# Necessary adjustments in ISO 9613-2 and CNOSSOS (industries) methods for noise forecasting in Wind Farms

**Vitor Rosão[1], Rui Leonardo[1], Pedro Santos[1]**

[1]SCHIU, Noise and Vibration Engineering, Faro, Portugal
vitor.schiu@gmail.com; rui.schiu@gmail.com; pedrosantos.schiu@gmail.com

**Abstract**
The European Directive 2015/996, of 19 May 2015, establishes common noise assessment methods (typically referred as CNOSSOS methods) within the European space, pursuant to Directive 2002/49/EC, of the European Parliament and of the Council. Thus, it is natural that the development of noise modelling of wind farms will be carried out based on the CNOSSOS method for industrial noise sources. The CNOSSOS method for industrial noise sources is based on the method of the standard ISO 9613-2: 1996. This article presents the precautions that must be taken when using these methods (CNOSSOS or ISO 9613-2) for noise modelling of wind farms, because, in some cases, an "unsafety" modelling may result in an underestimation of the sound levels perceived in the Receivers. This article therefore presents, and justifies, some recommendations on how to use the CNOSSOS or ISO 9613-2 methods, for safer predictions of sound levels in Receivers, due to the noise of Wind Farms.

**Keywords:** CNOSSOS, European Directive 2015/996, ISO 9613-2, Wind Farm Noise, Wind Turbine Noise.

## 1 Introduction

The noise from wind farms has been a topic of growing interest in the technical acoustics community, as demonstrated by the creation, in 2005, by INCE-Europe [1], of an exclusive biennial conference on the subject. In 2021, the conference had its 9th edition. Analyzing the Post-Conference Report [2] it appears that, in the present moment, the main points of interest are:

- Propagation: There is still pressure from manufacturers and developers for more accuracy on predictions, mainly across water and on meteorological conditions other than downwind (other than favourable propagation conditions).
- Regulations: Modern turbine control systems make possible to control turbines in different wind conditions so that the noise level at any point is as close to the maximum permitted as possible.
- Measurement and Assessment: New IEC TS 61400-11-2 (Measurement of wind turbine noise characteristics in receptor position), to be publish on 2022 [3] and the fact that $L_{den}$, as used by WHO in the 2018 European Guidelines [4] is not much liked by consultants.
- Tonality: Although tonality in turbines seems to be much less common than it used to be it still comes up as a problem in some instances.
- Amplitude Modulation (AM): Sometimes it appears to be of particular importance and other times not so. Unlike tonality where well-defined assessment techniques have been available for some time, the assessment of AM is at an earlier stage.
- Infrasound: The issue of infrasound does not seem to go away, in spite of the fact there is clearly no evidence that it has any direct impact either on the health of people near wind farms or on their perception of the noise.

Therefore, people working on the topic of noise from wind farms should be aware of:

- Possible future developments on propagation models, over water and for conditions other than downwind (other than favourable propagation conditions). Special care using current methods over water or for not downwind conditions. For offshore wind farms see [5,6].
- The future publication of the new IEC TS 61400-11-2, and the possible future disregard of the $L_{den}$ parameter for Wind Turbine noise analysis.
- The possible non-consideration/penalty of the prediction analysis, due to the existence of tonal characteristics – because it is unlikely for Wind Turbine noise – but the need for their control through monitoring and appropriate methods, for example the method of ISO/PAS 20065:2016 [7].
- The possible non-consideration/penalty of the prediction analysis, due to the existence of Amplitude Modulation (AM) – still not well established – but the need for its control through monitoring and adequate methods, for example the methods of the references [8,9].
- The need to equating continuous monitoring and active control of the operation of wind turbines, to ensure effective compliance with the noise limits established at points of interest.

