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

D5.1 Catalogue of noise reduction methods either for single turbine or the whole farm. For each method its effectiveness (confirmed empirically) and the conditions of applicability will be provided (M24)

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Executive summary

The Catalogue of noise reduction methods is divided into two sections describing "hard" methods (Part 1) and "soft" methods (Part 2).

"Hard" methods are considered to be solutions that aim to reduce the sound power level of the noise source (wind turbine – WT) itself, or are applied along the propagation path or at the immission point to decrease the noise level reaching protected areas. The main goal of using "hard" methods is to achieve acceptable noise levels at the boundary of acoustically protected areas (Dz.U. 2007 nr 120 poz. 826 2007). This document presents a range of solutions that can be applied to newly installed WT's or during their modernization. In most cases, the feasible solutions are based on the same mechanisms however, their effectiveness and implementation methods are specific to the particular device offered by a given manufacturer. Therefore, this Catalogue aims to present the options available to the farm Manager or Acoustic Consultant rather than pointing to specific solutions offered by a particular manufacturer.

Sometimes, despite meeting legal requirements regarding the permissible noise levels from wind turbines, residents of areas adjacent to the farm complain about excessive noise annoyance caused by the operation of the power plants. In such situations, the Catalogue includes descriptions of two "soft" methods for reducing noise annoyance by introducing solutions that mask the noise generated by wind turbines.

Authors	Date of submission	Confidentiality level
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1 "Hard" reduction methods

In this Chapter, hard methods are considered those aimed at reducing the noise generated by turbines. Hard methods of wind turbine noise reduction can be divided based on their area of action:

- at the source (at the noise source – methods affecting the operation of the power plant, the level of acoustic power, or the noise characteristics),
- at the immission point (at the observation point located in an acoustically protected area and/or close to the protected buildings). The reduction of noise generated by wind turbine is possible along the propagation path (e.g. cubic structures, different type of ground surfaces between source and receiver, forest) and/or by the acoustic isolation (e.g. installation of soundproof windows).

Reduction according to "hard" methods affects the sound levels measured at the source or at the immission point according to the appropriate measurement methodology. The primary goal of reduction using "hard" methods is to achieve appropriate acoustic conditions near the wind farm as defined by national permissible environmental noise levels.

Unfortunately, within the project the acoustic effectiveness of hard methods of noise reduction has not been confirmed. Only an analysis of known and currently available noise reduction methods was carried out.

1.1 Methods Applied at the Noise Source

A wind turbine consists of numerous elements (sub-sources) that contribute to noise generation (the overall noise). The main areas of noise generation in a wind turbine are the nacelle (and all the working devices contained within it) – the source of mechanical noise; and the blades interacting with the air flowing around the turbine – the source of aerodynamic noise. The main sources of wind turbine are presented in Figure 1. As can be seen one of the loudest sub-sources are: the gearbox, blades and generator.

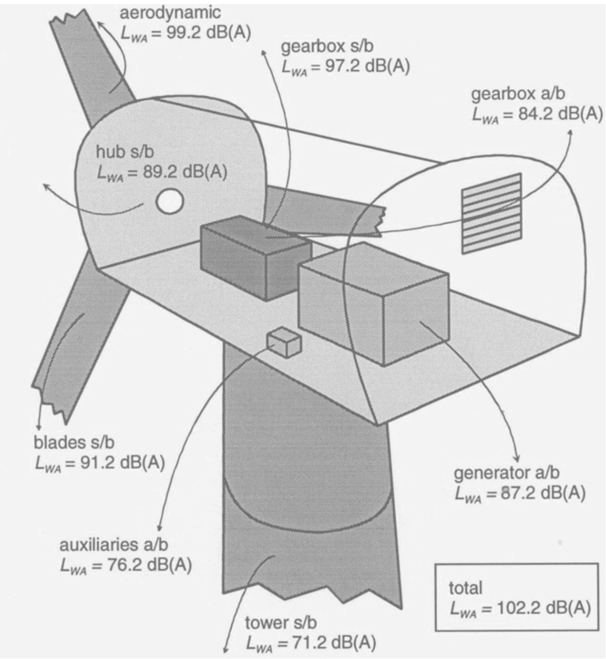


Figure 1. Contribution of individual components to the total sound power level of a wind turbine (Pinder 1992)

1.1.1 Mechanical Noise Reduction Methods

Mechanical noise is generated by the operation of devices within the wind turbine. The sources of this noise can be the devices themselves or vibrations transmitted to other parts of the turbine, such as the nacelle walls or the tower structure. The devices that primarily contribute to the generation of mechanical noise include the generator, gearbox, pitch control systems, yaw system, cooling equipment, and auxiliary apparatus.

Typical noise spectra for machinery noise are shown in Figure 2 and Figure 3.

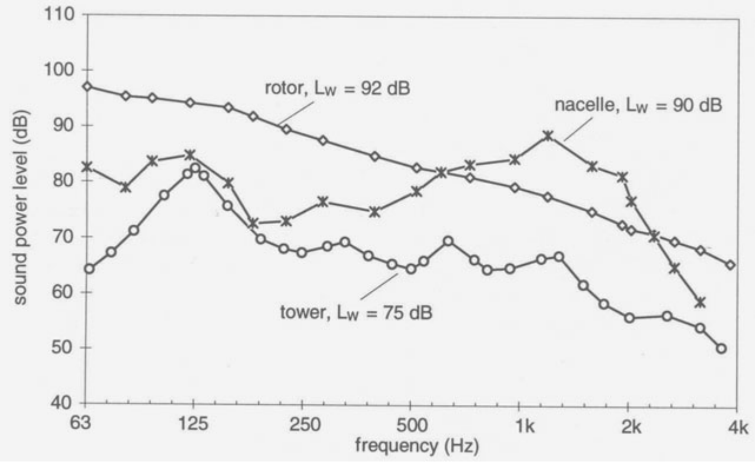


Figure 2.Contribution of individual components to the total sound power level of a wind turbine (Pinder 1992)

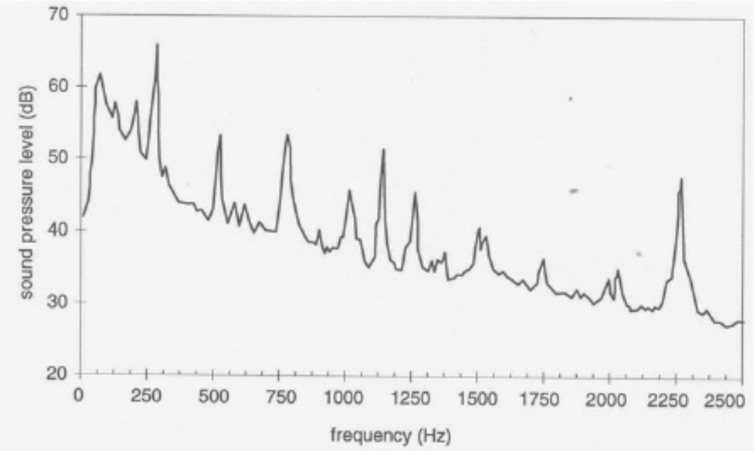


Figure 3. Contribution of individual components to the total sound power level of a wind turbine including gearbox contribution (Pinder 1992)

As can be seen in Figure 3 the mechanical noise is usually tonal or narrowband, which is more annoying than broadband sounds (Pinder 1992). In many countries, penalties are imposed on tonal noise added to the equivalent noise levels of wind turbines (Jiau, Rosen and G. 2012), (Alamir, Hansen and Catcheside 2021) significantly affecting the noise impact range and the feasibility of locating wind power plants.

