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

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# D2.1 Methodology of wind turbines noise measurement

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

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**Executive summary**

The main aim of WP2 was to prepare the methodology of wind turbines noise measurement. In this report elements of measurement of wind turbines noise methodology were presented. The methodology consists of:

- Measurement equipment requirements
- Measurement point location
- Recommendation for meteorological conditions
- Recommendation about duration of measurement, number of samples etc.
- Methods of background noise prediction
- Determination of final results of measurements

Authors of this methodology wanted that it will be applicable by lots of measurement laboratories in Poland without the need to expend laboratory equipment. Also, this methodology should be compatible with other legal acts ex. “Environmental protection law”. Due to various situations, two methods of measurement were prepared.

First method should be applicable for post-implementation analysis and for ex officio inspection. During the measurement participation of wind farm manager is required because this method need to turn-off wind farm partially or totally. When wind farm is off measurement of background noise should be done. Also, some data from wind farm manager should be hand over to measurement specialist.

Second method should be used when someone want to measure noise of wind turbine farm for his own knowledge. During this measurement participation of wind farm manager is not obligatory. In next chapters important aspects of each method was presented.

This methodology was prepared based on filed measurement session in Poland and Norway and also based on long-term (one year) measurements in Poland. Details of this method will be presented on next chapters of this document.

| Authors | Date of submission | Confidentiality level |
|---|---|---|
| Piotr Kokowski<br>Tomasz Kaczmarek<br>Paweł Libiszewski<br>Piotr Pękala<br>Michał Gałuszka | 27.XI.2023 | It can be made available on the project website:<br>https://hetman-wind.ios.edu.pl |

**Measurement equipment requirements**

The main assumptions during preparing wind turbines noise measurement method were that every accredited laboratory in Poland should use them without major investments in measuring equipment. All of these laboratories use I class sound level meters and also this type of sound level meter should be use for measuring wind turbines noise.

First class sound level meter should have valid calibration certificate (not older than 2 years) and also should record audio wave and might register sound levels in intervals 100 ms or lower. Audio recording is needed to eliminate unwanted sounds in postproduction. Due to noise measurements of wind turbines are realized in windy condition measurement set should be equipped in correct windshield which minimalize windshield noise on measurement result.

During research some tests of different windshields in aerodynamic tunnel was performed (Figure 1). We tested about ten different windshields.