In the following refences there are also important information on the "state of art" of Wind Turbine noise subject: [10,11]

## 2 The use of ISO 9613-2

There are several papers warning about the need for care in using ISO 9613-2 [12] in wind farm noise prediction, for example reference [13], in which it is stated that, in some cases, were measured values 15 dB above of the predicted value.
As the references [14,15] correspond to institutional documents, directed to the precautions to be taken in the use of ISO 9613-2 [12], in wind farm noise prediction, it seems to be appropriate to follow their explanations, which are summarized below.
Guide for ISO 9613-2 [12] utilization in wind farm noise prediction (just for on-shore, because does not cover long distance propagation over sea such as will be relevant to off-shore wind farms):

1. If there are spectral sound emission data, representative of the legal period of analysis in question, for the following 1/1 octave bands (63Hz, 125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz, 8000Hz) they must be considered, and the regular attenuations of ISO 9613-2 [12] can be used. If only broadband sound emission data are available, a conservative calculation should be carried out, assuming a fully reflective ground and an attenuation, due to the atmospheric absorption, associated with the 250Hz octave band.
2. In any case, a fully absorbent ground ($\alpha = 1$) should not be used. For safety reasons – which can be excessive in some cases – a fully reflective ground ($\alpha = 0$) should be used. In most cases the use of an intermediate ground absorption ($\alpha = 0.5$) is adequate.
3. At least when using a ground sound absorption coefficient of $\alpha = 0.5$, an uncertainty factor of +2 dB must be added to the sound power values tested by the manufacturer.
4. Even for receivers with only 1 floor, the height of the receiver, in the acoustic model, must never be less than 4 m above the ground.
5. Temperature and relative humidity values that represent a low attenuation due to atmospheric absorption must always be used. Recommended values: 10ºC and 70%.
6. A further correction of +3 dB (or +1.5 dB if using $\alpha$ =0) should be added to the calculated overall A-weighted noise level for propagation "across a valley", i.e. a concave ground profile, or where the ground falls away significantly, between the turbine and the receiver location. The following criterion of application is recommended:

$$h_m \geq 1.5 \times (\text{abs}\,(h_s - h_r)/2) \quad (1)$$

where $h_m$ is the mean height above the ground of the direct line of sight from the receiver to the source (as defined in ISO 9613-2 [12], Figure 3 (next Figure 1)), and $h_s$ and $h_r$ are the heights above local ground level of the source and receiver, respectively.

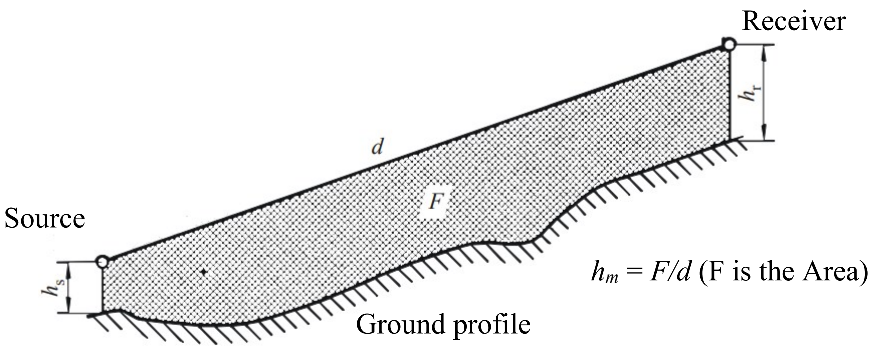


Figure 1 – Mean height above the ground (Figure 3 of ISO 9613-2 [12]).

7. Topographic screening effects of the terrain (ISO 9613-2 [12], Equation 12) should be limited to a reduction of no more than 2 dB, and then only if there is no direct line of sight between the highest point on the turbine rotor and the receiver location. If significant screening from a landform barrier is present near the receiver, higher barrier attenuation values of up to -10 dB(A) may be appropriate, but any such cases are uncommon and should be fully justified in the assessment.
8. Forecasts must be made, for safety, considering the maximum value of Sound Emission (Sound Power Level) and 100% probability of occurrence of favourable propagation conditions in all directions and for all reference periods, which in the great majority of cases must be very excessive.
9. The consideration of non-maximum sound emission and/or non-favourable propagation conditions, according with related statistics information, may be done with some care (see chapter "*4 Non-Maximum Sound Emission values*"and chapter "*5 Non-Favourable propagation conditions*").