The reduction of mechanical noise is mainly influenced by technological and structural factors, making their application standard engineering practice. In all properly constructed and maintained turbines, these solutions are present in some form.

In conclusion, the mechanical noise can be reduced to a large extent by properly shielding the nacelle, using sound absorbing materials and vibration suppression. This reduction has resulted in aerodynamic noise becoming a dominant noise source in wind turbines.

1.1.1.1 Vibroacoustic isolation

Vibrations generated in a wind turbine can be a source of noise. Vibrations transmitted through the main shaft to the gearbox and generator, without proper isolation, cause other structural elements of the turbine, such as the blades, nacelle walls, or tower, to vibrate, thereby becoming secondary noise sources (Grätsch 2019), (Hansen and Hansen 2020). Even turbines designed without a gearbox (direct-shaft) require vibroacoustic isolation. A common cause of noise due to vibrations is the excitation of turbine components to their resonance frequencies (Hanus 2017). Examples of vibroacoustic solutions include passive and active dampers, specially designed mounting elements, and "intelligent" management of blade pitch and angle of attack to reduce load on moving parts (Xu, et al. 2021). Solutions such as K-Dampers, which help dampen structural vibrations in the turbine due to strong winds or ground-transmitted vibrations, are also gaining popularity.

The insulation of the nacelle and isolation of vibrations between machine parts and the surrounding nacelle can result in noise reductions of up to 15 dB (Pinder 1992).

1.1.1.2 Gearbox noise

The gearbox is a major source of mechanical noise and typically produces narrowband or even tonal noise (Pinder 1992). One method of reducing tonal noise from the gearbox is using axial bearings instead of radial bearings (Windisch, Hensel and Drossel 2022). Another solution includes torsional dampers or elastic torsional couplers (Windhofer, et al. 2021), which not only dampen the noise generated by the gearbox but also alter the frequency characteristics of the vibrations, thus avoiding resonance vibrations. However, the choice of gearbox type usually remains at the discretion of the manufacturer. In turbines with direct shaft designs, this noise generation mechanism is completely eliminated.

1.1.2 Aerodynamic Noise Reduction Methods

Mechanical noise is relatively easy to control due to the numerous proven methods of reducing mechanical noise. These methods often coincide with or are a byproduct of efforts to improve the turbine's efficiency and energy production, which is a primary focus. Additionally, mechanical noise is minimally affected by varying weather conditions.

The difficulty in combating aerodynamic noise lies in its frequency characteristics and amplitude variability over time (known as amplitude modulation), which affects the subjective perception of noise and can be annoying to people.

Based on many papers (including experimental results) (Bruggeman and Parchen 1994), (Dassen, et al. 1994), (Deshmukh, et al. 2019), (Jianu, Rosen and Naterer 2012), (Carrelhas, Gato i Morais 2024), the following sources / types of aerodynamic noise of wind turbine are distinguished:

- blade tip noise,
- leading edge noise,
- trailing-edge noise,
- inflow-turbulence noise.

1.1.2.1 Trailing Edge Noise

Trailing edge noise arises from the turbulence at the trailing edge (TE) of the blade. TE noise is the primary source of aerodynamic noise (Hansen and Hansen 2020) and has a broadband spectrum covering mid-range frequencies (Oerlemans, An Explanation for Enhanced Amplitude Modulation of Wind Turbine Noise 2011), (W. 2010). The peak frequency of trailing edge noise lies between 500-1500Hz. This kind of noise occurs due to interaction of turbulent boundary layer with the sharp trailing edge of the airfoil.

- Three solutions are used to reduce TE noise:
- Well-chosen blade airfoil,
- Special TE serrations or feathers,
- Proper blade pitch to minimize turbulence (Oerlemans, An Explanation for Enhanced Amplitude Modulation of Wind Turbine Noise 2011), (Deshmukh, et al. 2019), (Barone 2011), (Oerlemans, Fisher, et al. 2009).

The last method is commonly used in the so-called quiet operation mode of wind turbines, which allows for noise reduction at the expense of a slight decrease in energy production. Serrated edges serve to extend the boundary layer around the blade so that the airflow remains as laminar (undisturbed) as possible. This should primarily affect the acoustic properties of the blade rather than its overall aerodynamics. Laminar airflow along the blade is achieved by adjusting the angle between the wind direction and the normal to the trailing edge (Figure 4). This is achieved by manipulating the angle of attack or the appropriate blade shape. Optimal use of trailing edge serrations can reduce the overall noise of the wind turbine by up to 4 dB (Oerlemans, Wind turbine noise: primary noise sources 2011).

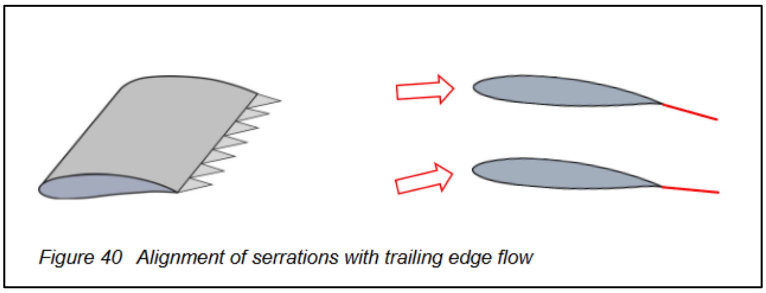


Figure 4. Adjusting the angle between the wind direction and the normal of the trailing edge. The Figure is from the work of (Oerlemans, Wind turbine noise: primary noise sources 2011)

The analysis presented in paper (Amiet 1975), (Blake 1986), (Fowcs Williams and Hall 1970) has shown that trailing-edge noise is proportional to $\sim M^5$, where M - is the Mach number. The value of M is greatest at the end of the blade. The velocity at the blade end depends on the rotor rotation frequency Ω, blade diameter D, wind speed V_w:

$$V_{tip} = \sqrt{\left(\Omega \frac{D}{2}\right)^2 + V_w^2} = \Omega \frac{D}{2} \sqrt{1 + \frac{1}{\lambda}}$$

where

$$\lambda = \frac{\Omega D}{2V_w}$$

is the tip speed ratio.

In report (Hagg, van der Borg and Bruggeman 1992) it has shown that sound power level of wind turbine can be calculated form the equation:

$$L_{WA} = 50logV_{tip} + 10logD - 4$$

As can be seen from the above relationship, the reduction of V_{tip} provides the reduction in sound power level. Unfortunately, the reduction of speed frequency, Ω, and blade diameter, D, also reduces the turbine's sound power level.

