Project: A healthy society - towards the optimal management of wind turbine noise

D 4.1 The complete methodology of noise prediction, verified and adapted to wind turbines including specific aspects of generation, propagation and perception, allowing for the determination of both short- and long-term noise

Projekt: **Healthy society - towards optimal management of wind turbines' noise**

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D 4.1 The complete methodology of noise prediction, verified and adapted to wind turbines including specific aspects of generation, propagation and perception, allowing for the determination of both short- and long-term noise indicators, ready to be introduced to state regulation on environmental noise

Executive summary

This is a State-of-the-art report prepared for the HETMAN project. It describes different aspects of wind turbine noise including noise generation mechanisms, propagation, and subjective assessment of annoyance. The report is based on the publication *Støy fra vindturbiner* (SINTEF Report 2022:00176)

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Work is currently being done to validate the choice of propagation module. We have comprehensive measurements of wind turbine noise from a wind farm A. For 13 measurement points at distances ranging from 250 m to 1500 m and microphone heights at 1.5 m and 4 m, the Nord2000 module gives the best result, that is the smallest difference between the measured and predicted level, in 12 out of 13 cases. For one situation the ISO 9613 module gives the best result, but the Nord2000 prediction is only 0.6 dB below the actual measured value.

These comparisons will be complemented by similar measurements from another wind farm. The preliminary results will be presented at the upcoming Internoise conference this August, and a more extensive presentation will be made in a peer-reviewed journal article.

It has been decided to use the Nord2000 sound propagation module for noise predictions in the project. Software has been made available for Akustix and preparations have been made to do parallel calculations using different propagation modules, and to compare the predictions with actual field measurements. Work is currently being done to validate the choice of propagation module. We have comprehensive measurements of wind turbine noise from a wind farm A. For 13 measurement points at distances ranging from 250 m to 1500 m and microphone heights at 1.5 m and 4 m, the Nord2000 module gives the best result, that is the smallest difference between the measured and predicted level, in 12 out of 13 cases. For one situation the ISO 9613 module gives the best result, but the Nord2000 prediction is only 0.6 dB below the actual measured value. These comparisons will be complemented by similar measurements from another wind farm. The preliminary results will be presented at the upcoming Internoise conference this August, and a more extensive presentation will be made in a peer-reviewed journal article.

Report

Noise from wind turbines
Physics and psychology

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Table of contents

1 Noise generation mechanisms

Sound[1] from modern wind turbines is almost exclusively generated by aerodynamical processes, the flow of air around the rotor blades and around the nacelle (hub) and the tower. Sound from earlier models also comprised contributions from mechanical components (gears etc. in the hub) but such sounds are more or less non-existing for modern equipment. If, on rare occasions, mechanical sounds may be observed, this is usually caused by defective parts that can be corrected or replaced. The sound insulation around the hub is also usually very good. A conference paper by Fritz van den Berg gives a good overview of the different sound generation mechanism (2013).

Trailing edge noise (TE) is the sound that is generated in the turbulent air flow at the rotor blade surface. The TE frequency spectrum depends on the thickness of the turbulent layer which in turn depends on the airflow speed, blade dimensions and rotor pitch. The TE spectrum has its maximum in the range 250-1000 Hz and trails off at -3 dB per octave towards higher and lower frequencies. The frequency of the maximum peak depends on the rotor speed and increases with increasing speed. TE sound is the dominating sound source of a wind turbine.

Inflow turbulent noise is generated when the rotor blade cuts through turbulent eddies in the inflowing air. Such eddies may be generated by the terrain and nearby constructions (buildings or other wind turbines). This noise has its maximum around 10 Hz and drops off rapidly towards higher frequencies.

Thickness noise is generated when the moving rotor blade displaces air. The contribution from this source is rather insignificant. However, each time a rotor blade passes in front of the turbine tower there is a rapid change in the forces on the blade which generates sound in the infra frequency region, 1-10 Hz, depending on the rotation speed and the dimensions of the tower and the rotor blades. The sound is not audible but can be detected as *typical wind turbine noise* with its characteristic frequency signature.

2 Typical sound levels

The source level of a modern wind turbine, *i.e.,* the total sound energy produced by the turbine, is typically in the region L_w 100 – 110 dBA. This will produce a sound level around L_p 50 – 60 dBA at a distance of 100 meters. Nearby dwellings and other noise sensitive buildings are typically located further away. At one kilometer the sound level from a wind turbine is typically L_p 30 – 40 dBA. The source level of large wind turbines is proportional to the size of the generator. The source level of a one-megawatt WT is typically 10 dB greater than a 100-kilowatt WT ((Møller & Pedersen, 2011). The source level of new WTs is generally lower than old ones of comparable size.

State-of-the art wind turbines (2022) have a capacity of typically up to 4 - 5 MW (but even larger ones are available). The height of the hub may be 100 – 120 meters above the ground and the rotor diameter 120 – 130 meters. A gear box is often used to increase the rpm of the generator. In older wind turbines this gear box could be the source of mechanical noise. However, in modern turbines mechanical noise is seldom a problem. Some turbines may also be of a direct-drive type without a gear box between the rotor and the generator. This will significantly affect the noise generation.

[1] Sound is a physical phenomenon (pressure variations in the air) whereas noise is a subjective quantity (unwanted sound). In this report we do not always distinguish between the two concepts.

The sound from a wind turbine will vary as a function of the wind speed, and the sound level in a certain fixed position will vary depending on the wind direction. Most turbines start to produce electricity at wind speeds as low as 2-3 m/s. Under stable wind conditions the sound level will be fairly constant and the difference between the equivalent level and the maximum sound level is small, typically 1 – 3 dB. Measurement or recording of the maximum sound level in addition to the equivalent level, $L_{p,T}$ therefore gives little additional information (van den Berg F. , 2008). The absolute sound level, L_p, however, may vary as much as 5 – 10 dB (see chapter on amplitude modulation).

Due to a great distance between the turbines or clusters of turbines in a wind farm (typically >500 meters) the total number of wind turbines is seldom important for the noise exposure at nearby dwellings. The sound levels at these residences are usually given by one or a few nearby turbines.