# 3 The use of CNOSSOS (Industry)

With the publication of the European Directive 2015/996 [16] – in the Portuguese case, transposed by Decree-Law 136-A/2019 – which establishes the use of the CNOSSOS [16] method in the European space, there may be a "temptation" to use this method to predict the noise levels associated with Wind Farms in Europe.
Thus, it is considered pertinent to compare the forecasts with the ISO 9613-2 [12] method and with the CNOSSOS [16] method, to understand the necessary adaptations to the CNOSSOS [16] method – when making noise forecasts in Wind Farms – having into account the necessary adaptations to the ISO 9613-2 [12] method, presented in the previous chapter "*2 The use of ISO 9613-2*".
The comparison was performed using the *Cadna A* software [17], for the 4 cross-sectional terrain profiles shown in Figure 1 to Figure 4, for two different ground absorption coefficients ($\alpha$=0 and $\alpha$=0.5) and for favourable and unfavourable propagation conditions.
In Table 1 are shown the comparison results in a more complete way, showing the based forecast values for ISO 9613-2 [12] and CNOSSOS [16] (Sound Power level of 100 dB(A)] and the differential, and the barrier effect attenuation and the final results and differential. In Table 2 are shown the comparison results in a simple way – just the final differential results – but for 63 Hz to 8000 Hz octave bands.
The comparison results, for favourable conditions (the unfavourable results are analysed in chapter "*5 Non-Favourable propagation conditions*") lead to the following main conclusions:

- The frequency values forecasts are different for ISO 9613-2 [12] and for CNOSSOS [16]. Sometimes the CNOSSOS [16] gives "final results" (after barrier effect correction) higher than ISO 9613-2 [12] (up to 2 dB difference, for 125Hz octave band, for 0.5 ground absorption and for Valley, Flat and Mount with line of sight ground profile), sometimes equal results (for example for all frequencies, for 0 ground absorption and for Valley and Flat profile) and sometimes lower results (up to -23dB, for 8000 Hz octave band, for 0 ground absorption and for Mount with line of sight profile).

- The 250 Hz octave band values forecasts are also different for ISO 9613-2 [12] and for CNOSSOS [16]. Sometimes the CNOSSOS [16] gives "final results" (after barrier effect correction) higher than ISO 9613-2 [12] (up to 2dB difference, for 0.5 ground absorption and for Mount with line of sight ground profile), sometimes equal results (for example for 0 ground absorption and for Valley and Flat profile) and sometimes lower results (up to -3dB, for 0 ground absorption and for Mount with line of sight profile, and for Favourable conditions, for 0 ground absorption and for Mount with no line of sight profile).
- The use of CNOSSOS [16] method for wind farm noise forecasts must be done with some care and the corrections to apply for more suitable results, based on ISO 9613-2 [12] corrections, are not constant, and can be higher, equal or lower correction than ISO 9613-2 [12] corrections, depending on the case.
- Given the lack of a known institutional form that establishes the necessary adaptations for the use of the CNOSSOS [16] method, when modelling the noise of wind farms, it is considered more appropriate to use – if possible – the ISO 9613-2 [12] method, with the adaptations explained in chapter "*2 The use of ISO 9613-2*", instead of CNOSSOS [16] method.

Table 1 – Comparison results with ISO 9513-2 and CNOSSOS (250Hz octave band; more complete results)

| **Method** | **Ground profile (see Figure 2)** | **Ground absorption coefficient** | **Noise Level [dB(A)] forecast (250Hz octave band)** | **Barrier effect attenuation** | **Noise Level [dB(A)] corrected for 0\|2 dB maximum barrier effect attenuation** |
|---|---|---|---|---|---|
| Favourable conditions | | | | | |
| ISO 9613-2 | Valley | 0 | 30 | 0 | 30 |
| CNOSSOS | Valley | 0 | 30 | 0 | 30 |
| CNOSSOS - ISO 9613-2 | - | - | 0 | 0 | 0 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Valley | 0 | 30 | 0 | 30 |
| CNOSSOS | Valley | 0 | 30 | 0 | 30 |
| CNOSSOS - ISO 9613-2 | - | - | 0 | 0 | 0 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Valley | 0.5 | 28 | 0 | 28 |
| CNOSSOS | Valley | 0.5 | 29 | 0 | 29 |
| CNOSSOS - ISO 9613-2 | - | - | 1 | 0 | 1 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Valley | 0.5 | 28 | 0 | 28 |
| CNOSSOS | Valley | 0.5 | 29 | 0 | 29 |
| CNOSSOS - ISO 9613-2 | - | - | 1 | 0 | 1 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Flat | 0 | 30 | 0 | 30 |
| CNOSSOS | Flat | 0 | 30 | 0 | 30 |
| CNOSSOS - ISO 9613-2 | - | - | 0 | 0 | 0 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Flat | 0 | 28 | 0 | 28 |
| CNOSSOS | Flat | 0 | 30 | 0 | 30 |
| CNOSSOS - ISO 9613-2 | - | - | 2 | 0 | 2 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Flat | 0.5 | 28 | 0 | 28 |

