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D1.2 Determination of wind turbine noise parameters crucial for annoyance (M12)

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

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D1.2 Determination of wind turbine noise parameters crucial for annoyance (M12)

Executive summary

In the study of annoyance due to wind turbines, the dominant approach takes into account only the noise generated by these sound sources. However, there are studies which show that this value alone is not enough to explain why for the majority of people living near wind turbines their noise is extremely annoying, despite the fact that the measured sound level values are relatively low. One way of solving this problem is to introduce a correction to the one-factor noise index. This has already been done by taking into account the time variability (amplitude modulation) of the sound generated by wind turbines. Another proposal is to establish a multifactorial noise index which includes not only the noise parameters, but also non-acoustic characteristics (mainly visual), which are supposed to influence the overall perception of the annoyance associated with wind turbines. These two approaches will be discussed in this paper.

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How to determine the annoyance due to wind turbines

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Abstract. In the study of annoyance due to wind turbines, the dominant approach takes into account only the noise generated by these sound sources. However, there are studies which show that this value alone is not enough to explain why for the majority of people living near wind turbines their noise is extremely annoying, despite the fact that the measured sound level values are relatively low. One way of solving this problem is to introduce a correction to the one-factor noise index. This has already been done by taking into account the time variability (amplitude modulation) of the sound generated by wind turbines. Another proposal is to establish a multifactorial noise index which includes not only the noise parameters, but also non-acoustic characteristics (mainly visual), which are supposed to influence the overall perception of the annoyance associated with wind turbines. These two approaches will be discussed in this paper.

Keywords: one-factor noise index, correction to the one-factor noise index, multifactorial noise index.

1. Introduction

Analysis of surveys on noise annoyance assessments shows that the noise index L_{den} explains less than 30% of the variance contained in the data obtained from respondents (Basner, et al., 2017; Guski, et al., 2019). This percentage relates generally to transportation noise. In the case of noise generated by wind turbines, this percentage of the explained variance is even smaller, amounting to 9% (Michaud et al. 2016). Nevertheless, this single-factor noise indicator for wind turbines is used in many countries in Europe and in the world. Davy et al. (2018) have presented a comprehensive overview of wind turbine noise limits, shown in Tab. 1. This information has been checked as far as possible against the 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 and 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 L_{den} and L_{dn}, and/or corrections for amplitude modulation and pure tones.

According to Davy et al. (2018) a limited number of countries have specific wind turbine sound limits (listed in Tab. 1.). In most other countries, industrial noise limits are applied to wind turbines. The latter situation also applies to Poland. The noise limits for industry (as well as for wind turbine noise) are expressed in L_{AeqD} with a reference time interval of the 8 most unfavorable hours of the consecutive day, and L_{AeqN} with a reference time interval of the 1 most unfavorable hour at night (Minister's regulation of January 22, 2014). The numerical values of these limits vary depending on the type of terrain and amount: for L_{AeqD} from 45 dB for the protection zone (e.g. hospitals) to 55 dB for urban zone cities with more than 100,000 inhabitants; and for L_{AeqN} from 40dB to 45dB.

Moreover, in Poland there is an Act of 20 May 2016 specifying the distance at which wind farms or residential buildings can be located and built. This distance is equal to or greater than ten times the height of the wind turbine measured from ground level to the highest the point of the structure, including technical elements, in particular the rotor with blades (total height of the wind farm). This is a piece of legislation (known as "10H") that does not exist at the state level in any other country. This suggests that the annoyance due to noise generated by wind turbines can be measured in "meters" regardless of the type of turbine, wind speed, time of day, etc.

Table 1. Current limits for wind turbine noise in some countries

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	

As can be seen from the data in Tab. 1, some countries propose a decibel correction of noise limits related to different wind speeds or due to the time of day and the type of terrain, and also due to the presence of amplitude modulation or tonal components in the noise spectrum. In this paper, several factors that should be considered when setting noise limits will be discussed.