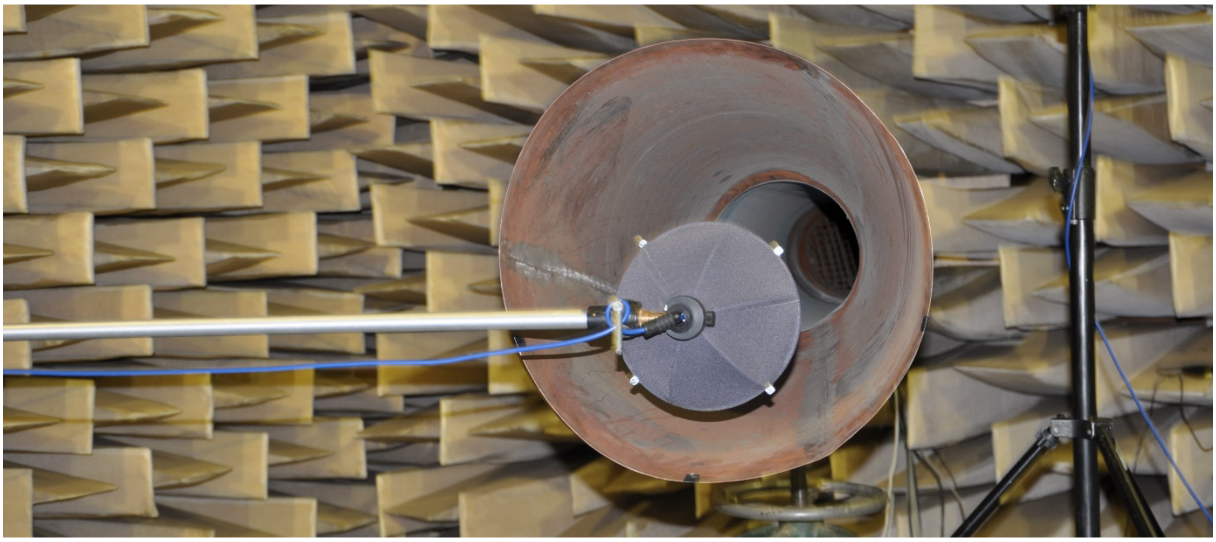

*Figure 1 Windshield testing setup in anechoic chamber.*

Based on them some windshields are chosen which generate lower sound level opposite to classic 60 mm windshield. On figure 2 difference between new windshields and classic was presented in function of wind speed.

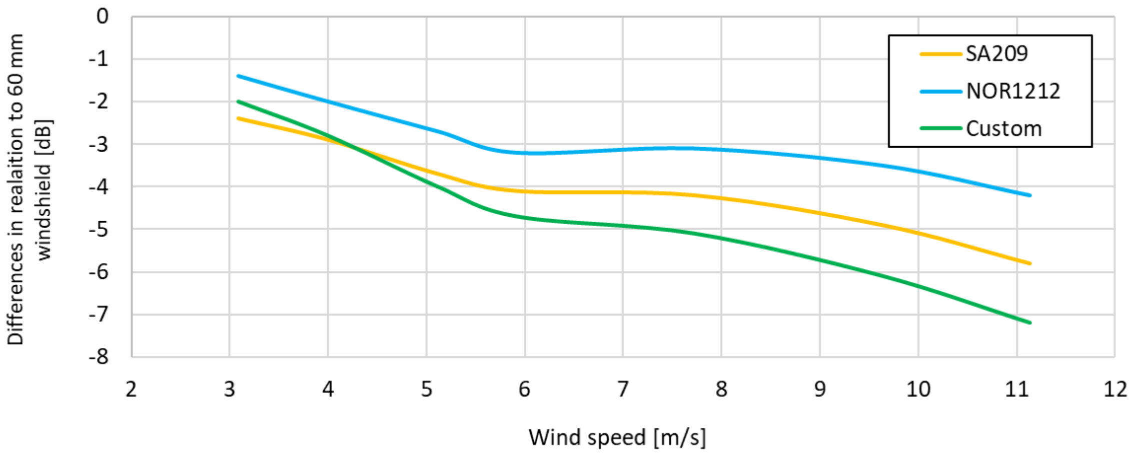


*Figure 2 Differences of sound levels which was caused wind on some windshields in relations to classic 60 mm windshield.*

According to data presented on figure 2 we can see that long-term measurement windshields ex. 130 mm windshield SA209 or elliptical Norsonic NOR1212 windshield has lower wind induced noise opposite to classical windshield. For 5 m/s (measurement limit speed – see section Meteorological conditions) differences equal 3,7 dB for SA209 windshield and 2,7 dB for NOR1212. Considering various solutions to reduce wind noise induced on the shield in the figure above (figure 2), the results for a prototype two-layer shield - with an external diameter of 200 mm - are also shown. The conclusions from the conducted research suggest that the ability to reduce noise generated on the cover is related to the outer diameter of the cover. For this reason, when measuring wind turbine noise, covers with diameters larger than the standard 60 mm should be used - such as the tested covers available on the Polish market from SVANTEK and Norsonic or others with an equivalent or lower level of wind-induced noise.

This solution (bigger windshields) in opposite to classic windshield increase signal to noise ratio what is a desirable phenomenon due to low noise from source during wind turbine measurements.

Second important device for wind turbine noise measurement method is meteorological station. It is important to know in what wind conditions have been during the noise measurement. Depending on the method we need one or two meteorological stations:

- One meteorological station is used when wind turbine farm manager takes part on measurement and we have data of the wind speed from the hub height. This meteorological station should be mounted on 1,5-meter height above the ground and allow to measure average speed and wind direction in 5-minute interval or lower.

