DOI: 10.61782/fa.2025.0614

FORUM ACUSTICUM EURONOISE 2025

OPTIMIZING ELECTRICITY PRODUCTION IN WIND FARMS WITH NOISE MITIGATION STRATEGIES

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ABSTRACT

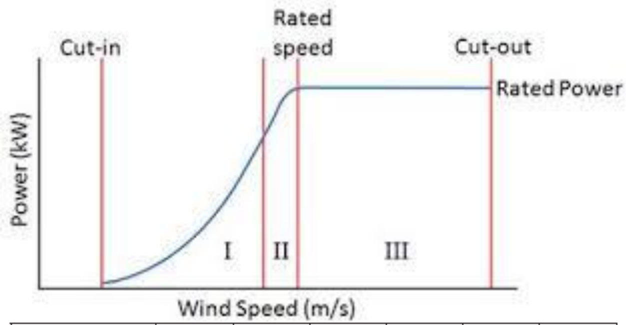
Wind power will be key to achieve the European Renewable Energy targets and making the EU carbon-neutral by 2050. Wind farms can cover several square kilometers of land and the permitting processes must consider the legitimate concerns of citizens regarding the environmental noise impact. In order to increase local acceptance of wind farm projects, a noise mitigation strategy should be available in cases where the noise standards are exceeded. A validated noise prediction model with monitored data will permit to verity the compliance of the noise regulations with best precision and limit the production of the wind turbines only when it is strictly required. This paper shows a methodology for the optimization of the electricity production of a wind farm, considering different noise calculation standards during the design of noise mitigation strategies.

Keywords: *wind farm, noise mitigation, low noise operation, CNOSSOS, ISO9613*

1. INTRODUCTION

Wind energy production constitutes a fundamental pillar of the energy sector, compensating for the energy deficit of the system through the development of alternative renewable energies, which have rapidly developed worldwide in recent decades. In Europe, wind farm capacity exceeds 270 GW, covering the wind energy almost a quarter of the demand in Spain [1].

From an acoustical point of view, wind turbines are a noisy source whose sound power level increases with their electrical power and depends on wind speed. When the wind turbine starts operating (usually at wind speeds between 4 and 30 meters at hub height), the sound power increases gradually until it reaches a stationary level as can be seen in Figure 1.



U_s m/s	4	5	6	7	8	9
Lw dB(A)	97.9	100.9	104.2	106.1	107.0	106.9

Figure 1. Evolution of electrical production and example of associated acoustic power (Lw) for a 3 MW wind turbine, according to wind speed [2][3]

Given these particular emission characteristics, the evaluation of the acoustic impact of wind farms requires a specific methodology regarding the development of prediction models and acoustic monitoring. Some countries, such as Australia or New Zealand, have developed methodological guidelines for the acoustic study of wind farms. Additionally, there are different studies and recommendations that refer to the need to adapt acoustic prediction models that were not designed for elevated sources:

- Studies [4] have demonstrated the deviations derived from the use of the ISO 9613-2 standard, so the selection of the calculation standard and input parameters must be carefully analyzed.
- The Institute of Acoustics [6] already established correction factors associated with visibility criteria

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or average height calculated independently for each receiver.

- Other authors [7] recommend the validation of the prediction models to ensure their suitability for the evaluation of wind farms, with the value of ground absorption (G) being one of the key parameters that determines the representativeness of noise predictions.

In the present study, an update of the validation of a noise prediction model under different calculation standards and different values of acoustic impedance has been carried out for a case study, in order to maximize the precision of the model and the optimization of the electrical production.

2. METHODOLOGY

The present study has developed the workflow described in to verify the effectiveness of the mitigation plan for an operating wind farm:

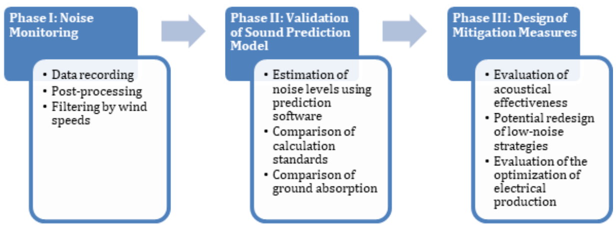


Figure 2. Workflow of the present study

In the phase of monitoring the noise of the wind farm, an in-situ acoustic testing campaign was carried out in accordance with ISO 1996-2 (under favorable conditions), with the aim of obtaining sufficient and representative sound records of the wind farm's operation at different wind speeds. The noise campaign was conducted over more than seven (7) days for a total of 368 hours of measurement and a database with more than 20,000 noise-meteorology-operation records of the park. The variation of sound levels with the wind speed was represented was obtained using the binned method, as described at in the Ontario Wind Farm Acoustic Measurement and Evaluation Guide [11], for each measurement position and period (day/night).