The paper (Hau, Langenbrinck and Palz 1993) shows quantitatively how the reduction of rotational frequency, Ω, and blade diameter, D, results in the reduction in sound power level (Figure 5). For example, 10% reduction in the rotational frequency, Ω, results the reduction of the sound power level of approximately 2dB and at the same time the reduction of the turbine output of approximately 2%. 10% reduction of blade diameter, D, results the reduction of sound power level of approximately 2.5dB. Unfortunately, 10% reduction of blade diameter, D, means the simultaneous reduction of the turbine's power output level of approximately 20%. This means that the reduction of blade diameter means a dramatic decrease in the turbine's power output level and is certainly not the best way to reduce noise level.

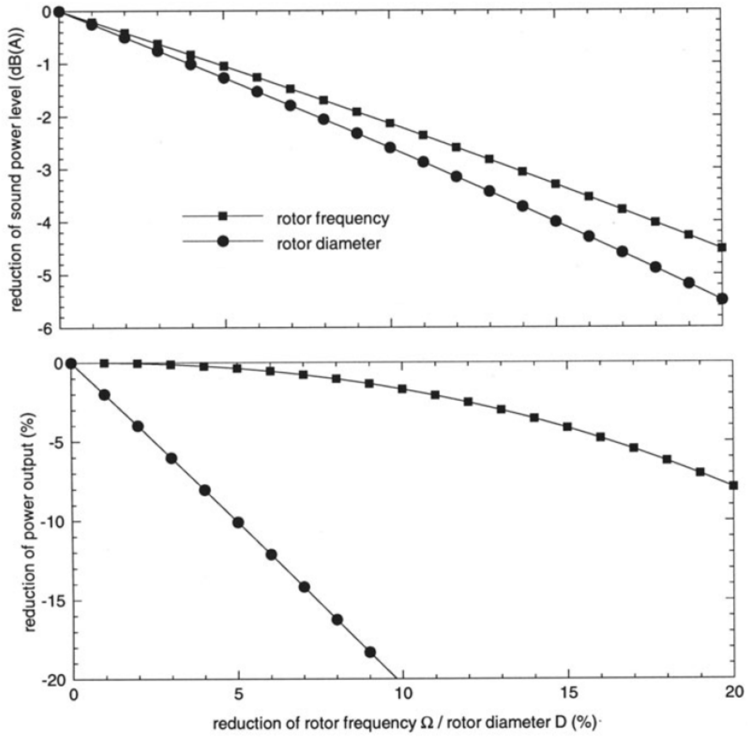


Figure 5.The reduction of noise level and turbine power output as a function of change of turbine diameter and speed (S. Wagner 1996)

The trailing edge noise can be reduced using trailing edge serrations (Barone 2011). In paper (Oerlemans, Fisher, et al. 2009) it was shown that by using a serrated rear blade edge, the average sound pressure level was reduced by about 3.0dB on average in the wind speed range of 6m/s to 10m/s (for a 2.3 MW test turbine). A similar noise reduction was presented in paper (B. Petitjean 2011). However, in report (Oerlemans, Fisher, et al. 2009), it is shown that the noise reduction dependents on wind speed – the least noise reduction occurs at low wind speeds. Unfortunately, the noise of wind turbines is often most noticeable at low wind speeds, when the background noise of the wind is relatively low and in consequence the effect of wind turbine noise masking by wind noise is negligible.

1.1.2.2 Leading Edge Noise

Leading edge noise arises from the interaction of the rotating blade with the inflow turbulence (Bowdler and Leventhall 2011). The noise level from this mechanism is highly dependent on the turbulence level of the incoming air mass. The main method of reducing leading edge noise is using blades with a specific cross-sectional shape – more rounded and thicker blades are less susceptible to this mechanism, see Figure 6 (Oerlemans, Wind turbine noise: primary noise sources 2011).

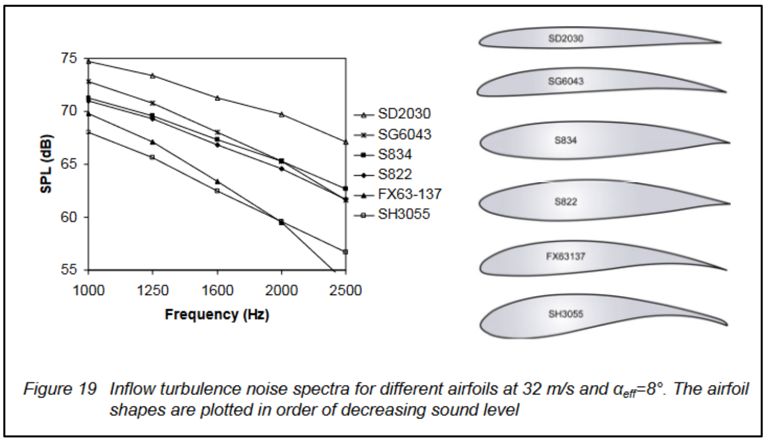


Figure 19 Inflow turbulence noise spectra for different airfoils at 32 m/s and α_{eff}=8°. The airfoil shapes are plotted in order of decreasing sound level

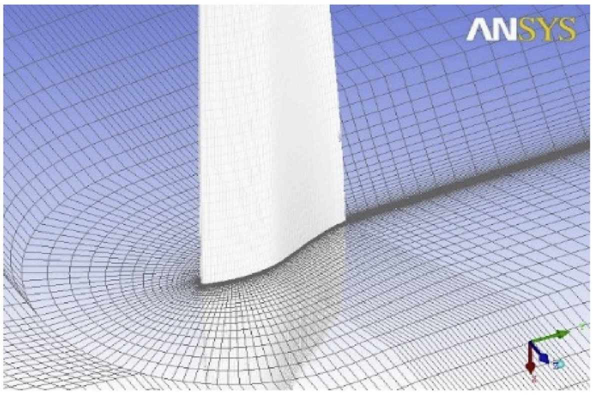
Figure 6. Effect of blade airfoil on noise generated at leading edge. The Figure is from the work of [(Oerlemans, Wind turbine noise: primary noise sources 2011)]

Current research is also focused on using special sinusoidal shapes at the leading edge, resembling serrations or notches. These solutions aim to mimic naturally occurring shapes like bird wings (Bodling, et al. 2017), (Paruchuri, et al. 2016). In laboratory conditions these methods have shown noise reduction up to 15 dB (Paruchuri, Joseph and Ayton 2018). However, these solutions are still in the experimental stage.

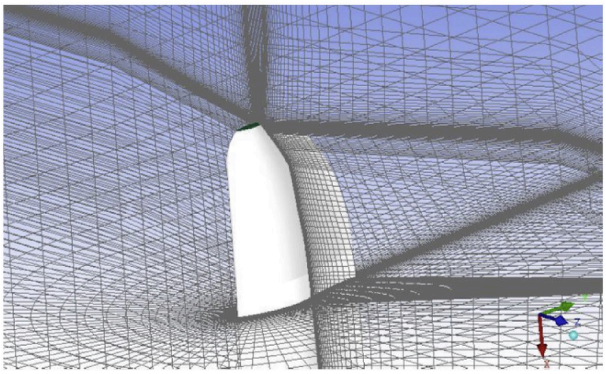
1.1.2.3 Tip noise

The high speed and small size of blade tips cause turbulence at the tips, generating high-frequency, broadband noise. Tip noise, alongside mechanical noise, is a significant source of annoyance for people living near wind farms, as it typically falls within the highly sensitive range of human hearing: 1-4 kHz (Deshmukh, et al. 2019).