- Two meteorological stations are used when wind turbine farm manager does not take part on measurements and we don't have data of wind speed and direction from him. These meteorological stations should be mounted on 1,5 meter and 10-meter height above the ground

Data from the meteorological stations will be used to control winds speed and its influence on wind generated noise on the microphone, also based on this data some correction to results will be determined (see chapter Determination of final results of measurements).

**Measurement points location**

Wind turbine farm noise measurement should be performed 1,5 meter above the ground. This height was chosen because of two aspects. Firstly, 1,5-meter height is similar to average height of standing human. Second factor which justifying this height is minimize wind noise influence on windshield.

*Figure 3 Measurements setup during measurements in Poland to find the best microphone position.*

Comparing the wind speeds at a height of 4 m (the height on which measurements are made in most environmental noise measurement methodologies in Poland) with those at a height of 1.5 m (figure 4), it can be seen that the speeds at the lower height are lower. When converting wind speeds to wind noise levels on the shield, significant differences can be seen (figure 4).

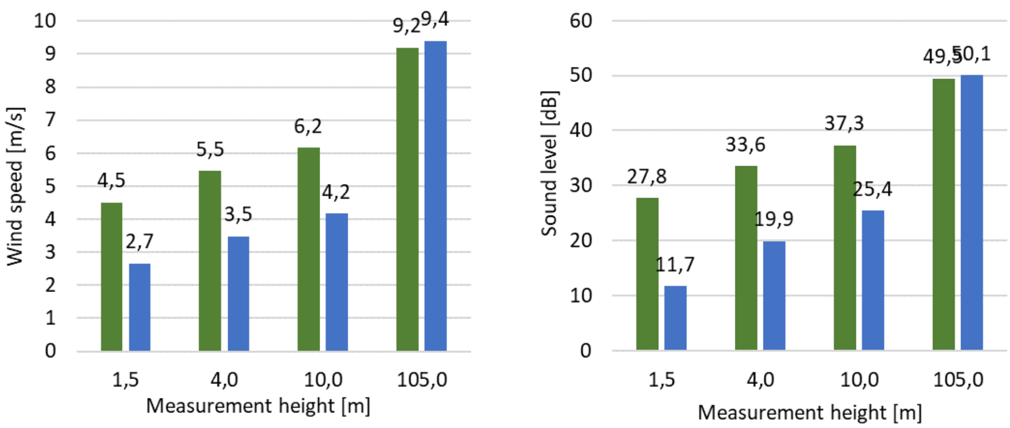


*Figure 4. Windspeed vs height of measurement for two wind profiles (left) and noise levels on windshield caused wind (right).*

Taking into account the influence of wind speed on the level of noise induced on the wind shield, using a lower noise measurement height can minimize the influence of wind speed on the measurement results. This means that lowering the measurement height provides another gain in the ratio between the measured value of the noise level from the wind farm and the acoustic background. By using an appropriate wind shield and measuring at a height of 1,5 m, the impact of wind noise on the wind shield on the measurement result can be significantly reduced, which, as previously mentioned, is desirable due to low levels measured at distances of up to 1 000 m distance from wind turbines.

**Recommendation for meteorological conditions**

This is obvious that noise of wind turbines depends of wind speed. But if we want measure this noise we should know when emission is high enough while also being able to measure. Our studies (long-term measurements) showed that measurement of wind turbines noise should be performed under following wind conditions:

- windspeed on 1,5-meter height near measurement microphone lower than 5 m/s
- windspeed $V_{gon}$ on height of hub unit higher than 6 m/s (recommended 9 m/s) when measurements are made with wind turbines farm manager or windspeed ($V_{ref}$) on 10-meter height higher than 5 m/s (recommended 8 m/s) when measurements are made without wind turbines farm manager.

The presented limit values of wind speed are related to two factors. Limit on height 1,5-meter guarantee that wind induced noise on windshield will be about 30 dB. For many measurements situation it will make it possible to subtract the influence of the acoustic background from the measured result (required difference of 3 dB – see *Methods of background noise prediction*). On the other hand windspeeds higher than 5 m/s on reference height (10 meter) (measurement without wind turbines farm manager) or 6 m/s on hub unit height (measurement with wind turbines farm manager) guarantee that turbines will work with some efficiency that will be measurable in 1000 meter distance from wind turbines. It follows from sound power level curve of wind turbines (figure 5).