The acoustic testing campaign was carried out in two buildings (see Figure 3) located in the vicinity of the eastern area of the wind farm, with dominant westerly winds (predominant in the area).

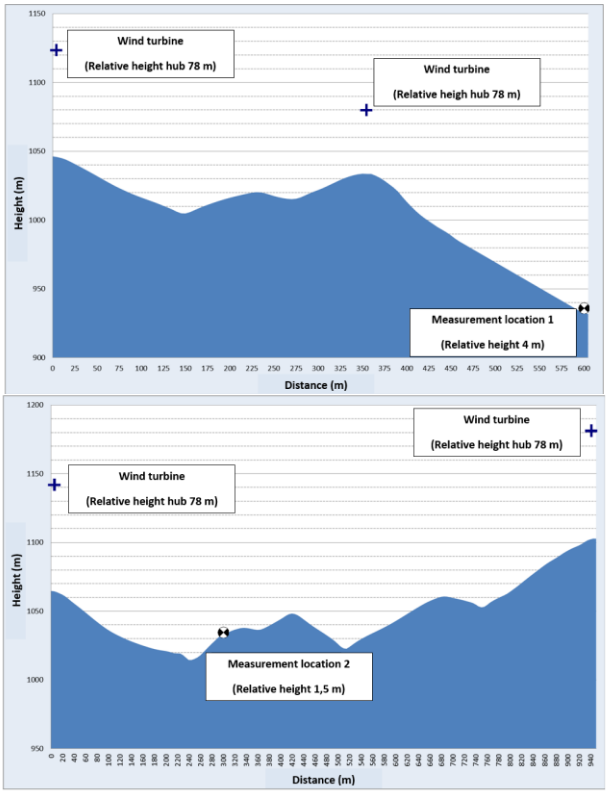


Figure 3. Elevation Profiles of Measurement Positions (Position 1 – up, Position 2 – down)

The noise prediction models were developed using the CadnaA acoustic software from Datakustik, for simulating the noise levels at the monitoring points according to the following calculation standards:

- ISO 9613-2:2024 "Acoustics — Attenuation of sound during propagation outdoors Part 2: Engineering method for the prediction of sound pressure levels outdoors" [12].
- CONCAWE-report 4/81, "The propagation of noise from petroleum and petro-chemical complexes to neighboring communities" [13]
- The Nordic sound prediction model NORD2000 [14]
- Common Noise Assessment Methods (CNOSSOS-EU) [15].

The ground absorption parameter has been configured for different scenarios including hard (G=0) and mixed ground (0,5) according to various European recommendations [16] as well as considering an absorption map based on land uses or covers established in the EAA Corine Land Cover (CLC) database [18]. The G absorption coefficient was established based on the different land use categories established in CORINE and following recommendations from previous studies [19], resulting an average G value for the study area of 0.71. More technical details about the developed noise campaign and prediction models can be found in [21] .

3. STUDY CASE

The wind farm under study is located in an extensive area situated between small towns, in a region with a marked rural-natural character dominated by crops, as well as scattered groves and scrubland. Especially during the nighttime period, human influence is practically nonexistent, and sound levels are mainly influenced by natural noise and the operation of the wind turbines.

The wind farm has more than 50 wind turbines and an installed capacity of over 100 MW. The wind turbine model under study develops an electrical power of 2 MW and has a rotor diameter of 90 meters and a total hub height of 78 meters. The wind turbines under study have a sound emission power provided by the manufacturer in accordance with IEC 61400-11, reaching a maximum power (106 dBA) at wind speeds above 6 m/s. This model can operate under low-noise configurations that can be used as corrective measures in the management of the wind farm to avoid exceeding the limit levels established by current regulations (45 dBA). Table 1 specifies the noise attenuation of the available low-noise modes for a hub height of 78 meters, in accordance with IEC 61400-14, with a reduction range of 1,4-4,8 dBA. Since noise attenuation relies on reducing the blade speed, implementing low-noise modes results in decreased electrical production from the wind turbine