The noise level measured with weighting curve A is the preferred way to describe the noise with respect to annoyance. But for noise sources with a large amount of low frequency components it has also become customary to make additional measurements with C-weighting. However, since the A-weighting curve is based on the equal-loudness contour for 40 phons, a noise signal at approximately 40 dBA will be perceived at the same loudness independent of the frequency spectrum. Extra measurements using C-weighting will therefore not give any additional information with respect to the annoyance at typical WT exposure levels. This has been confirmed in a large Canadian study where both A-weighted and C-weighted noise levels were analyzed (Keith, et al., 2016).

3 Human reactions to wind turbine noise

Following the increased construction of large wind farms there has been an increased focus on possible negative health effects from exposure to wind turbine noise. A large number of peer-reviewed papers have been published in the scientific literature along with an increasing number of articles of a more anecdotal character. Recent comprehensive articles describing *state-of-the-art* have been published by van Kamp and van den Berg (2017) and by Davy *et al.* (2020).

Attempts have been made to correlate different negative health effects with exposure to WT noise. The research results are rather non-conclusive and the only effect where a clear positive correlation has been found is noise annoyance. The annoyance increases with increasing exposure levels on a group or community level, but great individual differences may be observed.

Surveys on noise annoyance from transportation noise yield quite varying results. The prevalence of high annoyance (HA) caused by aircraft noise at an exposure level around L_{den} 65 dB may vary from 0 % HA to 90 % HA and 10 % HA may be observed at exposure level between L_{den} 35 dB to L_{den} 70 dB. Further analyses of surveys on noise annoyance have shown that cumulative measures of noise exposure *per se*, expressed in units similar to Day-Night Average Sound Level (DNL), rarely account for more than one third of the variance in community-level data (Basner, et al., 2017) (Guski, Schreckenberg, Schuemer, Brink, & Stansfeld, 2019) . The prevalence of noise-induced annoyance in communities is clearly moderated by factors other than noise exposure. There are reasons to believe that the same effect may also be observed for wind turbine noise.

Several authors report that annoyance from WT noise is linked to the presence of other non-acoustic factors. People that do not like the visual appearance of wind turbines, for instance, are more annoyed by noise than others. Similarly, people that fear that accidents may happen (“the wind turbine may tip over”, "rotor blades may fall off", etc.) are also more annoyed by WT noise (Michaud, et al., 2016). Several authors have found that there is a clear link between economic aspects and exposure to WT noise (Michaud, 2015) (Pedersen, van den Berg, Bakker, & Bouma, 2009). People that benefit economically from a wind farm are less annoyed than others. The same annoyance response may be observed at exposure levels ten to fifteen decibels apart. This makes it complicated to establish precise exposure response functions for wind turbine noise.

Sleep disturbance has often been reported. Objective methods for observing sleep disturbance (EEG, actimeter, etc.) are complicated and expensive to carry out on a large-scale basis. Most studies therefore rely on subjective methods such as self-reporting. The respondent is asked whether or not he or she is disturbed during sleep by WT noise. Non-acoustic factors may therefore have a large impact. Janssen *et al.* (2008) observed that a clear correlation between sleep disturbance and noise exposure could only be found if respondents with economic interests in the wind turbine industry were excluded from the data set. Michaud *et al.* (2016a) found no correlation between sleep disturbance and WT noise for exposure levels below L_{Aeq} 46 dB (yearly average). This is in line with observations by Griefahn (1993) who reports L_{ASmax} 47 dB as the limit for no awakening reactions for multiple exposures to noise events during sleep. A noise level L_{Aeq} 46 dB (yearly average) corresponds to L_{den} 52 dB for continuous operations.

Australian health authorities found no clear connection between sleep disturbance and sleeping disorders and exposure to WT noise (National Health and Medical Research Council., 2015). However, there seems to be a clear correlation between noise annoyance and sleep disturbance. People who are annoyed by WT noise also report a high prevalence of sleep disturbance regardless of the actual noise exposure level (Pedersen & Person Waye, 2007).

Other health effects that have been studied comprise diabetes, migraine, dizziness, tinnitus, asthma, hypertension, other cardiac phenomenon, depression, mental disorders, medication, etc. (Michaud, 2015). No convincing evidence has been found that link these effects to exposure to WT noise (van den Berg F. , 2013), (van Kamp & van den Berg, 2017), (WHO Europe, 2018), (Davy J. , Burgemeister, Hillman, & Carlile, 2020).

Annoyance due to transportation noise has been studied for about 60 years, and it has been shown that the annoyance caused by this type of noise can be fairly accurately described by the long-term A-weighted equivalent level, $L_{A,T}$ (yearly average) or a similar time-weighted equivalent level like L_{DN} or L_{den}. There are reasons to assume that the annoyance caused by other types of noise sources, for instance wind turbines, can be described by the same acoustic indicators as well (Michaud, 2015), (WHO Europe, 2018).

It is not clear how these indicators can be used to predict other effects than noise annoyance. If there are long periods without wind, the equivalent level during active energy production will be higher than the yearly average level. Acceptable exposure limits are usually defined relative to more or less continuous operations. If the wind turbine is active 50 percent of the time, the short-term level will be 3 dB above the L_{den} level (given same diurnal distribution) and the short-term level will be 5 dB higher if the turbine is active only 30 percent of the time.

Modern wind farms are usually located in areas that will give active production at least 80 % of the time. In such cases the difference between the yearly average and the level for the active periods is about 1 dB. However, due to meteorological differences the variation in one particular location may be much greater.

4 Infrasound and low frequency noise

In the non-scientific literature there is an abundance of references to negative health effects caused by exposure to low and ultra-low frequency noise from wind turbines. Exposure to non-audible infrasound ($f < 20$ Hz) from wind turbines has been attributed to a number of negative effects. Baliatsas *et al.* (2016) have published a comprehensive review of existing literature and conclude that there are no indications that exposure to low frequency sound and infrasound may cause other negative health effects than those that may be observed from exposure to noise at higher frequencies. Leventhall (2013) has shown that infrasound levels in the human body caused by heart beats, digestion, flow of blood, etc. are much higher than any of those levels that can be observed at some distance from a wind turbine.