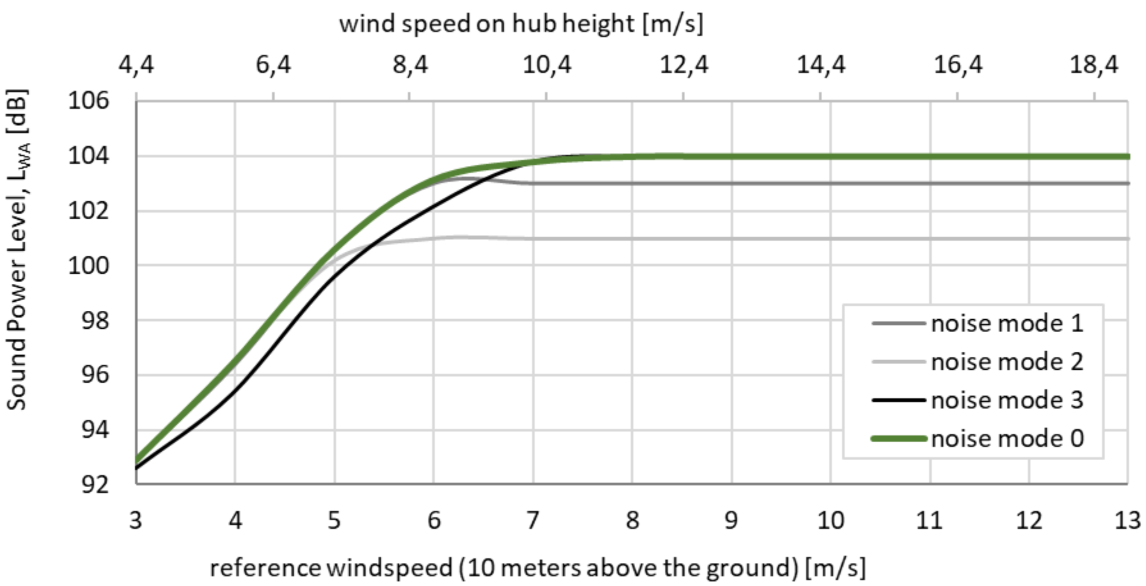


*Figure 5. Example sound power level curve of wind turbine*

As can be seen in the figure above (figure 5), for an example wind turbine at a speed of 5 m/s, the acoustic power level is approximately 50% of its maximum value (approximately 3 dB less). For wind speeds above 8 m/s at the reference height, the power level reaches the maximum value for most wind turbines in Poland. For this reason, the recommended wind speed at a height of 10 m when performing measurements is $v_{ref}$ 8 m/s or $v_{gon}$ 9 m/s and the minimum at which measurements can be performed is $v_{ref}$ 5 m/s or $v_{gon}$ 6 m/s.

Site measurements also allowed us to check what wind direction affects the noise range of wind turbines. During sessions our equipment was spread out in different directions (see figure 6)

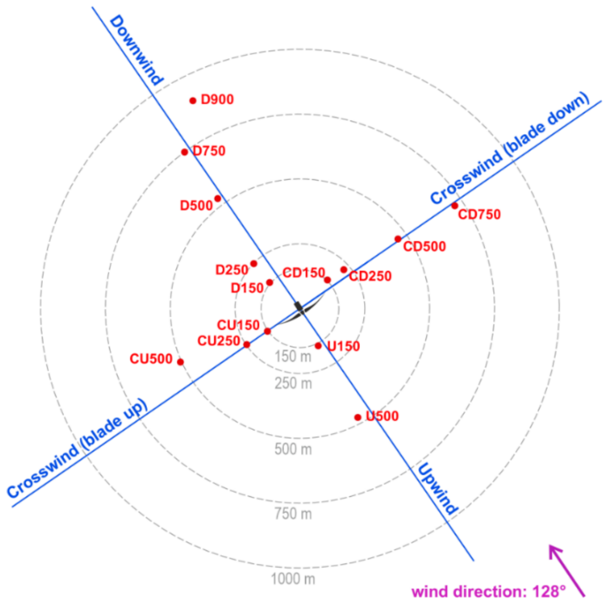


*Figure 6. One of the measurement equipment setups around a wind turbine*

That kind of measurements showed us that if we want to get result with the highest emission, we should put some correction to the result when measurement is not taken in ideal downwind conditions.