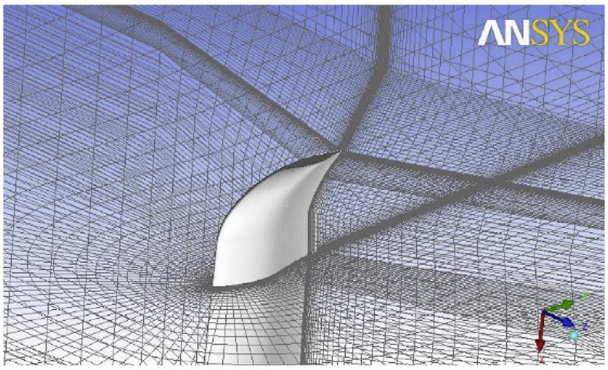
Using appropriate tip designs is a common method of reducing tip noise (Madsen and Fuglsang 1996). Similar solutions are used in aviation to reduce wing noise, providing many proven solutions. For wind turbines number of tip designs were proposed: slender, ogee or even resembling shark fin (Kinzie and Honhoff 2013), (Maizi, et al. 2018) (Figure 7). The impact of these designs can reduce overall noise levels by about 2-4 dBA, with the last solution (shark fin) showing a noise reduction of up to 7% in computational models.



a) Standard blade



b) Reference tip blade



c) Shark tip blade

Figure 7. The influence of the tip shape on wind turbine noise (Maizi, et al. 2018)

1.2 Other Source-Based Noise Reduction Methods

Intervening in the turbine's operation is also a method of reducing overall noise generated by the plant. The simplest solutions include:

- Reducing blade rotational speed,
- Adjusting blade pitch.

Blade rotational speed significantly impacts aerodynamic noise generation mechanisms. There are various theoretical relationships e.g. (W. 2010), that confirm the proportionality of the turbine's acoustic power level to blade rotational speed. Similarly, changing the blade pitch is crucial for reducing trailing edge noise, the dominant aerodynamic noise mechanism (Klug, et al. 1996).

Using these methods to reduce noise directly impacts the amount of electricity produced by each turbine, making them less preferred. However, these mechanisms, optimized for minimal energy production loss, are implemented in the quiet operation modes offered by almost every turbine manufacturer. Wind farm managers should use the quiet mode whenever there is a suspicion or confirmed exceedance of permissible noise levels in the environment.

1.3 Noise reduction methods at the immission point

If an acoustic climate assessment around a wind farm indicates that noise levels exceed permissible limits and source-based reduction methods are not feasible, the range of solutions becomes very limited.

The only significant method of reducing wind turbine noise at the immission point is increasing the acoustic insulation of residential building partitions. The overall insulation of an existing partition is most affected by its weakest element, often windows. Replacing windows with higher insulation ones (appropriate to the level of exceedance) is the correct solution. In Poland one can use guidelines from building acoustics standards, such as (PN-B-02151-3:2015-10 2015).

Due to the low-frequency characteristics of wind turbine noise and the presence of amplitude modulation, people more sensitive to noise may still experience annoyance despite the proper implementation of increased insulation. In such cases, using barriers (windows) with increased sound insulation, while a correct solution, may prove inadequate. Complaints about noise from wind farms may reach the wind park management even when noise standards are met.

2 “Soft” reduction methods

Wind turbine noise can cause annoyance in exposed individuals even when permissible noise levels are maintained. This affects satisfaction, quality of life, and leads to complaints against wind farm Managers. In such cases, the annoyance is not caused directly by the noise level but to the characteristics of its sound: spectrum (low frequency) and temporal pattern.

For wind turbine noise, it is considered that the main parameter influencing annoyance is amplitude modulation (as indicated by the HETMAN project results) – the noise level generated by the wind turbine periodically changing, decreasing and increasing, due to the rotation of the blades.

Annoyance is a measure of the subjective assessment of the source. Despite analyzing the impact of noise on annoyance, it cannot be ruled out that the overall annoyance is not solely related to the sounds emitted by the wind turbine. In many situations, it has been proven that non-acoustic factors, such as financial benefits from leasing land for turbines, properly conducted public consultations, visibility of the turbine from the residence, and landscape degradation, influence attitudes towards wind turbines.

The proposed "soft" methods presented in this part of the Catalogue are:

- Masking turbine noise with another noise source.
- Obstructing the wind turbine with greenery.

The first method tests the ability of another acceptable noise source to mask wind turbine noise. The combined noise level of the turbine and the masker may be higher, but the annoyance decreases due to reduced perception of amplitude modulation in the wind turbine noise.

The second method concerns reducing annoyance caused by the non-acoustic factor of the noise source's visibility. Covering the wind turbine does not significantly impact the perceived noise annoyance but is important in assessing the landscape and the overall attitude towards the environment in which the wind turbine is present but not visible or only partially visible.

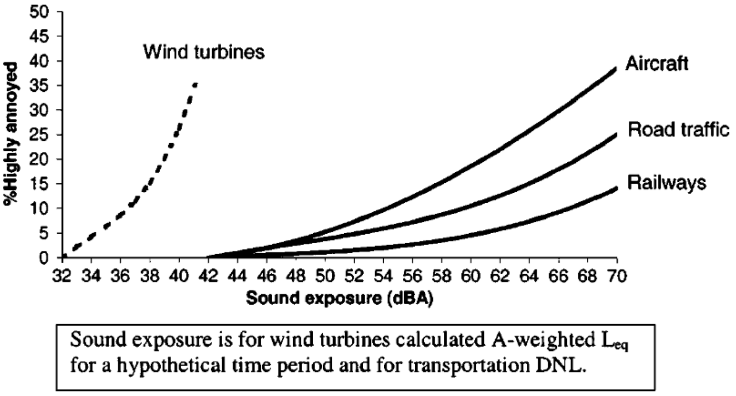
2.1 Masking effect as a tool to reduce wind turbine noise annoyance

2.1.1 Introduction

The masking phenomenon occurs when a masker sound (masker-M) causes an audio signal (signal-S) to become inaudible against a masker. The measure of masking is the increase of the threshold of hearing the signal in the presence of the masker. The masking phenomenon is used to test one of the basic properties of hearing - frequency selectivity, that is, just the perception of one sound against a background of another or other sounds. For maskers/stationary signals (e.g., unmodulated band noise and tonal signal), a masking model based on the power spectral density of the signal and the masker is used (Moore and Glasberg 1987). If the signal or masker is, for example, amplitude-modulated, or frequency-modulated, the effectiveness of masking is reduced, due to the occurrence of the CMR (comodulation masking release) effect, i.e. the phenomenon of unmasking (Schooneveldt and Moore 1989). As shown in earlier chapters, wind turbine noise (WTN) is characterized by periodic fluctuations in the instantaneous value of the sound level over time, called amplitude modulation for simplicity. Amplitude modulation certainly causes the effectiveness of wind turbine noise masking to be reduced.