Wind Speed W10 (m/s)	Noise Attenuation of Low-Noise Modes				
	NRS01	NRS02	NRS03	NRS04	NRS 05
5	0,5	0	0	0	0
6	4,4	3,9	3,2	2,4	1,4
7 – 10	4,8	4,3	3,6	2,8	1,8
dBA					

Table 1. Reduction of sound power level of low-noise mode compared to the normal operation (Source: Wind turbine manufacturer)

In the wind farm under study, low-noise operating modes were implemented, designed using a sound prediction model based on the CONCAWE standard with an absorption value of G=0.5 (developed prior to this study and validated with discrete noise records) to not exceed a sound level of 45 dBA during nighttime. This strategy is implemented exclusively during nighttime, from 5 m/s at measurement point 1 and from 6 m/s at measurement point 2.

4. RESULTS AND DISCUSION

4.1 Noise monitoring

Figure 4 below presents the wind bin analysis derived from the noise campaign data, after filtering and post-processing for the two measurement positions. The central line indicates the arithmetic mean of the sample records, and the upper (red) and lower (green) lines show the result of adding or subtracting the standard deviation value, respectively. In addition, tables with the arithmetic mean of the total noise (expressed as $L_A eq_{1\ min}$) and the standard deviation for each analyzed wind window are included.

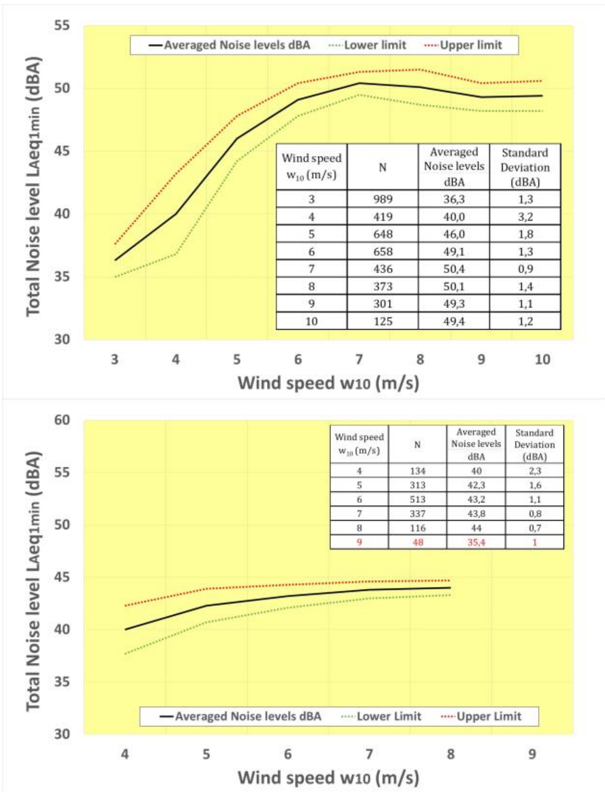
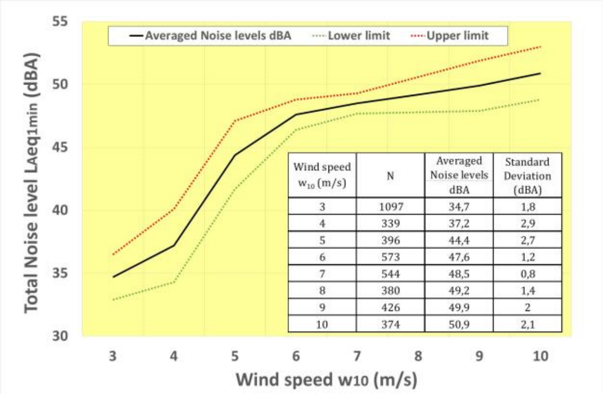


Figure 4. Monitored noise levels at measurement position 1 (Day – up, Night – down)