| Method | Ground profile (see Figure 2) | Ground absorption coefficient | Noise Level [dB(A)] forecast (250Hz octave band) | Barrier effect attenuation | Noise Level [dB(A)] corrected for 0\|2 dB maximum barrier effect attenuation |
|---|---|---|---|---|---|
| CNOSSOS | Flat | 0.5 | 29 | 0 | 29 |
| CNOSSOS - ISO 9613-2 | - | - | 1 | 0 | 1 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Flat | 0.5 | 25 | 0 | 25 |
| CNOSSOS | Flat | 0.5 | 29 | 0 | 29 |
| CNOSSOS - ISO 9613-2 | - | - | 4 | 0 | 4 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Mount (Line of sight) | 0 | 17 | 13 | 17+13-0= 30 |
| CNOSSOS | Mount (Line of sight) | 0 | 30 | 0 | 30 |
| CNOSSOS - ISO 9613-2 | - | - | 13 | -13 | 0 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Mount (Line of sight) | 0 | 15 | 13 | 15+13-0= 28 |
| CNOSSOS | Mount (Line of sight) | 0 | 25 | 0 | 25 |
| CNOSSOS - ISO 9613-2 | - | - | 10 | -13 | -3 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Mount (Line of sight) | 0.5 | 22 | 5 | 22+5-0= 27 |
| CNOSSOS | Mount (Line of sight) | 0.5 | 29 | 0 | 29 |
| CNOSSOS - ISO 9613-2 | - | - | 7 | -5 | 2 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Mount (Line of sight) | 0.5 | 20 | 5 | 20+5-0= 25 |
| CNOSSOS | Mount (Line of sight) | 0.5 | 24 | 0 | 24 |
| CNOSSOS - ISO 9613-2 | - | - | 4 | -5 | -1 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Mount (No line of sight) | 0 | 17 | 13 | 17+13-2= 28 |
| CNOSSOS | Mount (No line of sight) | 0 | 11 | 16 | 11+16-2= 25 |
| CNOSSOS - ISO 9613-2 | - | - | -6 | 3 | -3 |
| Unfavourable/Homogeneous conditions | | | | | |
| ISO 9613-2 | Mount (No line of sight) | 0 | 15 | 13 | 15+13-2= 26 |
| CNOSSOS | Mount (No line of sight) | 0 | 8 | 19 | 8+19-2= 25 |
| CNOSSOS - ISO 9613-2 | - | - | -7 | 6 | -1 |
| Favourable conditions | | | | | |
| ISO 9613-2 | Mount (No line of sight) | 0.5 | 17 | 10 | 17+10-2= 25 |
| CNOSSOS | Mount (No line of sight) | 0.5 | 8 | 19 | 8+19-2= 25 |
| CNOSSOS - ISO 9613-2 | - | - | -9 | 9 | 0 |
| Unfavourable/Homogeneous conditions | | | | | |

| **Method** | **Ground profile (see Figure 2)** | **Ground absorption coefficient** | **Noise Level [dB(A)] forecast (250Hz octave band)** | **Barrier effect attenuation** | **Noise Level [dB(A)] corrected for 0\|2 dB maximum barrier effect attenuation** |
|---|---|---|---|---|---|
| ISO 9613-2 | Mount (No line of sight) | 0.5 | 15 | 10 | 15+10-2= 23 |
| CNOSSOS | Mount (No line of sight) | 0.5 | 6 | 21 | 6+21-2= 25 |
| CNOSSOS - ISO 9613-2 | - | - | -9 | 11 | 2 |