A large study of possible effects of exposure to infrasound from wind farms has recently been published by a research team in Finland. Long-term registration of infrasound levels together with comprehensive social surveys were conducted in areas where possible symptoms of negative effects of infrasound from nearby wind farms had previously been reported. Residents from these areas also participated in lab studies. In these experiments they were exposed to the highest infrasound levels that had been recorded in the field. The test persons were divided in two groups: those who had reported negative infrasound effects and those who had not. The lab experiment showed that neither of the two groups could correctly determine if they were exposed to infrasound or not, there were no differences between the two groups in the reported annoyance, and no special reactions could be observed in the autonomous nerve system (Maijala & al., 2020).

INCE Europe is even more direct. This organization hosts conferences on wind turbine noise every other year. In the post-conference report after the 2021 conference INCE concludes (INCE Europe, 2021):

> *The issue of infrasound does not seem to go away in spite of the fact there is clearly no evidence that it has any direct impact either on the health of people near wind farms or on their perception of the noise. It is kept alive by a relatively small number of people in and outside the industry none of whom have recently attended our conferences.*

At equal A-weighted sound levels noise from wind turbines is judged more annoying than for instance aircraft noise or road traffic noise. A possible reason for this is the relatively large amount of low frequency components and also the typical amplitude modulation. Consequently, the limit for acceptable noise from wind turbines, L_{den} 45 dB, is much lower than for aircraft, L_{den} 52 dB, or road traffic, L_{den} 55 dB [2].

[2] The World Health Organization has recently published new recommendations for environmental noise (2018). They have triggered an ongoing discussion as the new recommendations are far more stringent that the old ones (Gjestland, 2018) (Guski, Schreckenberg, Schuemer, Brink, & Stansfeld, 2019), (Gjestland, 2019). They have been adopted by the EU in general, but not by any EU member countries.

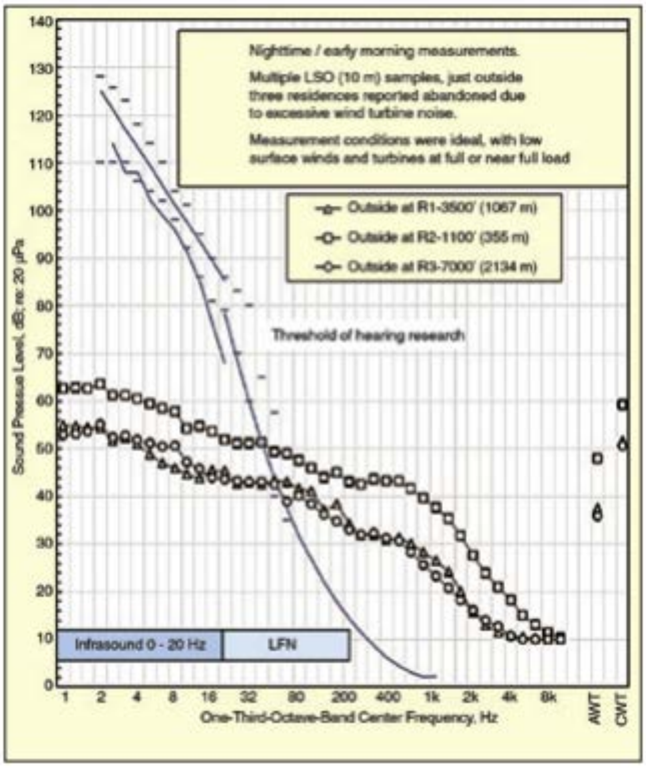

Figure 1. Typical wind turbine spectra and levels compared to threshold of hearing at low frequencies (Hessler, Leventhall, Schomer, & Walker, 2017).

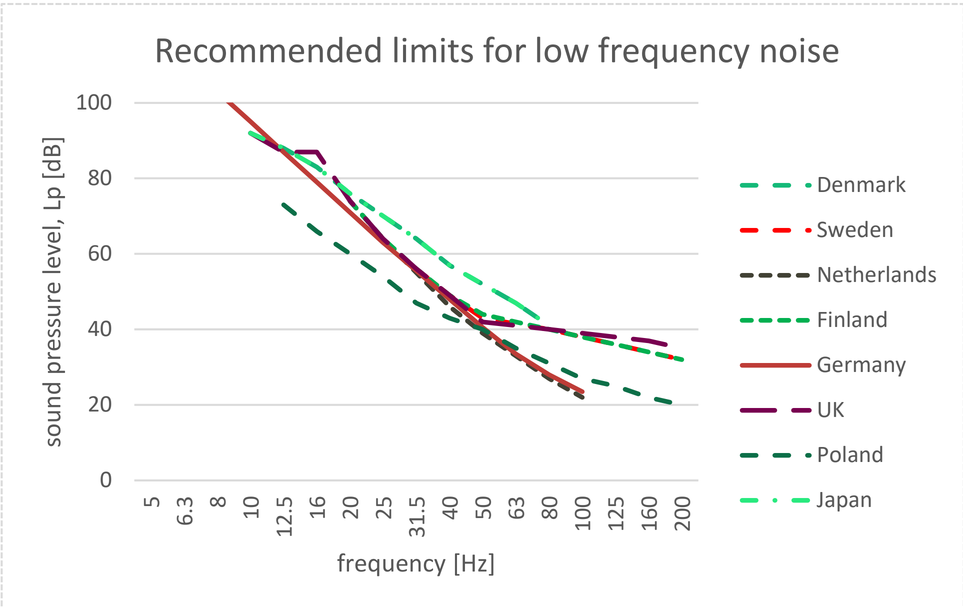

Figure 2. Recommended (acceptable) limits for low frequency noise exposure (Pawlaczyk-Luszczynska, Zamojska, Dudarewicz, & Zaborowski, 2013)

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Typical WT noise spectra have been compared with thresholds for human hearing in Figure 1 (Hessler, Leventhall, Schomer, & Walker, 2017). As indicated in this figure extremely high levels are required at very low frequencies to make WT noise "audible". It is a matter of definition whether the sound is "heard" *i.e.,* perceived via the ear and the auditory system, or detected or "felt" in a different way.

Relatively few countries have recommendations for low frequency noise exposure. Figure 2 shows recommended limits in some countries (Pawlaczyk-Luszczynska, Zamojska, Dudarewicz, & Zaborowski, 2013).

