevant Quadrant	Total % of Turbine Yield
1	180° – 270°	(19+22) = 41%
2	90° – 180°	(8+13) = 21%

1.1.2 Financial Implications

The total annual energy yield was calculated from the power curve of the turbine and based on power output over all wind directions. Information on the particular turbine power curve is contained in chapter 2.6 and presented below.

Figure 3 Turbine Power Curve



The total power output for one turbine across all wind speeds under normal operation was calculated as **5.2 GWh per annum**. In monetary terms, the value of 1kWh of electricity was taken as 4.8 cents, therefore the total electricity generated by 1 turbine has a value of **€249,600 per annum.**

From noise specification data, a 3dB noise reduction is expected during curtailed operation. In order to achieve the required noise reduction, the turbine in closest proximity to House 1 and House 2 will have to be curtailed at all times in the relevant wind directions. This will result in an average reduction of energy output by 17% (approximated by taking the difference in output from the power curve at the measured average wind speed of 50m at hub height).

The overall financial implications of reduced power output during curtailed operation at the relevant wind speeds are summarised in Table 2.

Table 2 Financial Summary

House ID	% of Total Turbine Yield [Note 1]	Normal Operation Value [Note 2]	Curtailed Operation Value [Note 3]	Loss of Revenue[Note 4]
1	41%	€ 102,336	€ 84,939	€ 17,397
2	21%	€ 52,416	€ 43,505	€ 8,911

Note 1: Determined from Figure 2 based on relevant wind directions,

Note 2: Calculated for each relevant wind direction based on the total energy yield value of €249,600 for the turbine at all wind directions,

Note 3: Calculated based on a 17% output reduction during curtailed operation,

Note 4: The total cost of curtailing operation in order to reduce noise levels (based on normal value minus curtailed value)