Table 2 – Comparison results with ISO 9513-2 and CNOSSOS (63Hz to 8000Hz octave bands; just differential and final results)

| Method | Ground profile (see Figure 2) | Ground absorption coefficient | Noise Level difference [dB(A)] forecast Hz | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Valley | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Valley | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Valley | 0.5 | -1 | 2 | 1 | 0 | 0 | 0 | -1 | 0 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Valley | 0.5 | -1 | 2 | 1 | 0 | 0 | 0 | -1 | 0 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Flat | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Flat | 0 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 0 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Flat | 0.5 | -1 | 2 | 1 | 0 | 0 | 0 | -1 | 0 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Flat | 0.5 | 1 | 4 | 4 | 3 | 3 | 2 | 2 | 0 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (Line of sight) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -23 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (Line of sight) | 0 | -2 | -2 | -3 | -3 | -3 | -4 | -2 | -23 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (Line of sight) | 0.5 | -1 | 2 | 2 | 0 | 0 | 0 | -1 | -3 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (Line of sight) | 0.5 | -4 | 0 | -1 | -6 | -7 | -6 | -2 | -3 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (No line of sight) | 0 | -2 | -4 | -3 | -3 | -3 | -3 | -3 | -4 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (No line of sight) | 0 | -1 | 0 | -1 | -1 | -1 | -2 | -1 | -2 |

| Method | Ground profile (see Figure 2) | Ground absorption coefficient | Noise Level difference [dB(A)] forecast Hz | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
| Favourable conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (No line of sight) | 0.5 | -2 | -1 | 0 | -2 | -1 | -2 | -2 | 0 |
| Unfavourable/Homogeneous conditions | | | | | | | | | | |
| CNOSSOS - ISO 9613-2 | Mount (No line of sight) | 0.5 | -1 | 3 | 2 | 0 | 1 | 1 | 0 | 1 |

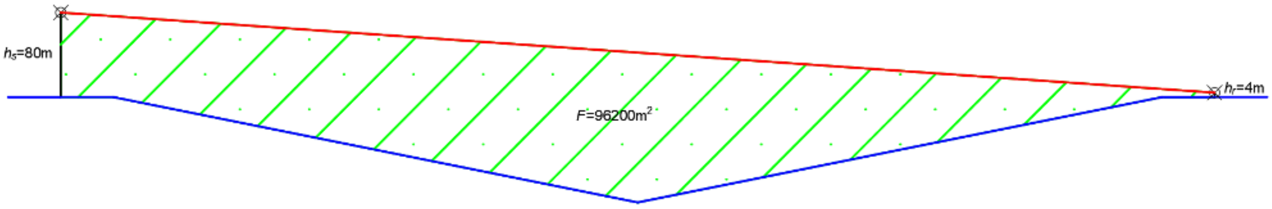


Figure 1 – Valley profile [$h_s$=80m; $h_r$=4m; $F$=96200m$^2$; $d$=1103m; $h_m$=87m; 1.5 × (abs ($h_s$ - $h_r$) /2)=57m].

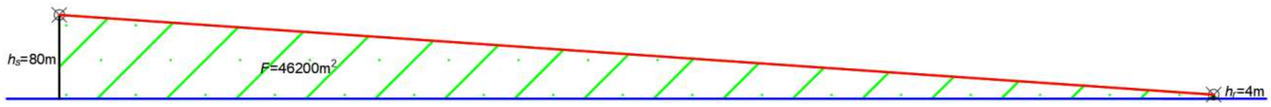


Figure 2 – Flat profile [$h_s$=80m; $h_r$=4m; $F$=46200m$^2$; $d$=1103m; $h_m$=42m; 1.5 × (abs ($h_s$ - $h_r$) /2)=57m].