Sweden has recommendations down to the 1/3 octave at 31.5 Hz (Leq 56 dB) (Folkhälsomyndigheten, 2014). Denmark has special recommendations for low-frequency noise from wind turbines. The limit is L_{pA} 20 dB for the A-weighted 1/3 octave frequencies 10 – 160 Hz (Jakobsen, 2012). Note that A-weighting (and not C-weighting) is being used. The A-filter has a weighting factor -70 dB at 10 Hz as opposed to the C-filter having only -15 dB. The Danish recommendation thus allows rather high levels of low frequency noise before the limit is exceeded.

In Norway there is an ongoing discussion regarding the lower frequency limit for building acoustic measurements. Previous versions of the Norwegian standard, NS 8175 - Acoustic conditions in buildings, had recommendations expressed as C-weighted limits for noise from technical installations. However, in the latest (2019) revised version of this standard, only A-weighted limits remain. A-weighting is defined for frequencies down to 20 Hz, but for practical building acoustic measurements the lower limit is usually the 1/3 octave band around 50 Hz. Sometimes measurements are even limited to frequencies above the 1/3 octave around 100 Hz. This implies that there are no special recommendations or regulations for noise in the low frequency or infrasound range in Norway.

5 Exposure-response relationships

A small number of noise surveys have been conducted around wind farms, but the existing data material is rather inconclusive. A reason for this is that relatively few people are exposed to WT noise at levels that may cause significant reactions.

The results from seven surveys on wind turbine noise have been plotted in Figure 3. The surveys were conducted/reported between 2004 and 2016. The results have been analyzed using the CTL method (Michaud, et al., 2016), (Pedersen & Person Waye, 2007), (Pedersen, van den Berg, Bakker, & Bouma, 2009), (Yano, 2013).

The World Health Organization, WHO, considers 10 % highly annoyed as the limit for adverse health effects. This criterion is independent of the source. The average CTL value for the seven surveys shown in Figure 3 is L_{CT} 61.2 dB corresponding to 10 % highly annoyed at an exposure level L_{den} 44 dB. WHO has conditionally recommended that exposure to wind turbine noise should be kept below L_{den} 45 dB to prevent adverse health effects. WHO considers the evidence to be of low quality and recommends further studies (WHO Europe, 2018).

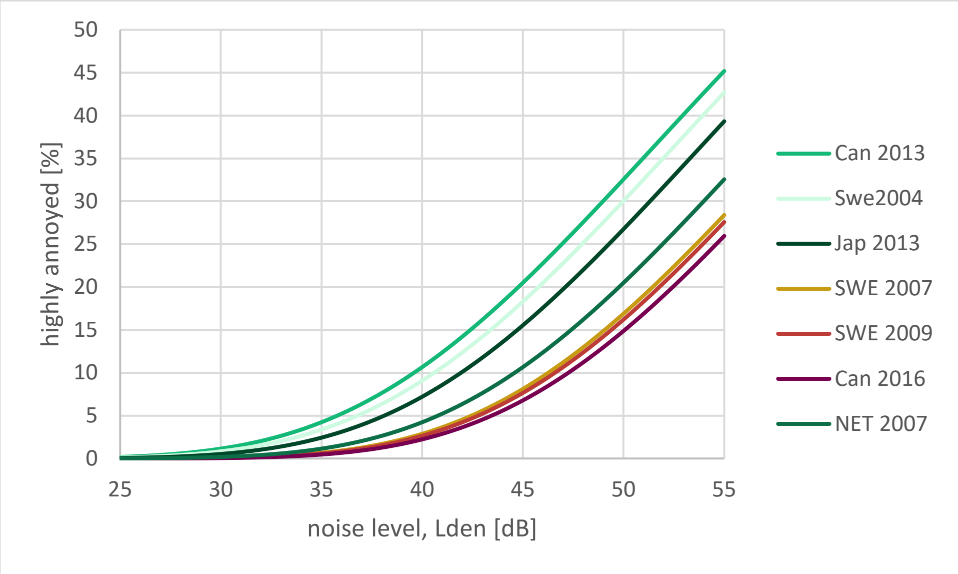

Figure 3. Results from seven surveys on wind turbine noise. Analyses based on the CTL method.

Figure 4 shows the two dose-response functions presented in the WHO report (green and red lines) together with the dose-response function corresponding to L_{CT} 61.2 dB (black line). The dashed lines indicate ± 1σ (standard deviation). The recommended limit for 10 % HA, L_{den} 45 dB, seems like a reasonable choice.

Davy et al. (2018) have published the results from an Australian study on WT noise. They conclude that the exposure level associated with 10 % HA lies in the range 40.4 dB < L_{den} < 46.4 dB. Their conclusion is based on conventional regression analysis.

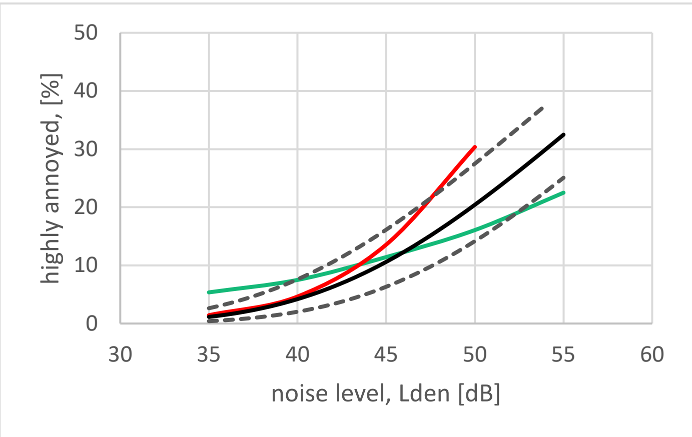

Figure 4. Percentage of highly annoyed vs. exposure to wind turbine noise. Results from Sweden and Netherlands (red line) (Janssen S. , Vos, Eisses, & Pedersen, 2011). Results from Japan (green line) (Kuwano, Yano, Kageyama, Sueoka, & Tachibana, 2014). CTL analysis of results from six studies with flanking ± 1σ (black lines) (see also Figure 3).