Due to the wind direction from the wind farm to the receiver point and the associated wind direction angles relative to the line connecting the measurement point with the nearest wind turbine, directivity-related D corrections are applied and should be added to the result:

- D = 0 dB, for angles from 0° to 30°.
- D = 1 dB for angles from +/- 30° to 60°;
- D = 2 dB, for angles from +/- 60° to 90°.

In different angles measurement are not allowed. Idea of D corrections is presented on picture below (figure 7)

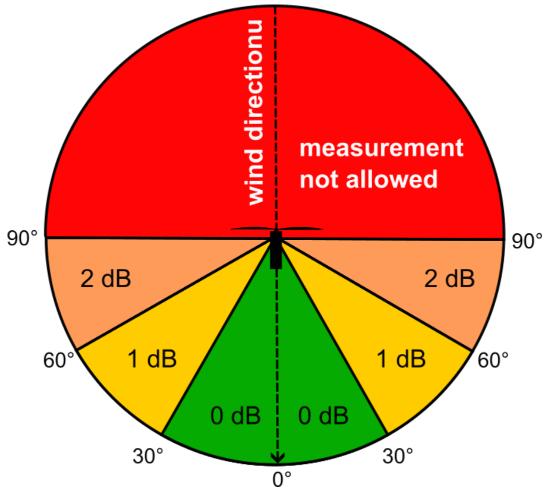


*Figure 7. D corrections schema according to wind direction angle*

In addition to the requirements regarding wind speed, noise measurements of wind turbines should be carried out in the absence of precipitation and in conditions of atmospheric pressure, air humidity and air temperature not exceeding the limits presented in the specifications of the sound level meters used.

**Recommendation about duration of measurement, number of samples**

Measurements of noise from wind turbines should be continuous according few hours with parallel measurement of wind parameters (wind speed, wind direction). Then analysis of measured data should be performed in appropriate software and noise samples should be taken.

From recorded time history 5 minutes sound equivalent level, $L_{Aeq,5min}$, must be selected. Undesirable sound like dog barking, birds, car pass-byes should be deleted from this samples.

Every sample should contain only wind turbine noise level value. To easily remove adverse events in a sample, it is recommended to record time history of equivalent sound level values at steps of 100 ms or less. This method of recording also allows you to observe the modulation of the noise level, which is characteristic of the source, such as a wind turbine.

Number of samples which be collected during measurements of wind turbines noise should be higher or equal than 7. This is due to two aspects, firstly, the dispersion of the results obtained and the standard deviation related to, among others, with changes in the sound power level of the source caused by momentary changes in wind speed, and secondly with the accepted acceptable error size when determining the noise level of wind turbines using the sampling method.

According to requirements of ISO1996-2 (Patent nr ISO 1996-2:2017 (en), 2017) number of samples should be determined according to the following formula:

$$\delta = \left( \frac{t_p(v) \times s_x}{\sqrt{n}} \right) \tag{1}$$

where:

$s_x$ - standard deviation, which is 1 to 2 dB for 5 minutes length of equivalent sound levels
$\delta$ - accepted mesurement error

n - number of samples,
$t_p(v)$ - t-Student distribution values.

By plotting a graph of the error function depending on the number of samples and the adopted standard deviation based on equation (1), it is possible to read for what number of samples with the assumed standard deviation δ the error value is less than or equal to 1 (figure 8).