2. Health effects related to wind turbine noise

In the review paper (updated to 2020) on the health effects related to wind turbine noise (van Kamp & van den Berg, 2021), the following effects are discussed: **annoyance, sleep disturbance, cardiovascular effects, metabolic effects, mental health** and **cognition**.

2.1. Annoyance

Annoyance seems to be the most important health effect related to wind turbine noise. The percentage of highly annoyed (%HA) people is obtained from responses to a standard survey question (ISO/TS 15666:2021) referring to wind turbine noise. There is a conditional recommendation in the WHO document (2018) regarding the permissible noise level generated by wind turbines. If the value of this level is less than 45 dB L_{den}, then any health effects below this value are acceptable (including annoyance). The main conclusion is that wind turbine noise is associated with noise annoyance, and is moderated by several personal and contextual aspects, such as noise sensitivity, attitude towards wind turbines, or economic benefit (van Kamp & van den Berg, 2021)

2.2. Sleep disturbance

Studies on sleep disturbance are usually based on measures such as self-reported sleep disturbance, and on certain objective sleep parameters measured with polysomnography (Freiberg et al., 2019). The conclusions of their studies are in line with an earlier study by Basner et al., (2018) that the evidence for sleep disturbance from wind turbine noise is only emerging and no ERF (exposure-reaction function) exists as yet.

2.3. Cardiovascular effects, metabolic effects

The results of the WHO evidence review on both cardiovascular and metabolic effects (van Kempen et al., 2018) do not support any association between wind turbine noise and hypertension, ischemic heart disease or stroke. The same is true for a higher risk of diabetes.

2.4. Mental health and cognition

Clark, et al., 2020 concluded that there is very low-quality evidence to support a connection between wind turbine noise and mental disorders (anxiety, depression). A similar conclusion was drawn by Freiberg et al., 2019.

3. Factors influencing the assessment of noise generated by wind turbines

3.1. Amplitude modulation

Noise generated by wind turbines is always more or less amplitude modulated. This amplitude modulated sound is very characteristic for wind turbines and makes it easy to recognize wind turbine noise even at very low levels. A modulation depth of only 2 dB is sufficient to clearly identify the noise from a wind turbine (Yokoyama, et al., 2013). Lee et al. (2011) have shown that the annoyance increases with increasing modulation depth. There are plans, for example in the UK, to introduce a special penalty for amplitude modulation. 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 (Perkins, et al., 2016). This has been validated in a lab experiment by Lotinga and Lewis (2021). In Australia, New South Wales, a 5 dB penalty is applied if the modulation depth is greater than 4 dB (NSW, 2016).

3.2. Infrasound and low frequency noise

Baliatsas *et al.* (2016) have published a comprehensive review of the 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 the possible effects of exposure to infrasound from wind farms has recently been published by a research team in Finland. Long-term recording of infrasound levels and comprehensive social surveys were carried out 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 subjects 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 had been 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).

3.3. Pure tones

Noise containing pure tones is considered more annoying than broadband noise. Most standards for assessing noise therefore recommend 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. Pure tone correction is not an important issue for modern wind turbines.

3.4. Wind turbine noise and background noise levels

The problem related to the background noise level is particularly important in those countries where noise limits refer to the so-called "ambient sound level". If the wind farm is located near a highway, the noise generated by highway traffic may mask the noise generated by wind turbines (van Renterghem, et al., 2013). In addition to other noise sources that can mask wind turbine noise, the sound generated by the wind itself can be a good masker. Wind speeds of around 6-8 m/s may generate sound levels at around Lp 50 – 70 dBA, whereas the noise from a wind turbine is typically Lp 40 – 50 dBA at the closest dwellings. Both sources produce broadband noise (Gjestland, 2008)

3.5. Noise propagation characteristics

There are many characteristics related to the noise propagation of wind turbines whose values have an impact on the measured or forecast noise level at the recipient site. These characteristics relate primarily to meteorological conditions like **temperature** or **humidity**, but also to **ground surface conditions**, **wind speed** and **wind direction**. After all, if the noise level at the recipient site is forecast, its value depends on the model by which it is forecast. The issue here is the possible applications of one of the noise forecasting models existing in the literature: ISO 9613, Nord-96, Cnossos-EU or Nord 2000.