6 WTN and background noise levels

The relationship between annoyance caused by exposure to a specific noise source, for instance aircraft or road traffic, and the general background noise level has been studied extensively. It may be reasonable to assume that an intruding noise will be particularly annoying in a quiet area where the background level is below average. Fields' analysis (1993) of people's reactions to transportation noise in otherwise quiet or noise areas indicate that the reactions to a specific noise are more or less independent of the background. People react to a certain noise source in a certain way regardless of the presence or absence of other sources. Wind turbine noise, however, was not included in this analysis.

Several national and international standards for environmental noise recommend stricter exposure limits, up to 10 dB, if the background noise is particularly low (ISO, 2016) (ANSI, 1996). The justification for stricter limits may be that the noise is actually considered more annoying, or it may be a desire to preserve quiet areas as specified in the EU Noise directive (European Commission, 2002).

A review of existing recommended exposure limits for WTN reveals different strategies. Some countries have stricter limits for quiet areas (rural areas) whereas others allow higher levels outside densely populated areas. According to an analysis by Michaud et al. (2016) the annoyance caused by WTN is only marginally higher in especially quiet areas with no other anthropogenetic sounds than WTN.

7 Amplitude modulation

Wind turbine noise is always more or less amplitude modulated meaning that the instantaneous sound level will vary between a minimum and a maximum value in a rhythmic way. The noise generated by each rotor blade will vary depending on its position. At some distance the noise will be a combination of the contribution from three similar sources 120 degrees out of phase with each other. The resulting sound will vary with a modulation frequency 1-2 Hz depending on the rotation of the turbine. The modulation depth, that is the difference between the maximum and minimum instantaneous sound level, can be as much as 10 dB, but 3-4 dB is more normal (Bass, 2021). This amplitude modulated sound is very characteristic for wind turbines and makes it easy to recognize WTN even at very low levels. A modulation depth of only 2 dB is sufficient to clearly identify the noise from a wind turbine (Yokoyama, Sakamoto, & Tachibana, 2013). Lee et al. (2011) have shown that the annoyance increases with increasing modulation depth.

We must assume that the exposure-response functions shown in Figures 3 and 4 are based on amplitude modulated noise. However, as the modulation depth increases, these exposure-response functions may underestimate the annoyance. At some distance from a wind farm the noise is likely to comprise contributions from several turbines that are not completely synchronized. This will reduce the modulation depth of the combined sound but may increase the modulation frequency. Van Renterghem et al. (2013) have shown that a modulation frequency of 4 Hz seems to cause the highest annoyance.

In UK there are plans to introduce a special penalty for amplitude modulation. A penalty is added to the actual measured (or predicted) noise level before a comparison with regulatory noise limits. Noise with a modulation depth of 3 dB will get a 3 dB penalty increasing to 5 dB penalty for a modulation depth of 10 dB (Dept of energy and climate change, 2015), (Dept of energy and climate change, 2016). In this case the acceptable limit for WTN must be based on exposure to noise with very low modulation depth. There is also a UK proposal for an objective method of measuring the amplitude modulation of WTN (Perkins, Lotinga, Berry, Grimwood, & Stansfeld, 2016). This method has been validated in a lab experiment by Lotinga and Lewis (2021).

New South Wales, Australia, applies a 5 dB penalty if the modulation depth is greater than 4 dB (NSW, 2016).

In order to achieve maximum efficiency for the wind turbine the angle of attack between the wind vector and the rotor blade should be as large as possible. The wind speed, however, typically varies as a function of the height above the ground and the air flow may be more or less turbulent. For unfavorable combinations of wind speed, rotor pitch and turbulence in the incoming airflow the angle of attack may exceed the critical limit for stalling. This will cause a rapid increase in the trailing edge noise. The rotor blade is turning so the decisive parameters are constantly changing. The rotor may get in and out of stalling mode which causes a very loud amplitude modulated noise. This is known as OAM (other amplitude modulation). The exact mechanisms that cause this noise is not fully known. Turbulence caused by the terrain and nearby structures (for instance other wind turbines) may be part of the explanation.

8 Pure tones

Noise containing pure tones is considered more annoying than broadband noise. Most standards for assessing noise therefore recommends a penalty to adjust for pure tones. ISO 1996:2016, for instance, recommends a 5 dB penalty for audible pure tones.

In most instances pure tones from wind turbines are generated by gears etc. in the nacelle and not as wind generated noise. Pure tones used to be a problem with old wind turbine constructions, but the nacelles of modern wind turbines are very well isolated against noise. In those few cases where pure tones become a problem, this is most likely caused by mechanical defects that should be corrected.

Some countries, e.g., Denmark and Germany, recommend pure tone penalties/corrections. It may be difficult to detect pure tones in the noise signal due to very low signal levels. An “exclusion” technique may be used. If pure tones cannot be detected close to the source (the turbine) pure tones are neither present in any observation point further away. However, if pure tones are present in the noise signal near the source, they may not necessarily be detected further away due to effective masking by the background noise. The standard ISO 1996 (2016) specifies a method for measuring pure tones embedded in a noise signal. Pure tone correction is not an important issue for modern wind turbines.

9 Noise propagation

The noise propagation will usually be affected by meteorological conditions at distances above approximately 100 meters. In flat terrain and with free line of sight from the observer to the turbine, meteorology plays only a minor role, but for sound that propagates near the ground, large variations may be expected depending on weather conditions.

Meteorology is included to various extent in the standard noise prediction programs. Some programs base the calculations on “moderately favorable weather conditions”. For a yearly average this will usually give a somewhat conservative estimate. Other programs include detailed meteorological parameters, which allow more accurate calculations. The meteorological input parameters must be based on local weather observations or statistics.

Note that *favorable* in this context means favorable for the sound propagation, that means weather that gives *little sound attenuation*. The noise level at the receiver location will therefore be high and consequently the exposure situation for the listener will be *unfavorable.*

The noise propagation is especially affected by wind speed and temperature and their gradients, *i.e.,* how these parameters vary as a function of height above the ground. Likewise, the interaction between the sound waves and the ground affects the propagation. The physical properties of the ground surface (absorbing/reflecting) are therefore important. High frequency sounds are also affected by the humidity in the air.