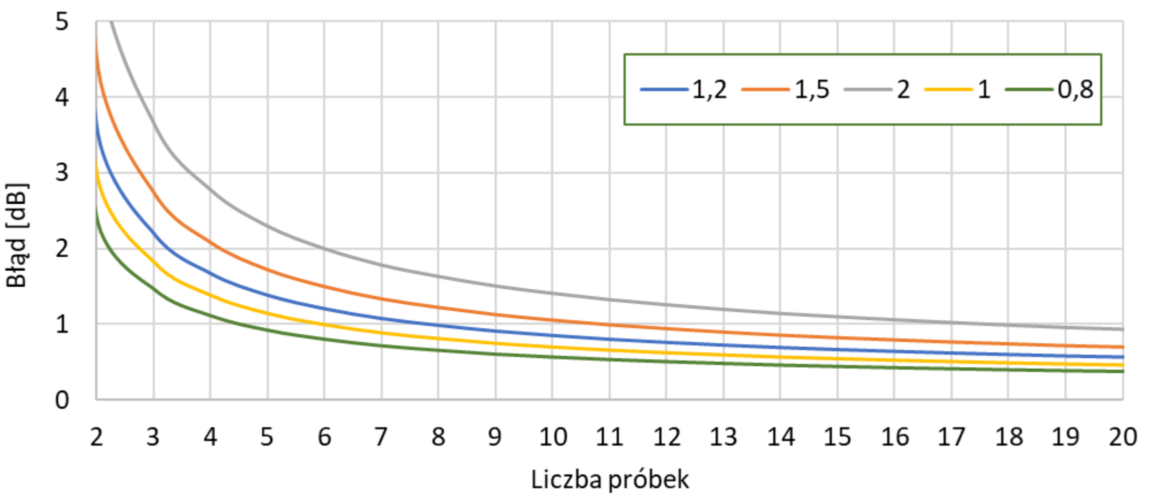


*Figure 8. Values of the error in estimating the mean value depending on the number of samples and the standard deviation of the samples.*

As we can see on figure above (figure 8) for error value about 1 dB for standard deviations from 0,8 dB to 1 dB number of samples should be equal 7 or higher. Values of standard deviation$L_{Aeq,5min}$ was determined by long-term measurement. All measured samples, during measurements without the participation of the manager, should be recorded under the same wind speed conditions, i.e. in one of the following ranges:

- 4,5 < $v_{ref}$ ≤ 5,5 m/s
- 5,5 < $v_{ref}$ ≤ 6,5 m/s
- 6,5 < $v_{ref}$ ≤ 7,5 m/s
- 7,5 < $v_{ref}$ ≤ 8,5 m/s

or when manager participate:

- 5,5 < $v_{gon}$ ≤ 6,5 m/s
- 6,5 < $v_{gon}$ ≤ 7,5 m/s
- 7,5 < $v_{gon}$ ≤ 8,5 m/s
- 8,5 < $v_{gon}$ ≤ 9,5 m/s

on height of hub.

**Methods of background noise prediction**

In this methodology three different method of background noise measurement was proposed

***Method 1 – measuring in the same place***

First method is to measure background noise in the same place as wind turbines noise but after turning off wind farm. This measure should be done directly after measurement when wind turbines farm was on. During the background noise measurement, it is not necessary turning off whole wind farm. Only these wind turbines should be off which are located at a distance of less than three times the distance between the measurement point and the nearest wind turbine to the measurement point.

On the example below (figure 9) was presented which wind turbines should be off during background noise measurement (purple points inside green circle)

*Figure 9. Wind turbines location (purple points) and measurement point (red point) – turbines inside green circle should be off during background noise measurements.*

This method is recommended and obligatory when measurements will be done for post-implementation analysis or during ex officio inspection. It means that during this measurement wind turbines farm manager has an obligation to turn off installation partially or totally during background noise measurement.

***Method 2 – using statistical level***

Second method for determining background noise based on statistic level L99 and turning off of wind turbines farm is not necessary. As our measurements showed using statistic level L99 for determining background noise is possible only when single wind turbine is measured. Analysis which are performed during Hetman project shows that L99 level determined from instantaneous noise level values (logger step 100 ms) is similar to real background noise but only when one wind turbine is measured.