There are many different types of sounds in the environment that constitute the so-called acoustic background that could be potential maskers for wind turbine noise. As for natural sounds, it could be the sound of the sea or the sound of trees. As for artificial sources of masking sounds, it could be traffic noise, especially from vehicle traffic on expressways and highways. One of the primary factors related to the location of WTN is the windiness of the area. Therefore, it can be considered that wind noise can be used as a masking sound. Unfortunately, the wind speed near the ground surface (about 1.5m above ground level) with a wind turbine in operation can be much lower than that prevailing at the height of the TW nacelle. Thus, wind sound is a rather unstable type of masker.

The situation is different for traffic noise from vehicles moving on expressways and highways. The noise level varies depending on the intensity of traffic, but practically occurs throughout the day. In addition, the areas around these types of roads have a rather limited use, related precisely to the impact of traffic noise. Therefore, it can be assumed that for locating a wind turbine in a traffic noise impact area, it will be possible to take advantage of the WT noise masking effect. In addition, the dose-response curves, presented in Figure 8 show that traffic noise is rated as annoying as wind turbine noise at higher levels. This means that masking wind turbine noise is possible with sound that does not increase the overall feeling of annoyance caused by the noise for people living near their sources.



Sound exposure is for wind turbines calculated A-weighted L_{eq} for a hypothetical time period and for transportation DNL.

Figure 8. A comparison between the dose–response relationship for transportation noise. Figure is from article (Pedersen and Persson Waye, Perception and annoyance due to wind turbine noise—a dose–response relationship 2004)

The idea of masking WTN noise by natural sounds or traffic noise is not a new issue. In the existing literature, one can find papers on this topic. However, it is important to distinguish whether the studies concerned the determination of detection thresholds for WTN noise against a masker, or a comparison of the annoyance of the masker and the masker against which WT noise was presented.

Researchers (Bolin, Nilsson and Khan 2010) investigated the ability of natural sounds to mask WTN sounds. Three types of natural sounds were used the noise of a forest of deciduous trees, coniferous trees and the noise of sea waves. WTN sound was recorded from a distance of 200 m or 400 m. Turbine sounds were presented at 40 dBA. The measurements took place in an acoustically isolated room, and all sounds were presented through headphones. The masking thresholds for WTN sounds, expressed by the SNR value (the ratio of the WTN noise level to the noise level of natural sounds), ranged from -10 to -9 dB for a single turbine and -11.4 to -8.3 dB for seventeen turbines. Taking into account 95% confidence intervals, SNR values reached as low as -13 dB. This means that only when the sound level of the maskers exceeded the sound level of the WTN by several dB then the masking of WTN occurred.

In a paper (Pedersen, van den Berg, et al. 2010), the authors showed that when perceiving WTN sound against traffic noise with LDEN 20 dB greater than wind turbine noise, WTN is identified in about 30% of cases. Moreover, in a paper (Pedersen, van den Berg, et al. 2010) the authors indicated that for WTN masking to be effective, the traffic noise level should be about 20 dB greater than the WTN level.

A publication (Johansson, Bolin and Alvarsson 2019) studied the masking effect of WT by the sound of a deciduous forest, urban traffic and traffic noise. When WTN noise was presented against a background of maskers, then WTN sound was only perceptible for a SNR range of -14 to -7 dB, very weakly annoying when the SNR was between -8 and -4 dB, weakly annoying when the SNR was between -4 and -2 dB, and moderately annoying when the S/N was between 2 and 4 dB.

(Schaffer, et al. 2016) compared the annoyance of wind turbine sound with that of traffic noise. For both WT and traffic noise, sound samples were prepared without amplitude modulation, with random AM modulation and regular AM modulation. It was shown that for the same signal levels, the sound of WTN was more annoying than that of road noise, even when they were unmodulated sounds.

The above-mentioned conclusions of the papers mostly refer to the thresholds of WTN sound perception expressed in dB SNR, not to the thresholds of perception of differences in annoyance of sounds, and they do not include the aspect of the relative difference in distance between the observer and the source of the masker and signal.

2.1.2 Experiments

A series of psychoacoustic experiments were carried out, the purpose of which was to determine the discrimination thresholds of WTN annoyance against traffic noise, depending on the relative distance between the source of the signal (WT) and the source of the masker (the road lane on which motor vehicles travel). For fixed observer-lane distances (250, 500, 1000 and 2000m), the smallest observer-TW distance for which traffic noise is as annoying as WTN noise against road noise was determined. The results were then converted into values expressed in dB SNR. Two series of tests were performed, in the first series (Experiment 1) the sounds presented were traffic noise and WTN noise against road noise. In the second series of tests (Experiment 2), wind noise was added to all stimuli, which was recorded using a B&K artificial head and torso placed in an anechoic chamber during the flow of a 4m/s airstream. The wind speed was equal to the wind speed at the observation point during WT operation, the noise of which was evaluated in the experiment. The tests were performed in an acoustically isolated room under free-field conditions, with the levels of the presented sounds as in real conditions. Twenty-four people with normal hearing participated in both series of experiments. Details of the study are provided in the paper (Buszkiewicz, Wicher and Pyffel 2023). Figure 9 shows the results of the study.

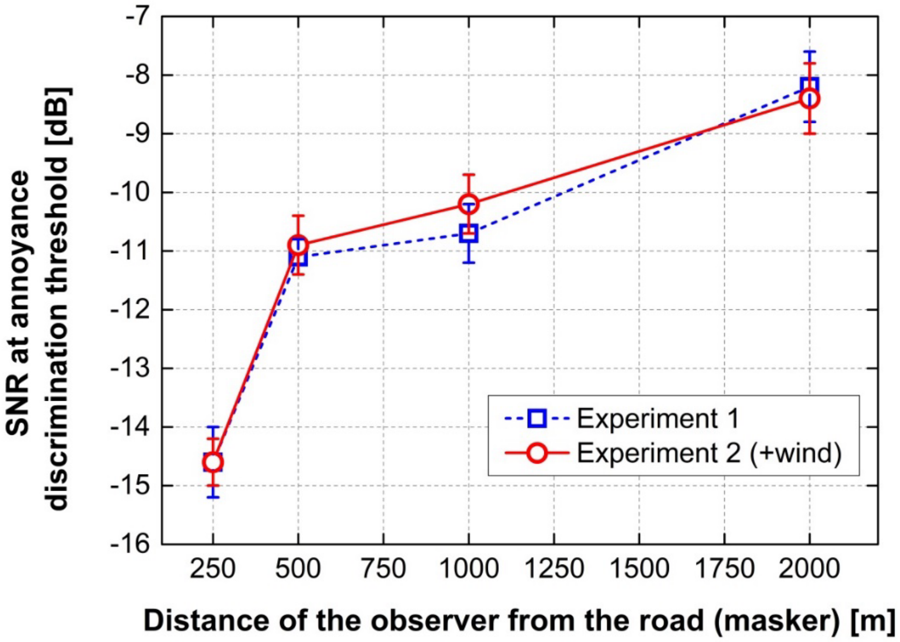


Figure 9. Mean SNR values at the annoyance threshold as a function of the observer's distance from the road. Vertical bars indicate 95% confidence intervals for mean values.