Downwind from a turbine there will be a tube-like wake with reduced wind speed. This wake forms a sound channel. The wind speed above the wake is usually higher than the speed below the wake. This will force the sound waves downwards and in flat terrain this will give high noise levels at a long distance (Heimann, Englberger, & Schady, 2017). At some distance the wake will start to break up. Exactly where this will happen depends on the wind gradient. Turbulence in the incoming airflow will reduce the length of the wake (Barlas, Zhu, Shen, & Andersen, 2016).

Barlas et al. (2017) have carried out numerical simulations of sound propagation in a turbulent air flow. They have shown that the amplitude modulation down-wind is amplified when the sound propagates a section of turbulent air. Turbulence from nearby structures or terrain and instability in the wake ("wake meandering") will contribute to the total down-wind turbulence. The sound level up-wind is usually much lower than down-wind. It is therefore likely that up-wind amplitude modulation is more or less masked by background noise.

In order to simplify the description of meteorological conditions for sound propagation calculations a concept of *weather classes* has been introduced. These weather classes can be defined using standard meteorological parameters like *wind speed, wind direction, cloud conditions and time of the day.* The two latter parameters define meteorological stability that describes, among other things, the temperature gradient.

A total of 25 weather classes have been defined, but 16 of these are not very common. That leaves 9 classes that are sufficient to characterize most meteorological situations. Some noise propagation programs have simplified the calculations even further and use only four or even just two classes. In Nord2000 all 9 weather classes can be handled.

The influence of these 9 weather classes can be summarized in four typical propagation situations: *unfavorable, neutral, favorable, and very favorable.* Note that these characteristics refer to the actual sound propagation.

Under unfavorable conditions the sound waves will bend upwards and the sound level at some distance from the source will be low. Under neutral conditions the sound propagates in straight lines, and under favorable conditions the sound waves will be bend towards the ground. This will give higher sound levels at some distance, and the sound may seem to propagate beyond obstacles. The sound level may be high even if the direct line of sight between the source and the receiver is blocked.

To illustrate the effect of different weather conditions the sound propagation from a typical wind turbine installation has been calculated. The source is assumed to be a 2 MW turbine with a source level, L_w = 105 dB, and the nacelle is located 80 meters above the ground. The receiver height is 4 meters. To illustrate the propagation the source level is kept constant independent of the wind speed.

9.1 Ground surface conditions

Different conditions of the ground surface will affect the attenuation of the propagating sound waves. If the sound travels across a hard surface (water, concrete, rock, etc.) most of the sound energy will be reflected. A soft, porous surface (snow, grass, etc.) will absorb energy. The porosity is described by the flow resistance. The acoustic ground impedance that defines the attenuation of a propagating sound wave depends on this flow resistance.

The Nord2000 calculation program divides the flow resistance in eight classes, A—H. Class A “very soft” (moss, snow) has a flow resistance σ = 12,5 kPa/m^2, and class H “very hard” (asphalt, concrete, water) has σ = 200 000 kPa/m^2. At a distance of 100 meters the sound from an 80 meters high wind turbine will differ only 2 dB between class A and class H ground surface (class H gives higher level). At 300 meters the difference is 2.2 dB. The calculation has been done for flat terrain and free line of sight between the turbine and the observer.

This calculation can be considered an extreme situation. It is very rare to have a surface class H “very hard” all the way between the turbine and the receiver (except propagation across water). The difference between summer conditions and winter conditions when the ground is covered with snow, will therefore normally be smaller than shown above. Class D, σ = 200 kPa/m^2, is a good approximation for the ground in typical rural areas (hard grass covered ground). At 300 meters the difference between class A and class D is only 1.5 dB for an 80 m high turbine.

9.2 Wind speed and wind direction

The wind speed has little effect on the sound propagation. The A-weighted downwind sound level from an 80 m high turbine will be the same at wind speeds 1 m/s up to 16 m/s for distances up to 1000 meters (the source level is assumed to be constant). The reason for this is that downwind the sound will propagate high above the ground and the terrain will have minimal effect. Downwind means that the wind is blowing from the turbine and towards the observer.

Upwind, that is wind blowing from the receiver towards the turbine, the situation is different. At moderate distances, 300-500 meters, the effect is small. At 500 meters the sound level will decrease only 0.8 dB if the wind speed increases from 1 m/s to 16 m/s. but at 1000 meters the reduction will increase to 16.4 dB. The reason for this is that the sound waves will propagate a long distance close to the ground and will be effectively absorbed. These calculations are valid for flat terrain.

9.3 Humidity

Relative humidity has very little effect for the sound propagation. Air with high humidity will absorb more high frequency energy, but at 300 meters the A-weighted level difference between 50% and 90 % relative humidity and 20^o C temperature will be only 0.1 dB. At 0^o C the difference is 0.3 dB.

9.4 Topography

The effect of meteorological parameters becomes more pronounced when the terrain is not flat. This is illustrated in Figure 5. The sound propagation from a wind turbine located on a hill has been calculated for unfavorable, favorable, and very favorable conditions.