***Method 3 – measuring in equivalent place***

Third method of background noise measurement is based on measure in equivalent place. Equivalent place is that place where surroundings (vegetation, sound sources) are similar to place where wind turbines noise is measured. It is recommended to measure background noise in equivalent place in the same time that measuring the wind turbines noise because of maintaining the same wind conditions. Regardless of the choice of the background measurement method, the minimum ratio between the measured level during wind farm operation and the acoustic background should be 3 dB. The number of background measurement samples should be close to the number of measured turbine noise level values. The measurement time of background samples should also be 5 minutes and the samples themselves should be free from incidental events such as birds chirping, dogs barking, motor vehicle passing, etc.

**Determination of final results of measurements**

***Measurement with wind turbines manager participation***

When measurements are done with participation of wind turbines farm manager we should get from them the following data:

- sound power level curves vs wind speed $v_{ref}$ or $v_{gon}$
- average wind speed measured on hub height or determined on the basis of electrical energy was produced

In next step we will use this data to add some correction to the values which we get from site measurements. Values from the measurements should be prepared and emission level should be calculated using formula 2, below.

$$L_{Aeq} = 10 \times \log_{10}(10^{L_{Aeq,5min}} - 10^{L_{Aeq,5tło}}) \quad (2)$$

gdzie:
$L_{Aeq,5min}$logaritmic averege level from wind tubines noise samples
$L_{Aeq,5tło}$logaritmic averege level from background noise samples

The next step is calcculation of result according to formula 13 the highest emission level that is to the situation when wind farm wokrs with the highest sound power level.

$$L_{Aeq\,D} = L_{Aeq} + K(V_{gon}) \quad (3)$$

$$L_{Aeq\,\mathrm{N}} = L_{Aeq} + K(V_{gon})$$

This calculation is performed through adding to result K($v_{gon}$) correction. K($v_{gon}$) is determined using sound power level curve which is delivered by wind turbine farm manager which should be calculated using formula 4:

$$K(V_{gon}) = \left|L_{WA}(V_{gon}) - \max\left(L_{WA}(V_{gon})\right)\right| \quad (4)$$

Examples of calculated corrections K($v_{gon}$) vs wind speed was presented in table 1.

*Table 1. Example data of sound power levels of wind turbines vs wind speed and appropriate corrections K($v_{gon}$)*

| $v_{gon}$ [m/s] | $L_{WA}$ ($v_{gon}$) | K($v_{gon}$) |
|---|---|---|
| 6 | 100,0 | 5,0 |
| 7 | 102,2 | 2,8 |
| 8 | 103,5 | 1,5 |
| 9 | 104,4 | 0,6 |
| 10 | 105,0 | 0,0 |
| 11 | 105,0 | 0,0 |

In the next step, based on data from the table 1 and winds speed $v_{gon}$, which occurred while wind turbines noise sample was measured appropriate correction should be taken into account. If the measured wind speed is different than in table 1 the result should be rounded to the closest 0,5 m/s. If the sound power level curve is defined with an accuracy of 1 m/s, K($v_{gon}$) value for example wind speed, 6,5 m/s, 7,5 m/s etc. should be determined as average value from two adjacent values. For example based on values from table 13-1, K($v_{gon}$) value for wind speed 9,5 should be equal 0,3 dB.

If the wind direction relative to the line between closest wind turbine and measurement point is between 30 to 60 degrees D correction equal 1 dB should be added into result. When this direction will be between 60 to 90 degrees the correction D = 2 dB should be added (see *Recommendation for meteorological conditions*)

***Measurement without wind turbines manager participation***

If the wind turbines farm manager is not participating in measurement we don't have information about wind speed on the hub height, also we don't have sound power level curve. This is the reason that we have to measure wind speed at the height of 10 m above ground level. This measurement should be performed at 5-minute intervals, coinciding with the measurement period of the noise level samples. Its result will be used to determine the K ($v_{ref}$) correction.

During the noise measurements without participating of wind turbine manager we don't know the sound power level curve vs wind speed on hub height so we can't determine K ($v_{gon}$) correction.