2.1.3 Results

The results in Figure 9 show that the average SNR value at the annoyance discrimination threshold between traffic noise and WTN noise against traffic noise increases as the distance of the masker from the observer increases. Considering the lower value of the 95% confidence interval, it can be assumed that the minimum SNR values for each distance from the road are as shown in Table 1

Table 1 Minimum SNR values (after rounding) corresponding to annoyance discrimination thresholds for individual distances of observation points from the road. Results obtained from Experiment 1 and 2.

Distance of observation point from road [m]	Minimum SNR for annoyance discrimination threshold [dB] (Experiment 1)	Minimum SNR for annoyance discrimination threshold [dB] (Experiment 2)
250	-15	-15
500	-11	-11
1000	-11	-11
2000	-9	-9

Since the results of Experiment 1 and Experiment 2 in Table 1 are the same, so the final minimum SNR values for the discrimination threshold are summarized in the table below (Table 2).

Table 2. Minimum SNR values corresponding to annoyance discrimination thresholds for particular distances of observation points from the road.

Distance of observation point from road [m]	Minimum SNR for annoyance discrimination threshold [dB]
250	-15
500	-11
1000	-11
2000	-9

2.1.4 Discussion and implementation techniques

The data in the Table 2 indicate that the masking of WTN noise by road noise is not very effective. However, these results can be used at the stage of planning the placement of individual wind turbines in the area around expressways and highways. If in a given area the value of traffic noise level is equal to or greater than the absolute value of SNR (|SNR|) then traffic noise is the dominant factor affecting annoyance, and the contribution of WTN noise to the resultant annoyance can be ignored.

2.2 The influence of the visual factor in evaluating wind turbine noise annoyance

2.2.1 Introduction

The negative attitude of a significant part of the public towards wind turbines is due not only to the annoyance caused by the noise generated by wind turbines. Many factors beyond acoustics influence the perception of this technology. It turns out that for people living near wind farms, acoustic factors are not the decisive criterion influencing their attitude toward wind turbines (Caporale, et al. 2020). These factors include the location of the wind turbine, the economic benefits of the turbine(s), general attitudes toward wind power and renewable energy sources, education about the effects caused when the turbines are operating, transparency in decision-making by the authorities, and visibility where people live. The latter aspect is often cited in surveys (Klæboe and Sundfør 2016) as an effect that pollutes the landscape and (along with noise) affects the decline in parcel values (Gibbons 2015) (Jensen, et al. 2018) (Pedersen and Persson Waye, Audio-visual reactions to wind turbines 2003). Visual stimuli are often overlooked in psychoacoustic studies - not just those devoted to wind turbines. These studies mainly focus on assessing the annoyance of isolated auditory stimuli. However, reports in the literature show that audiovisual presentation allows subjects to be more engaged in experiments (Opoku-Baah, et al. 2021) (Woodcock, Davies and Cox 2019), allows for better understanding of speech, and places listeners in the appropriate "context," in which the presented sounds may actually occur (so-called "ecological validity") (Fichna, et al. 2021) (Maffei, et al. 2013) (Sun, De Coensel and Echevarria Sanchez, et al.

2018). In the case of noise annoyance studies, the purpose of visually presenting a sound source is to examine its impact on auditory perception. The placement of other visual objects can lead to a reduction in the negative impact of the sound source on annoyance by masking the noise source. The main indicator of the effectiveness of such masking is the reduction in annoyance rating (on the ICBEN scale: 0-10).

In considering the annoyance of wind turbine noise, numerous studies have been conducted that take into account the influence of the visual factor on the assessed annoyance. In experiments comparing ratings of wind turbine noise annoyance from a presentation of the sound of the turbine alone and a presentation of the sound combined with a video, it was shown that the view of a wind turbine negatively affects annoyance rating (Gibbons 2015), (Pedersen and Larsman, The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines 2008). Therefore, it can be concluded that obstructing an existing wind turbine will result in the opposite trend. The results of the WINDFARM perception project also indicate that the visibility of wind turbines can potentially amplify noise annoyance. A suggested reason for this effect is the high contrast between the landscape and the wind turbine(s), which stand out from their surroundings. The proposed solution was to reduce the visibility of the turbine. On the other hand, in a large-scale survey of attitudes toward wind technology, it was observed that attitudes toward the appearance of wind turbines strongly influenced ratings of the annoyance of the noise generated by them (Pedersen and Larsman, The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines 2008). The effect was even more significant when the terrain surrounding the respondents' households allowed wind turbines to be easily seen (it was flat, without vegetation or buildings). The study used forms with illustrations of wind turbines, and the immission values (for acoustic exposure analysis) in were calculated. The paper (Gille, Marquis-Favre and Lam 2017) even pointed out that the view of a noise source (not necessarily a wind turbine) can increase annoyance ratings even if the visual stimulus does not correspond to the visual stimulus. It should also be noted that the visual aspect alone (the sight of a turbine) can induce an extremely negative attitude toward wind turbines and increase the number of people declaring extreme annoyance (% HA - highly annoyed). We are talking about the phenomenon of shadow-flicker, which occurs when a turbine blade cuts through a beam of sunlight falling on a people's place of residence (e.g., through a window into the interior of a house) causing a stroboscopic effect. The annoyance caused by shadow flicker correlates with wind turbine noise exposure and feelings of safety (Pedersen and Persson Waye, Audio-visual reactions to wind turbines 2003) (Voicescu, et al. 2016). Covering up a wind turbine casting a flickering shadow can eliminate its negative impact and reduce potential health effects (including reported nausea).

The influence of a visual factor on annoyance ratings cannot always be clearly established. A number of studies have observed that the presence of a visual stimulus (the view of a traffic noise source) was not related to annoyance ratings (Sun, De Coensel and Echevarria Sanchez, et al. 2018). The visual stimulus, however, had an impact on the ability to focus of the subjects, who declared greater sensitivity to visual sources of distraction (just as noise-sensitive individuals obtain higher annoyance ratings) which, consequently, may lead to a more negative evaluation of the entire stimulus. Ambiguities also arise when considering the type of objects intended to cover the noise source. Most often, two groups of objects are considered: "green," having a natural source such as trees, shrubs or landscaping; and artificial, man-made such as buildings, screens, walls, vehicles, etc. In studies on the type of objects obstructing the view of a noise source, it has been observed that it is not statistically significant whether one is dealing with a "green" veil (trees, shrubs) or a man-made object when it comes to influencing annoyance ratings (Sun, De Coensel and Gemma Maria, et al. 2016).

So-called HMDs ("head-mounted display"), also known as VR goggles, are increasingly being used for psychoacoustic research that takes into account the influence of visual factors. The use of goggles in psychoacoustic experiments ensures greater involvement of listeners in the study by placing them in a context that corresponds to real-life listening conditions thereby increasing so-called "ecological validity" (Maffei, et al. 2013). Most contemporary designed experiments in VR environments use 3D game engines (e.g. Unity, Unreal Engine). Such studies, similar to computer games, allow subjects to interact with the virtual environment and provide a greater amount of data provided to researchers (including by collecting responses from controllers or recording the areas the subjects look at).

2.2.2 Experiment

The HETMAN project conducted a study using audiovisual stimuli presented in a virtual reality environment using HMD goggles. The study tested whether the partial covering of a wind turbine affects the evaluation of noise annoyance. The study used audio recordings collected during environmental measurements at a wind farm in central Poland. During the measurements, the Farm Manager allowed some of the turbines to be turned off, so the recorded sound came from only one device. The recordings were made at distances of 500m, 750m and 1000m using an ambisonics microphone, the noise level was controlled with a class 1 sound level meter. Wind speed and other meteorological parameters were also recorded during the measurements.