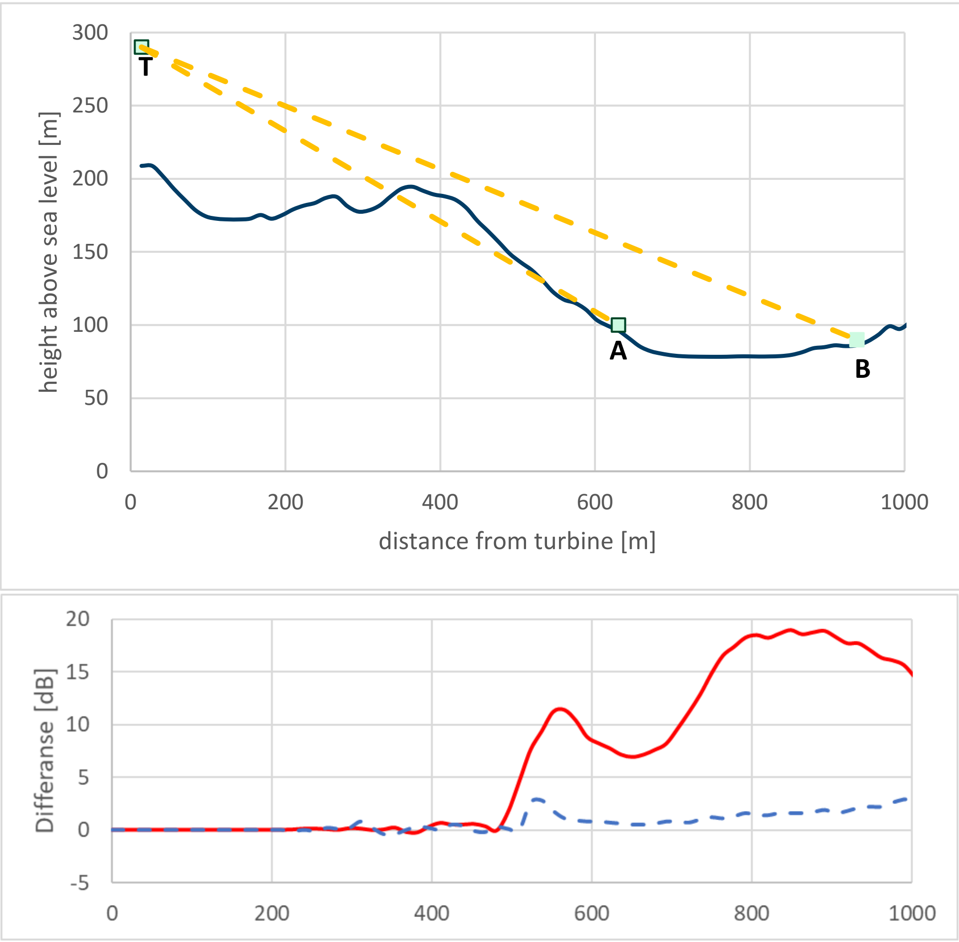

Figure 5.
Wind turbine, T, located in hilly terrain (top panel). Two observation points, A and B, are indicated. Lower panel shows the sound level difference between *very favorable* and *unfavorable* conditions (red line) and between *favorable* and *unfavorable* conditions (blue dashed line)

The top panel of Figure 5 shows the terrain profile. The turbine, **T**, is located to the left with the nacelle 80 meters above the ground. Two observation points, **A** and **B**, have been indicated. The line of sight (dashed lines) between the nacelle and the observation point **A** is broken, whereas the nacelle is clearly visible from observation point **B**.

The lower panel shows the difference in the A-weighted sound level between very favorable and unfavorable weather conditions (red curve) and between favorable and unfavorable conditions (blue curve) respectively. At distances below 400 meters there is a free line of sight to the turbine, and the weather conditions have little or no effect. At around 500 meters the turbine is no longer visible. For unfavorable conditions the terrain will act like a barrier and the sound will be attenuated. Under favorable and very favorable conditions, however, the sound waves will curve downwards and the sound level behind the terrain obstacle will still be quite high. The weather conditions thus play an important role in situations where the line of sight is broken by the terrain. In point **A** the differences between unfavorable and favorable or very favorable are 0.7 dB and 7.4 dB, and in point **B** the same differences are 2.2 dB and 17.4 dB. At very favorable weather conditions, i.e., very favorable sound propagation conditions, very large differences may be experienced.

Typical yearly weather statistics for wind farm locations in Norway indicate that very favorable weather conditions can be expected 16 % of the time. The rest of the year the weather conditions are evenly distributed between the other three classes. This implies that residents in these areas may experience exceptionally high levels of wind turbine noise about 60 days per year.

The wind speed is a key parameter for characterizing the sound propagation conditions. In open flat terrain this parameter plays a minor role, as opposed to a hilly terrain where the line of sight from the observer to the wind turbine may be partly broken. In order not to underestimate the noise impact standard procedures call for predictions at 8 m/s downwind (the wind is blowing from the turbine and towards the observer). This situation will normally be classified as very favorable conditions.

10 Limits for WTN in some countries

Davy et al. (2018) have presented a comprehensive overview of wind turbine noise limits shown in Table 1. This information has been checked as far as possible against current limits (January 2022).

National noise limits have been established using two different strategies. Most countries or local regions specify their limits as fixed levels in decibels. Some countries, however, base their limits on *emergence.* This implies that the limit is defined relative to the background noise level, and the wind turbine noise may exceed the background or ambient level by a certain number of decibels. The background noise in this context comprises contributions from all other noise sources except the wind turbines but includes all anthropogenic sources like transportation noise and industry.

The preferred noise indicator is the A-weighted equivalent level, often with a time-of-day weighting like DENL and DNL, and/or corrections for amplitude modulation and pure tones.

Quite often the noise limits depend on area characteristics, for instance urban vs. rural surroundings. However, even for this purpose different strategies have been chosen. Some countries have more stringent limits in rural less populated areas most likely because people expect such areas to be quiet and new noise sources may be considered especially annoying. Stringent limits may also reflect a desire to protect and preserve existing quiet areas. Other countries, however, have more stringent limits in built-up areas, to protect the largest number of people, and allow high noise levels in areas with low population density where few people will be annoyed. The current limits for some countries are listed in Table 1.

10.1 Current limits for wind turbine noise in some countries

Table 1

Country	Noise indicator	Rural	Urban
Belgium - Flanders	LAeq[dBA]	Day: 48 Evening/night: 43	Day: 44 Evening/night: 39
Belgium - Wallonia	LAeq [dBA]	45	
Canada - Alberta	LAeq [dBA]	40	
Canada - Ontario	LAeq [dBA]	40 - 4 m/s 45 – 8 m/s 51 – 10 m/s	45 - 4 m/s 45 – 8 m/s 51 – 10 m/s
Denmark	Lden + corr.[dBA]	42 – 6 m/s 44 – 8 m/s	37 – 6 m/s 39 – 8 m/s
Finland	LAeq [dBA]	Day - 45, night - 40	
France	LAeq [dBA]	Day – ambient + 5 dB, night – ambient + 3 dB	
Germany	Lden + corr.[dBA]	Day – 60, night - 45	Day–50/55, night-35/40
Netherlands	Lden [dBA] Lnight [dBA]	47 41	
New Zealand	LA90,10min [dBA]	35 or ambient + 5	40 or ambient + 5
Norway	Lden [dBA]	45	
South Australia	LAeq,10min [dBA]	35 or ambient + 5	40 or ambient + 5
Sweden	LAeq – 8 m/s [dBA]	35	40
United Kingdom	LA90,10min [dBA]	Day: ambient + 5 >35 - 40 Night: ambient + 5 >43	
USA	EPA rec. Ldn [dBA]	55	