4. Multifactorial noise index- aggregate annoyance index

Already in 2016 it was found (Michaud, et al.,2016) that the noise annoyance model for wind turbines based on one factor (the sound level) explains only 9% of the variance. The percentage of the explained variance is 58% if other factors which are present during wind turbine operations are also taken into account, such as the visual impacts, shadow flicker or vibrations. This line of thinking has led to the creation of a multifactorial noise index, the so-called aggregate annoyance construct. An aggregate annoyance construct has been developed to account for magnitudes of annoyance that range from not at all annoyed to extremely annoyed with regard to **five wind turbine features** (Michaud, et al., 2018). These features included **noise**, **shadow flickers**, **blinking lights**, **visual impacts** and **vibration**. In practical terms this meant that participants were asked to indicate their magnitude of annoyance in response to noise, blinking lights, shadows or flickers of light, visual impact and vibration or rattles noticed indoors that coincided with participant's recollection of wind turbine operations. The annoyance response categories were: not at all, slightly, moderately, very, and extremely annoyed. The possible range in aggregate annoyance was 0 to 20. A score of 0 reflects no perception of/annoyance toward any wind turbine features, and a score of 20 reflects extreme annoyance experienced in response to all 5 features. Of the five aggregate annoyance factors, it was found that when the sources of annoyance were eliminated one by one, all had a similar effect on reducing aggregate annoyance. The exception was annoyance in response to vibration, which did not result at any apparent change in aggregate annoyance. The idea of a multifactorial noise index is very promising , but in the present form it is very difficult to apply this for regulatory purposes. However, it may be used to try to explain the combined effect of wind turbine noise.

5. Discussion

As for the health effects that can be associated with the operation of wind turbines, more recent literature data confirmed the WHO (2018) conclusion that only annoyance correlates with this noise in a statistically significant way. Wind turbine noise is not associated with hypertension, ischemic heart disease or stroke, or with sleep disturbance, mental health and cognition. Therefore, the recommendations regarding the noise limits for wind turbines were established only on the basis of this health effect, i.e. annoyance (WHO, 2018), and it is expressed in the L_{den}. However, as is well known, the relationship between the noise annoyance assessment (%HA) of wind turbines and the noise dose expressed as L_{den} explains only 9% of the variance, of course referring to *in situ* studies.

Hence, researchers constantly attempt to modify the noise indicator L_{den} with corrections that would take into account other factors apart from the level of noise characteristics. Among the other factors mentioned in this article that may affect the perception of annoyance due to wind turbines, the presence of amplitude modulation in the noise spectrum generated by wind turbines is crucial. To the best of our knowledge, in New South Wales, Australia, there is a 5 dB penalty if the modulation depth is greater than 4 dB (NSW, 2016).

In the case of infrasound and low frequency noise, the prevailing view is 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. This conclusion is supported by the study performed in Finland in 2020. Furthermore, tonality is no longer a problem with the perception of noise from wind turbines. Tonal components do not occur in the spectrum of wind turbine noise generated by newer installations.

However, a problem is posed by the ratio of wind turbine noise to background noise. This ratio is not constant for different wind farms, therefore making noise limits dependent on the background level seems to be the right solution. The same is true for the noise propagation characteristics. Their value significantly influences the measured or forecast noise level. Hence it is not surprising that the value of noise limits depends on e.g. wind speed or the nature of the terrain as well as on background noise (see Tab.1).

As can be seen from the discussion so far, the single-factor noise index needs to be corrected for many factors, or it should be replaced by a multifactorial noise index, such as an aggregate annoyance index. First, we shall note the advantages of this proposal. In this approach, it is possible to determine the effect of each of the 5 factors studied on the overall annoyance generated by wind turbines. It has already been established by preliminary analyses that the vibration factor can be neglected when calculating the overall annoyance. For the first time, the visual factors that affect the total annoyance calculated by this indicator were also exposed in a quantitative manner.