The experiment was prepared in the Unity game engine. A series of scenes were prepared showing a single wind turbine set at distances correlating with those from measurements. With spatial sound recordings, the wind turbine was played in a way that mirrored real conditions - by moving their heads (with VR goggles on), the subjects changed the angle from which they heard the source. The sound levels of the reproduced sounds were calibrated to the levels recorded with a sound level meter. Professional headphones with flat frequency response were used to present the turbine recordings.

Scenes were varied due to the distance of the turbine from the observation point, but also due to the degree of obscuration. Three degrees of obscuration were used:

- (1) only the tip of the blade of the propeller visible,
- (2) half of the blade working surface of the propeller including the nacelle visible,
- (3) the turbine completely visible (Figure 10).

The article (Palmer 2022) was the inspiration for the degrees of obscuration used.

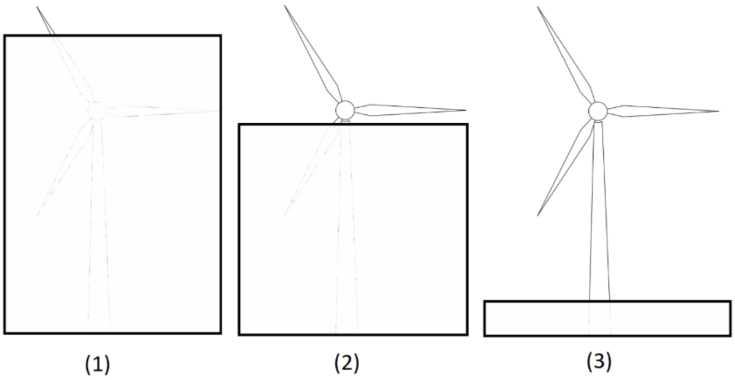


Figure 10. Degrees of obscuration of the wind turbine; (1) only the tip of the blade is visible, (2) half of the working surface of the blade including the nacelle is visible and (3) the turbine is completely visible

The objects used to obscure the turbine were trees and landforms. The scenes were fully animated: the turbine ran at the frequency observed during the measurements, the trees moved in the wind, the subjects changed their viewing (and hearing) angle depending on which direction they turned their heads. The experiment involved 20 normal-hearing subjects aged 20-52. Each subject was asked to rate the sounds on an ICBEN scale (0-10, where: 0-not at all annoying, 10-extremely annoying) that they heard during an audiovisual presentation. After answering, the experiment presented the next scene. Each type of stimulus had several variations, and all types were presented several times, for 30 seconds, in random order.

2.2.3 Results

The results of the experiment show that the degree of obscuration of the turbine has no significant effect on the evaluation of annoyance (F=1.761; p=0.173). The effect of the distance of the wind turbine from the listener, and therefore the noise level correlating with it, was significant (F=23.410; p<0.01). The influence of the listener was random. The results of the experiment are shown in the Figure 11. The results of the statistical analysis are included in the Table 3 below. The contrast analysis can be found in the Table 4.

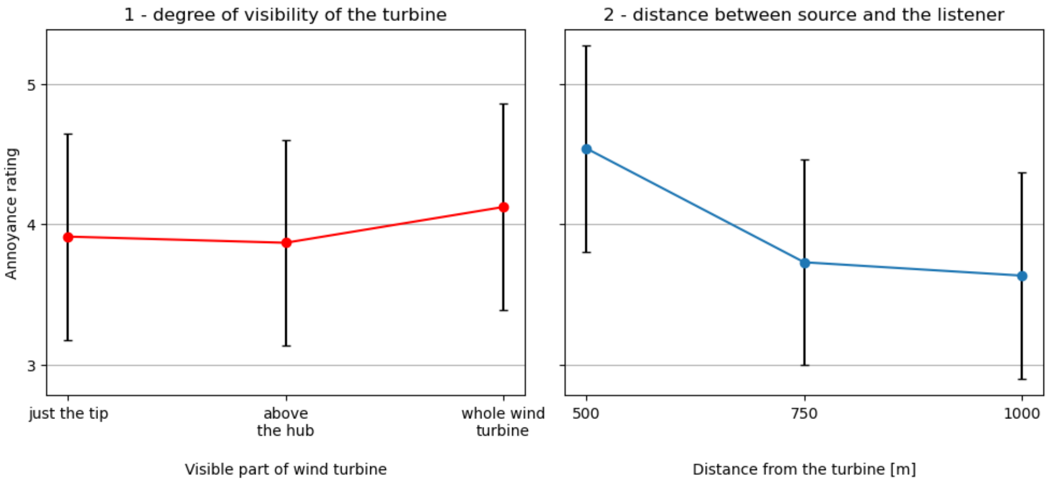


Figure 11. The results of the experiment - influence on the evaluation of annoyance: (1) factor: the degree of obscurity of the turbine, (2) factor: the distance from the tested

Table 3. Results of statistical analysis

Source	F	df1	df2	Significance
Corrected model	6.674	8	531	<.001
distance	23.410	2	531	<.001
visibility	1.761	2	531	0.173
distance * visibility	0.762	4	531	0.550

Table 4. Contrast analysis for the variable: distance

Pair contrasts							
Distance - Pairing Contrasts	Contrast estimation	Standard error	t	df	Corrected significance	95% confidence interval	
						Lower threshold	Upper threshold
500 - 750	0.811	0.146	5.574	531	3.955E-8	0.525	1.097
500 - 1000	0.906	0.146	6.224	531	9.870E-10	0.620	1.191
750 - 500	-0.811	0.146	-5.574	531	3.955E-8	-1.097	-0.525
750 - 1000	0.094	0.146	0.649	531	0.517	-0.191	0.380
1000 - 500	-0.906	0.146	-6.224	531	9.870E-10	-1.191	-0.620
1000 - 750	-0.094	0.146	-0.649	531	0.517	-0.380	0.191
The corrected significance level for the least significant difference is 0.05.							

2.2.4 Discussion and implementation techniques

Several conclusions are reached from the results:

1. The evaluation of annoyance is not affected by the degree of obscurity of the wind turbine.
2. The distance at which the wind turbine is presented is a statistically significant factor. This is probably due to the noise level of the wind turbine correlating with the distance, which confirms the previous theory of the main effect of sound level on the annoyance rating.
3. The statistical analysis shows that significant differences in annoyance ratings are obtained for the distance of the turbine from 500m to 750m or from 500m to 1000m. This leads to the conclusion that shifting the wind turbine further away than 750m will not result in a greater gain in annoyance rating.

The above results refer to the case in which the wind turbine worked under specific meteorological conditions. For planning purposes, such as the extent of the noise impact, it is always necessary to consider levels calculated taking into account all possible meteorological conditions.

The literature and studies conducted indicate that the effect of the visibility of the sound source has little or no significant effect on lowering noise annoyance ratings. In addition, this effect may be due to individual characteristics of people exposed to visual and auditory stimuli such as attitudes toward the appearance of turbines, sensitivity to noise or general attitudes. Such a tendency is noticeable for all noise sources, including wind turbines. Total or partial cover of a wind turbine also has no significant effect on the evaluation of noise annoyance, as evidenced by the results presented here.