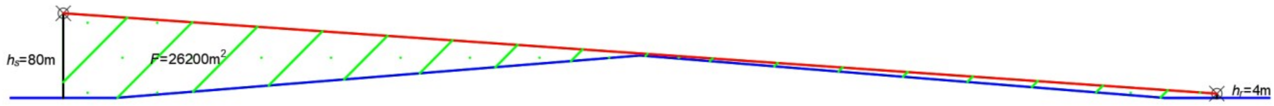


Figure 3 – Mount (line of sight) profile [$h_s$=80m; $h_r$=4m; $F$=26200m$^2$; $d$=1103m; $h_m$=24m; 1.5 × (abs ($h_s$ - $h_r$) /2)=57m].

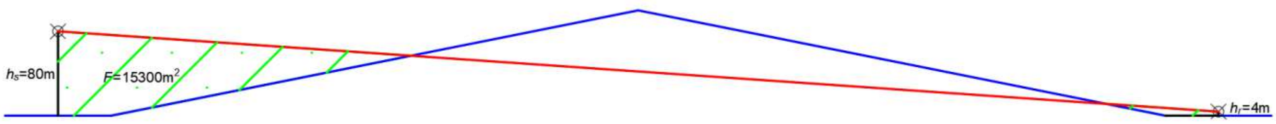


Figure 4 – Mount (no line of sight) profile [$h_s$=80m; $h_r$=4m; $F$=15300m$^2$; $d$=1103m; $h_m$=14m; 1.5 × (abs ($h_s$ - $h_r$) /2)=57m].

# 4 Non-Maximum Sound Emission values

Since a great majority of requirements related with long term average values – for example in the Portuguese case (Decree-Law 9/2007) annual average for the called Maximum Exposition Criterium (11.st Article) and more critical month average for the called Discomfort Criterium (13.rd Article) – the use of just maximum sound emission values can be too much conservative.
Theoretically, if we have daily/hourly information of the actual wind turbine sound emission (Sound Power Levels) we can calculate the annual average (energetic/logarithmic average of the daily/hourly sound power levels) and the more critical month average (energetic/logarithmic average), for the day period (Portuguese case 7am to 8pm), the evening period (Portuguese case 8pm to 11pm) and the night period (Portuguese case 11pm to 7am).

Normally we don´t have the information of daily/hourly sound emission values during a year, but we can have the information of the daily/hourly rotor speed, and have a relation of rotor speed with wind turbine sound emission (sound power level). If it is the case, normally we can use this information to calculate the annual or more critical month Wind Turbine Sound Power Level to use.
It is very usual to have the information of daily/hourly wind speed at 10 m high and the relation of this speed values with wind turbine sound power levels for a neutral atmosphere (see [18]). If it is the case, we must be very careful, because for a stable atmosphere – mainly at night – the Wind Turbine Sound Power levels can be higher than the values given for a neutral atmosphere (see [18]).
In some way we want to relate the wind speed $v_{ref}$ at a reference hight $h_{ref}$, with the wind speed $v_h$ at other hight. The reference [18] uses the following equation (equation (4) of [18]):

$$v_h = v_{ref}\,(h/h_{ref})^m \qquad (2)$$

Some values of $m$ (table 1 of [18]): very unstable: $m = 0.09$; neutral: $m = 0.22$; very stable: $m = 0.41$.

# 5 Non-Favourable propagation conditions

As explained above, a great majority of requirements related with long term average values. Therefore, to use just favourable propagation conditions can be too much conservative.
We must be aware that the ISO 9613-2 [12] method and CNOSSOS [16] method tends to give much higher values than reality, for non-favourable conditions. The CNOSSOS [16] method majorize the values for unfavourable conditions (upwind) assuming homogenous conditions.
The point 4.4.3 of chapter "*4.4 Propagation Directivity*" of reference [14] gives the results summarized on Table 3.

Table 3 – Result for favourable and non-favourable conditions (figure 6 of [14])

| Landscape | Distance between wind turbine and receiver | | | |
|---|---|---|---|---|
| | < 5,25×Rotor hight | 7,5×Rotor hight | 11×Rotor hight | 18×Rotor hight |
| Flat landscape downwind | 0 dB | 0dB | 0dB | 0dB |
| Flat landscape crosswind | -2 dB | -2dB | -2dB | -2dB |
| Flat landscape upwind | 0 dB | -4dB | -9 dB | -13dB |
| complex landscape downwind | 0 dB | 0dB | 0dB | 0dB |
| complex landscape crosswind | -2 dB | -2dB | -2dB | -2dB |
| complex landscape upwind | 0 dB | -2dB | -5 dB | -8dB |