However, there are serious drawbacks to this approach. First, aggregate annoyance is calculated as the sum of individual annoyances related to each factor, i.e. annoyances scores are added together. This means that we can assess the individual annoyances associated with these factors only for existing installations. It is not known what objective measurable parameters these annoyance assessments relate to in the case of shadow flickers, blinking lights and visual impacts. For example, how can shadow flickers or visual impact be measured, and in what quantities should these factors be presented? Such knowledge is necessary if we want to design a new wind farm and predict how these factors will affect the assessment of annoyance due to a given wind farm. Another problem relates to the annoyance scale used for aggregate annoyance. How does the five-point scale relate to the percentage of people who rate a given noise as extremely annoying (% HA)?

Finally, it is puzzling why the authors limited this multifactorial approach mainly to visual factors. It seems that it could be successfully applied to factors previously discussed in this article, e.g. amplitude modulation or wind speed.

It is possible to make a composite measure for the annoyance due to wind turbine noise for instance by combining L_{den} and some other features, but it should also be possible to check in a simple way if any regulation limits are exceeded. That means the index used for regulation must be easy to "measure". It is of no use for regulatory purposes if a very sophisticated "annoyance index" is designed that is equally complicated when it comes to measuring whether a limit has been exceeded or not

6. Conclusion

There seems to be room for developing a multifactorial noise index related to annoyance due to wind turbines noise or for introducing more corrections to the one-factor noise index. However, this requires that the measures of these factors be defined quantitatively.

Based on the knowledge drawn from the literature presented in this paper, in our opinion the following factors should be considered when setting noise limits:

- noise level expressed in dB A, $L_{Aeq,T}$ or L_{den} ,or ambient+xx dB
- amplitude modulation,
- wind speed,
- S/N ratio (where S is wind turbine noise and N is a background noise),
- nature of the environment (rural or urban)
- well-defined visual factors (shadow flickers, blinking lights, visual impacts)

What should not be forgotten when determining the role of factors influencing the assessment of annoyance due to wind turbines are the people living in their vicinity. This factor cannot be quantified, but by creating conditions in which residents can participate in the planning and location of wind farms and in the process of balancing costs and benefits, the feeling of annoyance can be reduced. This statement is in line with conclusion of the van Kamp and van den Berg 2021 paper.

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References

1. M. Basner, C. Clark, A. Hansell, J. Hileman, S. Janssen, K. Shepherd & V. Sparrow; Aviation noise impacts: State of the science; Noise and Health, 2017, 41-50.
2. R. Guski, D. Schreckenberg, R. Schuemer, M. Brink & S. Stansfeld; Comment on Gjestland, T. A Systematic Review of the Basis for WHO's New Recommendation for Limiting Aircraft Noise Annoyance. Int. J. Env. Res. Pub. Health 2018, 15, 2717; Int. J. Env. Res. Pub. Health, 2019, 16(7). DOI:10.3390/ijerph16071088