However, the idea for obscuring wind turbines should not be completely dismissed. Natural, "green" coverage should be considered as a means to make wind turbines located near households more acceptable. It is not only acoustic criteria that determine the attitude of respondents towards wind technology. One should also not forget purely visual factors, such as shadow flicker, which can be reduced by covering the turbine. Attention to the aesthetics of the surroundings of wind farms, even if it does not result in less noise-induced annoyance, can contribute to a more positive perception of wind technology and, consequently, its acceptance as an alternative to current energy sources.

3 Summary

Two groups of methods have been proposed for reducing noise/annoyance from wind turbines (WTs) so-called: "hard" - referring to noise sources, and "soft" using, among other things, the presence of other noise sources than WTNs and terrain. Table 5 and Table 6 which presents summary of described methods are placed in the end of this Deliverable.

WTN noise sources can be divided into two main categories: mechanical and aerodynamic noise sources. Noise reduction studies consider three areas where action can be taken: at the source of the noise, along the propagation path and at the point of immission. Mechanical noise reduction is achieved through the use of vibroacoustic isolation of equipment operating inside the nacelle. Aerodynamic noise is caused by the formation of air turbulence between the turbine blade and the incoming wind - methods to reduce it focus on shaping the blades to make them more aerodynamic. There are also methods related to the organization of WTN operation such as reducing blade speed or asynchronous operation of turbines in a wind farm. At the point of immission, windows with increased sound insulation can be used to reduce noise entering homes.

With regard to "soft" methods of reducing WTN noise annoyance in the environment, there are many different types of sounds that could be potential maskers for WT noise. In the case of artificial sources of masking sounds, this could be traffic noise from vehicles traveling on expressways and highways. A series of psychoacoustic experiments were carried out with the aim of determining the discrimination thresholds of WTN annoyance against traffic noise, depending on the relative distance between the source of the signal (WT) and the source of the masker (the traffic lane on which the vehicles travel). For fixed observer-lane distances (250, 500, 1000 and 2000m), minimum values expressed in dB SNR were determined, corresponding to annoyance discrimination thresholds for particular distances of observation points from the road. These results can be used at the stage of planning the placement of individual wind turbines in the vicinity of expressways and highways. If, in a given area, the value of the traffic noise level is equal to or greater than the absolute value of the SNR (|SNR|) then traffic noise is the factor affecting annoyance, and the contribution of WTN noise to the resultant annoyance can be ignored.

The HETMAN project also tested another of the so-called "soft" methods of reducing WT annoyance, relating to reducing the visibility of the working WT at the observation point. A study was conducted using audiovisual stimuli presented in a virtual reality environment using HMD goggles. The study tested whether partial obscuring of a wind turbine affects the evaluation of noise annoyance.

Due to the spatial sound recordings, the wind turbine was played in a way that reflected real-world conditions - by moving their heads (with VR goggles on), the participants studied changed the angle from which they heard the source. The objects used to obscure the WTN were trees and landforms. The scenes were fully animated. The results indicate that the degree of obscuration of the turbine has no significant effect on the evaluation of annoyance. The effect of the distance of the wind turbine from the listener, and thus the noise level correlating with it, turned out to be significant. However, the validity of obscuring wind turbines should not be overruled. Natural, "green" shading should be considered as a means to make WTs located near households more acceptable. It is not only acoustic criteria that determine attitudes toward wind technology. Factors such as shadow flicker, which can be reduced by covering the turbine, should also not be overlooked. Attention to the aesthetics of the surroundings of wind farms can contribute to a more positive perception of wind technology and, consequently, its acceptance as an alternative energy source.

Table 5. Wind turbine noise/annoyance reduction methods - "hard" methods

"HARD" METHODS			
Scope of impact	Method	Noise source	Effectiveness
Methods of reducing mechanical noise.	Increased insulation of nacelle partitions and vibro-acoustic isolators used between units.	Equipment operating inside the nacelle: gearbox, generator, cooling equipment - also generating noise of a tonal nature.	Reduction of the total noise level by 15 dB.
			Reducing tonal components (avoiding tonality penalties).
Methods of reducing aerodynamic noise.	Turbine propeller speed reduction.	Turbulence arising at the back edge of the blade ("trailing edge"), the tip of the blade ("tip"), and turbulence arising from the reaction of the rotating propeller with incoming air masses (so-called "inflow turbulence").	Reducing the rotational speed has a non-linear effect on reducing the sound power level. However, at the same time, as the rotational speed decreases, the power of the turbine decreases (a relationship that is also nonlinear).
	Adjusting the angle of attack of the blade.		Reducing the angle of attack by 1° reduces the sound power level by 1dB. At the same time, the power of the turbine decreases by about 1-3% (per year).
	Use of blade tips with a shape that reduces so-called "tip noise".	Turbulence generated at the ends ("tip") of a rotating wind turbine propeller.	7% reduction in sound power level, with a 3% reduction in turbine power.
	Use of comb-like blade ends to reduce turbulence.	Turbulence arising at the back edge of the blade("trailing edge").	Reduced sound pressure level by about 3.2 dB in 6-10m/s winds.
	Use of blades with a special cross-section (airfoil) - reduction of turbulence resulting from passes through areas with different wind speeds.	Turbulence arising at the leading edge of the blade.	Reduction of noise levels by 2-4 dB.
Noise reduction methods at the point of immission.	Use of windows with improved sound insulation.	WTN noise as a whole whose level and spectral characteristics depend on propagation conditions.	> 30 dBA

Table 6. Wind turbine noise/annoyance reduction methods - "soft" methods

<table>
<tr><th colspan="4">"SOFT" METHODS</th></tr>
<tr><th>Scope of impact</th><th>Method</th><th>Noise source</th><th>Effectiveness</th></tr>
<tr><td>Organizational methods.</td><td>Organizational changes in the operation of turbines on the farm.</td><td>All wind turbines on the farm whose propellers rotate in the same phase.</td><td>Reducing the depth of amplitude modulation of noise propagated from the entire wind farm can have a positive effect on reducing annoyance.</td></tr>
<tr><td rowspan="2">WTN annoyance reduction method.</td><td>Using traffic noise as a masking sound for WTN.</td><td>Turbine noise considered as a whole, spectrum, time course and (according to WP1 results) amplitude modulation.</td><td><table>
<tr><th>Distance between observation point and road [m]</th><th>Minimal SNR for annoyance discrimination threshold [dB]</th></tr>
<tr><td>250</td><td>-15</td></tr>
<tr><td>500</td><td>-11</td></tr>
<tr><td>1000</td><td>-11</td></tr>
<tr><td>2000</td><td>-9</td></tr>
</table></td></tr>
<tr><td>Obscuring the WT view with objects (buildings, trees, etc.), as well as taking advantage of the terrain.</td><td>A view of the working WT.</td><td>No significant impact. However, this method is recommended due to the reduction of the shadow flicker effect from WTN blades and the improvement of aesthetics in the surroundings of wind farms.</td></tr>
</table>

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