Comparing Table 3 results with Table 1 results – assuming that Table 1 results ($d$ = 1103m) can be compared with 11×Rotor hight (11x80=880 m) Table 3 column – we can see that ISO 9613-2 [12] gives, at maximum, a difference of 3 dB between downwind and upwind, and Table 3 gives a difference of 9dB, for flat landscape, and 5 dB for complex landscape. CNOSSOS [16] gives, at maximum, a difference of 5 dB between downwind (favourable conditions) and upwind (unfavourable conditions).

# 6 Monitoring

Nowadays, with greater ease of access to continuous monitoring systems (see for example [19]), the possibility of continuous monitoring should be duly considered, at least for those wind farms with a greater probability of noise problems. In the monitoring that is carried out – continuous, without the presence of a technician, or by sampling with the presence of a technician – It should be possible to record the noise emission data of the wind turbines, or associated information, to properly determine the most critical month of noise emission (special interest for the Portuguese legislation). In the case of the presence of a technician and the wind turbine being visible, the technician must count, for control, the speed of rotation of the blades of the nearest wind turbines (similar to the need of traffic count when we do traffic noise measurements).
It should also seek to characterize, at least for information, the presence of tonality and Amplitude Modulation, through the best available methods [7,8,9].

# 7 About $L_{den}$

The equations to calculate $L_{den}$, for Portugal are the following (equation (3) for Continent and Madeira Islands and equation (4) for Açores Islands):

$$L_{den} = 10*\mathrm{Log}((1/24)\times(13\times10\text{^}(L_d/10)+3\times10\text{^}((L_e+5)/10)+8\times10\text{^}((L_n+10)/10))) \quad (3)$$

$$L_{den} = 10*\mathrm{Log}((1/24)\times(14\times10\text{^}(L_d/10)+2\times10\text{^}((L_e+5)/10)+8\times10\text{^}((L_n+10)/10))) \quad (4)$$

In some way, we are assuming that the human sensibility to noise is 5 dB higher at evening time and 10 dB higher in night-time, comparing with daytime, what, typically, is adequate for residential kind of use. For other kind of use, with typical higher sensibility on daytime, for example a school. $L_{den}$ is not adequate.
When WHO 2018 European Guidelines [4] recommends, for Wind Turbine noise, just $L_{den} \leq 45$ dB(A), and no specific limits for $L_d$, $L_e$ and $L_n$, the requirements for $L_{den}$ can be achieved by the following different set of values (in this demonstration we are using just equation (3)):

- $L_d < 45$ dB(A); $L_e < 40$ dB(A); $L_n < 35$ dB(A) (this set fulfils the typical relation of residential human sensibility for day, evening and night time).
- $L_d < 30$ dB(A); $L_e < 35$ dB(A); $L_n < 40$ dB(A) (this set fulfils the reverse of the typical relation of residential human sensibility for day, evening and night time).
- $L_d < 39$ dB(A); $L_e < 39$ dB(A); $L_n < 39$ dB(A).

Because of this, some consultants, and some countries, think that is advisable to establish requirements in terms of $L_d$, $L_e$ and $L_n$, and not just in terms of $L_{den}$ and $L_n$ and, even worst, not just in terms of $L_{den}$.
According with refence [20] Table 1, Belgium, Bulgaria, Spain and Sweden, in Europe, establish limits for $L_d$, $L_e$ and $L_n$.

# 8 Conclusions

As explained above, it is recommended, if possible, for winf farm noise calculation, to use the ISO 9613-2 [12] method, with the adaptations explained in chapter "*2 The use of ISO 9613-2*", instead of the CNOSSOS [16] method, because CNOSSOS [16] does not have a known official document with the necessary adaptations. The results obtained, when comparing the results with the ISO 9613-2 [12] and CNOSSOS [16] methods, demonstrate that the necessary adaptations for the CNOSSOS [16] method, in relation to the ISO 9613-2 [12] method, are not constant (sometimes positive, sometimes null and sometimes negative) depending on the case.