For comparison of noise indicators - Lden = LA_{eq} + 6 dB (continuous operation)
Comparison with Norwegian exposure limits:
Belgium-Flanders: Limits 6-10 dB higher than Norway. Higher levels in rural areas
Belgium-Wallonia: Limits about 6 dB higher than Norway
Canada-Alberta: Limits similar to Norway
Canada-Ontario: Limits for urban areas 6 dB higher than Norway for low and moderate wind speeds. Higher levels at higher wind speeds.
Denmark: Variable limits depending on wind speed. At comparable wind speed, limit similar to Norway for rural areas, but 6 dB more stringent for urban areas.
Finland: Limits about 6 dB more lenient than Norway
France: Very different noise indicator
Germany: Limits more lenient than Norway, but difficult to compare.
Netherlands: Limits 2 dB higher than Norway
New Zealand: Limits for urban areas similar to Norway. Lower levels in rural areas.
South Australia: Same as New Zealand. Similar to Norway in urban areas.

Sweden: Limits similar to Norway for urban areas, more stringent I rural areas.
United Kingdom: Very different noise indicator
USA: Limits about 10 dB higher than Norway
World Health Organization: Recommended limit Lden 45 dB. Similar to Norway.

11 Wind shadow

Sound from a wind turbine is of course only present when the wind is blowing, and the blades are rotating. The wind also generates local sound at the observer location. At high wind speeds this locally generated sound may get loud enough to mask the noise from nearby turbines.

Wind blowing through trees and bushes especially through the foliage of deciduous trees may generate quite high noise levels as illustrated in Figure 6 .

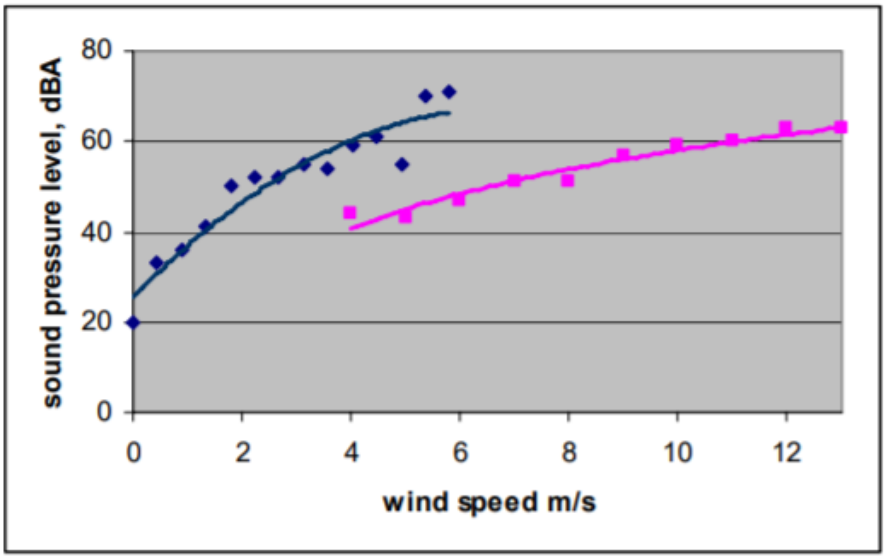

Figure 6. Sound levels generated by wind in two types of vegetation (Gjestland, Background noise levels in Europe, 2008)

Wind speeds around 6-8 m/s may generate sound levels around L_p 50 – 70 dBA whereas the noise from a wind turbine is typically L_p 40 – 50 dBA at the closest dwellings. Both sources produce broadband noise. Figure 6 clearly illustrates that locally produced noise may very well mask the noise from nearby wind turbines.

Occasionally the observation point may be located in a shadow zone with very little wind. This may be the case in general, or it may occur only for certain wind directions. The turbines are typically located on a windy hilltop whereas nearby residences may be located in a valley with quite different wind conditions so masking by locally generated sound rarely occurs. Masking may also be very dependent on the wind direction. The audibility and hence the annoyance from the WTN may therefore change drastically with the wind direction.

12 Prediction of noise from wind turbines

There are numerous methods for calculation and prediction of sound propagation outdoors. Most of these methods, however, have been developed for sound sources close to the ground such as road or rail traffic. Some of the methods can be used for most sources in general.

- ISO 9613 describes a standardized propagation model that is used world-wide. Typical areas of application are industrial noise, transportation noise and noise from guns and artillery. The method does not handle different meteorological conditions in a detailed way. The propagation model is implemented in most calculation programs for outdoor noise. The model is unfit for calculating the propagation for specific weather conditions.

- Nord-96 defines a set of propagation models developed during the nineties for use in the Nordic countries. One of these methods, *Nordic method for calculation of industrial noise,* can be used for wind turbine noise. However, similar to ISO 9613 the method does not distinguish between different weather conditions. The Nord-96 methods are widely used in the Nordic countries and are implemented in most noise prediction programs.

- Cnossos-EU is based on a French prediction program for outdoor noise propagation (NMPB 2008). This method has been adopted by the EU and is the preferred method for strategic noise mapping. Different weather conditions are accounted for statistically by using two different propagation classes. Homogeneous class is defined as stable weather with little wind and constant temperature and favorable class is defined by moderate down-wind conditions. The method was originally developed for noise sources close to the ground, and it is unclear whether it is also applicable for sources at some height such as wind turbines.

- Nord 2000 is a method developed by the Nordic countries to replace the Nord-96 methods. Nord 2000 is quite advanced compared to the other methods listed above. Nord 2000 can handle detailed meteorological information and seems to be capable of accurate prediction of wind turbine noise, both for long term average and for short term noise levels under specified weather conditions. The method is rather complex and only available as a module in a few prediction programs.

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