During this research a replacement curve was developed. This curve has been determined by averaging sound power level curves for reference wind speed ($v_{ref}$) normalized to maximum value. To prepare these curves sound power level functions form many wind turbines existing in Poland was used.

The list of curves on the basis of which the replacement curve was calculated is shown in the figure below (figure 10).

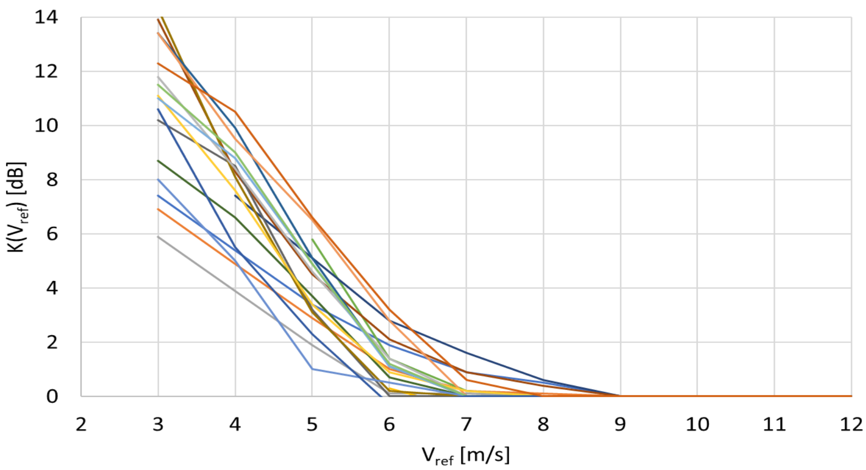


*Figure 10. K ($v_{ref}$) corrections value for some types of wind turbines existing in Poland*

On the figure below (figure 13-8) replacement curve was presented and also its equation.

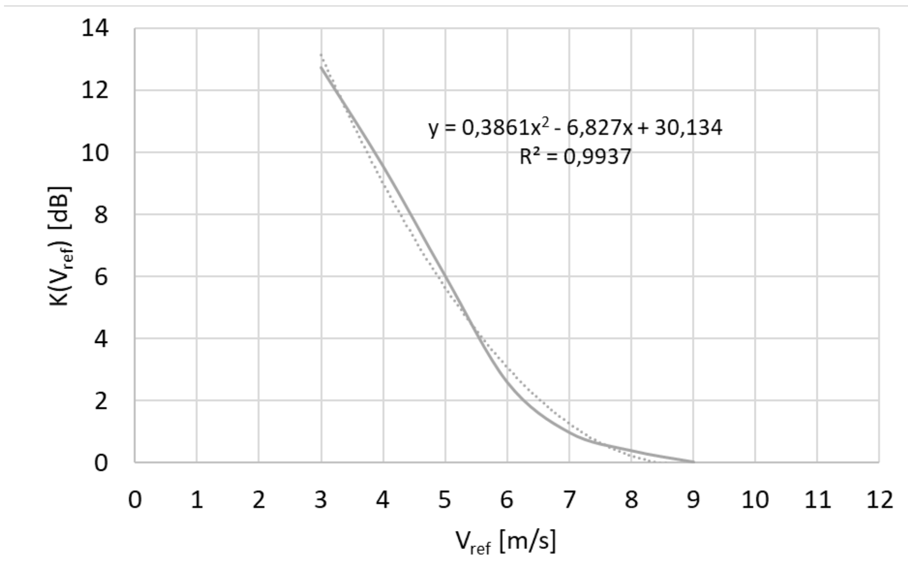


*Figure 11. K ($v_{ref}$) corrections values averaged for some wind turbines existing in Poland with fitting curve and its equation – replacement K($v_{ref}$) curve*

Final result, similarly to measurements with the participation of the manager, should be calculated using formulas (2) and (3) by replacement K($v_{gon}$) correction using K($v_{ref}$) correction. K($v_{ref}$) correction should be calculated using formula which is showed on figure 11 using windspeed measured during the noise measurement on height 10 meter above the ground. Other steps are the same like in measurement with wind turbines manager participation.