3. D. Michaud, S. Keith, K. Feder, S. Voicescu, L. Marro, J. Than, M. Guay, T. Bower, A. Denning, E. Lavigne, C. Whelan, S. Janssen, T. Leroux & F. van den Berg; Personal and situational variables associated with wind turbine noise annoyance; J Acoust Soc Am, 2016, 139, 1455-66. https://doi.org/10/1121/1.4942390
4. J. Davy, K. Burgemeister & D. Hillman; Wind turbine sound limits: Current status and recommendations based on mitigating noise annoyance; Applied Acoustics, 2018. 288 - 295. DOI:10.1016/j.apacoust.2018.06.009
5. I. van Kamp & F. van den Berg; Health effects related to wind turbine sound: A review; Proceedings of the Inter Noise Conference, Washington, DC, USA, Austria, 1-5 August. 2021.
6. ISO/TS 15666; Acoustics — Assessment of noise annoyance by means of social and socio-acoustic surveys, 2021, Geneva, Switzerland: International Standard Organization.
7. Environmental Noise Guidelines for the European Region; World Health Organization, 2018, ISBN 978 92 890 5356 3.
8. A. Freiberg, C. Schefter, J. Hegewald, & A. Seidler; The influence of wind turbine visibility on the health of local residents: A systematic review; Int. Arch. Occup Environ Health, 2019, 92, 609-628. DOI:10.1007/s00420-019-01403-w
9. M. Basner, S. McGuire; WHO environmental noise guidelines for the European region: A systematic review on environmental noise and effects on sleep; Int. J. Env. Res. Pub. Health;2018,15(3), 519. DOI:10.3390/ijerph15030519
10. E. van Kempen, M. Casas, G. Pershagen & M. Foraster; WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary; Int. J. Env. Res. Pub. Health; 2018, 15(2), 379.
11. C. Clark, C. Crumpler & H. Notley; Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer, dementia, birth, reproductive outcomes and cognition; Int. J. Env. Res. Pub. Health, 2020,17:2, 393.
12. S. Yokoyama, S., Sakamoto, & H. Tachibana; Study on the amplitude modulation of wind turbine noise; Proceedings of the Inter Noise Conference, Innsbruck, Austria, 15-18 September 2013.
13. S. Lee, K. Kim, W. Choi, & S. Lee; Annoyance caused by amplitude modulation of wind turbine noise; Noise Control Eng. J., 2011, 38-46.
14. R. Perkins, M. Lotinga, B. Berry, C. Grimwood & S. Stansfeld; A review of research into the human response to amplitude-modulated wind turbine noise and development of a planning control method; Proceedings of the Inter Noise Conference, Hamburg, Germany, 21-24 August 2016.
15. M. Lotinga & T. Lewis; Subjective response to wind turbine noise amplitude modulation; Proceedings of 9th International Conference on Wind Turbine Noise, remote from Europe,18-21 May 2021.
16. NSW. 2016. NSW Wind Energy Guideline. Sydney, NSW, Australia: NSW Government, Planning and development.
17. C. Baliatsas, I. van Kamp, R. van Poll & J. Yzermans; Health effects from low-frequency noise and infrasound in general population: is it time to listen? A systematic review of observational studies; Sci Total Environment, 2016. 163-9. DOI: 10.1016/j.scitotenv.2016.03.065.
18. G. Leventhall; Infrasound and the ear; Proceedings of the 5th int conference on wind turbine noise. Denver, USA, 28-30 August 2013.
19. P. Maijala, A. Turunen, I. Kurki, L. Vainio, S. Pakarinen, C. Kaukinen, K. Lukander, P. Tiittanen, T. Yli-Tuomi, P. Taimisto, T. Lanki, K. Tiippana, J. Virkkala, E. Stickler, M. Sainio; Infrasound Does Not Explain Symptoms Related to Wind Turbines; Helsinki: Statsrådet, Publikasjonsarkivet. 2020, http://julkaisut.valtioneuvosto.fi/handle/10024/162329
20. ISO 1996-1 Acoustics- Description, Assessment and Measurement of Environmental Noise - Part 1; 2016, Geneva, Switzerland: International Standardization Organization.
21. T. Van Renterghem, A. Bockstael, V. DeWeirt, D. Botteldooren; Annoyance, detection and recognition of wind turbine noise; Sci. Total Environ. 2013. 456–57, 333–345. https://doi.org/10.1016/j.scitotenv.2013.03.095.
22. T. Gjestland; Background noise levels in Europe; 2008. https://www.easa.europa.eu/sites/default/files/dfu/Background_noise_report. pdf
23. D. Michaud, L. Marro, J. McNamee; Derivation and application of a composite annoyance reaction construct based on multiple wind turbine features; Canadian Journal of Public Health, 2018, 109, 242-251 https://doi.org/10.17269/s41997-018-0040-y