# References

[1] https://www.windturbinenoise.eu/.

[2] https://www.windturbinenoise.eu/files/post-conference-report-2021.pdf.

[3] https://www.iec.ch/ords/f?p=103:38:705117756786760::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1282,23,101795.

[4] World Health Organization (Europe) – *Environmental Noise Guidelines for the European Region*. 2018. https://www.euro.who.int/__data/assets/pdf_file/0008/383921/noise-guidelines-eng.pdf.

[5] Ontario Ministry of the Environment and Climate Change – *Sound Propagation Modelling for Offshore Wind Farms*. 2016. https://files.ontario.ca/sound_propagation_modelling_for_offshore_wind_farms.pdf.

[6] Lukas Mylonas – *Assessment of noise prediction methods over water for long range sound propagation of wind turbines*. Uppsala University (Sweden), Master of Science Program in Wind Power Project Management, 2014. https://www.diva-portal.org/smash/get/diva2:746398/FULLTEXT01.pdf.

[7] International Organization for Standardization – *ISO/PAS 20065: Acoustics — Objective method for assessing the audibility of tones in noise — Engineering method*. 2016. https://www.iso.org/standard/66941.html.

[8] Steven Cooper – *A simplified method for determination of "amplitude modulation" of audible and inaudible wind turbine noise*. Aachen, Proceedings of the 23rd International Congress on Acoustics, 2019. https://pub.dega-akustik.de/ICA2019/data/articles/000070.pdf.

[9] Institute of Acoustics – *A Method for Rating Amplitude Modulation in Wind Turbine Noise*. 2016. https://ioa.org.uk/sites/default/files/AMWG%20Final%20Report-09-08-2016_0.pdf.

[10] Colin Hansen, Kristy Hansen – *Recent Advances in Wind Turbine Noise Research*. Acoustics 2020, 2, 171–206. https://www.mdpi.com/2624-599X/2/1/13/pdf.

[11] John Laurence Davy, et. al. – *A Review of the Potential Impacts of Wind Turbine Noise in the Australian Context*. Acoustics Australia (2020) 48:181–197. https://link.springer.com/content/pdf/10.1007/s40857-020-00192-4.pdf.

[12] International Organization for Standardization – *ISO 9613-2: Acoustics — Attenuation of sound during propagation outdoors — Part 2: General method of calculation*. 1996. https://www.iso.org/standard/20649.html.

[13] Alice Elizabeth González, et. al. – *Environmental noise due to large wind turbines: what we have learnt*. Buenos Aires, Proceedings of the 22nd International Congress on Acoustics, 2016. http://www.ica2016.org.ar/ica2016proceedings/ica2016/ICA2016-0245.pdf.

[14] Institute of Acoustics – *A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise*. 2013. https://www.ioa.org.uk/sites/default/files/IOA%20Good%20Practice%20Guide%20on%20Wind%20Turbine%20Noise%20-%20May%202013.pdf.

[15] Institute of Acoustics – *A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise: Supplementary Guidance Note 1: Data Collection*. 2014. https://www.ioa.org.uk/sites/default/files/IOA%20GPG%20SGN%20No%201%20Final%20Sept%202014_0.pdf.

[16] Official Journal of the European Union - *Commission Directive (EU) 2015/996*: e*stablishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council*. 2015. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L0996&from=EN.

[17] https://www.datakustik.com/products/cadnaa/cadnaa/.

[18] G.P. van den Berg - *Effects of the wind profile at night on wind turbine sound*. Journal of Sound and Vibration 277 (2004) 955–970. https://www.researchgate.net/publication/222417053_Effects_of_the_wind_profile_at_night_on_WT_sound.

[19] Christophe Delaire, et. al. – *Research into a continuous wind farm noise monitoring system*. Glasgow, 6th International Conference on Wind Turbine Noise. 2015. https://www.marshallday.com/media/1368/wtn2015-research-into-a-continuous-wind-farm-noise-monitoring-system.pdf.

[20] Vitor Rosão, et. al - *Em Busca dos Melhores Limites Legais de Ruído* Ambiente. Coimbra, Acústica 2008. http://schiu.com/sectores/artigos/Art-690-BuscaRequisitos.pdf.