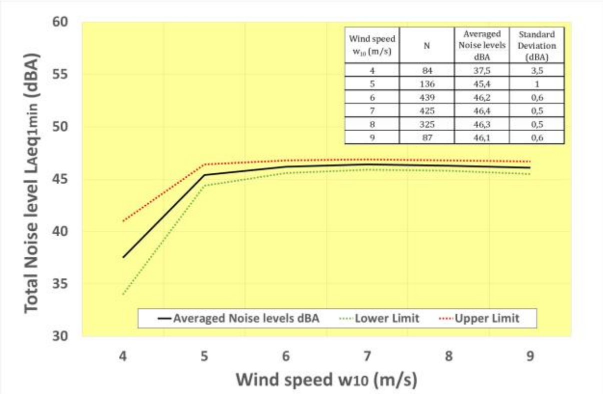


Figure 5. Monitored noise levels at measurement position 2 (Day – up, Night – down)

This analysis provides highly valuable information about the most probable average value, as well as the dispersion of samples within that interval. Generally, the variation of arithmetic averages increases with wind speed during the daytime period. During the nighttime period, the moment when mitigation measures come into operation is more clearly identified to achieve the regulatory compliance of 45 dBA: for measurement point 1 at 5 m/s (42.3 dBA) and for measurement point 2 at 6 m/s (46.2 dBA).

4.2 Noise predictions

Table 2 shows the average deviations (simulated value minus measured noise levels) for each calculation standards considering the different G values considered. The analysis of the results has revealed the following for the case study:

- All calculation standards predict conservative estimations (around 3 dBA) for hard ground, with CONCAWE showing significantly higher deviations of up to 7 dBA.

Table 2. Average deviation of noise calculations according to ground absorption for all studied cases

Calculation Standard	Average Deviation (dBA) (Predicted – Monitored)		
	Absorption G=0	Absorption G=0.5	Absorption G=CLC (0,71)
CONCAWE	6,9	2,7	2,7
NORD2000	2,6	1,9	1,5
ISO9613	2,8	-0,1	-1,2
CNOSSOS	2,7	1,0	0,3

- As the ground absorption value increases, the prediction models reduce deviations from monitored levels, without underestimations except in the case of the ISO 9613 standard (-1,2 dBA deviation). These results are in line with the recommendation not to use values above 0.5 with this standard, confirming the recommendation of the Institute of Acoustics [6] and other references [12].
- CONCAWE and NORD2000 overestimate monitored sound levels for all considered scenarios, although in the case of the NORD2000 standard, the smallest deviations are obtained with porous absorption values (deviations of 1.5 dBA for G values of 0.71).
- For the case study, the ISO9613 and CNOSSOS standards are the most accurate (below 0.5 dBA) for absorption values of 0.5 and 0.7 respectively. In the case of the CNOSSOS method, there are no underestimations in any studied scenarios.
- The results obtained for the ISO9613-2 standard are explained by other authors [22] considering the topography and the distance of the receivers vary. The ISO 9613-2 model with hard terrain has been used in other studies as a conservative model [24] with deviations ranging between 1.5 and 2.7 dBA depending on the degree of terrain irregularity. These data are in line with the deviations found of 2,8 dBA for hard terrain in the case study. The consideration of mixed terrain (0.5 or CLC) results in slight underestimations (0.1 dBA in the case of G=0.5) and -1.2 dBA in the case of absorption based on land uses.

Additionally, it is relevant to identify how the G absorption value affects the range of average deviations found for each calculation model. The CONCAWE model presents the greatest range of variation (4.2 dBA) followed by the ISO9613 model (4.0 dBA) and CNOSSOS (2.4 dBA). The NORD2000 model is confirmed as the standard with the least variations regarding terrain attenuation (1.1 dBA). It is observed that the CNOSSOS-EU model has a lower tendency to underestimation compared to the ISO9613 model as the acoustic impedance of the terrain increases, in line with previous studies in which CNOSSOS-EU predicts higher levels than ISO 9613 [28]. These results differ from other previous studies for this case study [21], although such deviations might be explained by the different versions of the standards used and their implementation in the simulation software itself.

The NORD2000 model presents overestimations of the monitored level in the range of 1.5-2.6 dBA, being the most accurate model that uses land use covers based on CLC, making this database relevant for absorption evaluation with this standard, in line with Kokowski et al. [29] .

Finally, it is noteworthy that the CONCAWE model obtains predictions with overestimations of monitored levels, especially considering hard terrain (6.9 dBA), and in the case study, it should only be used from a conservative point of view with porous terrain absorption values and/or prior validation through acoustic tests.

The following Figure 6 graphically represent the deviation of each noise prediction model based on the G value.

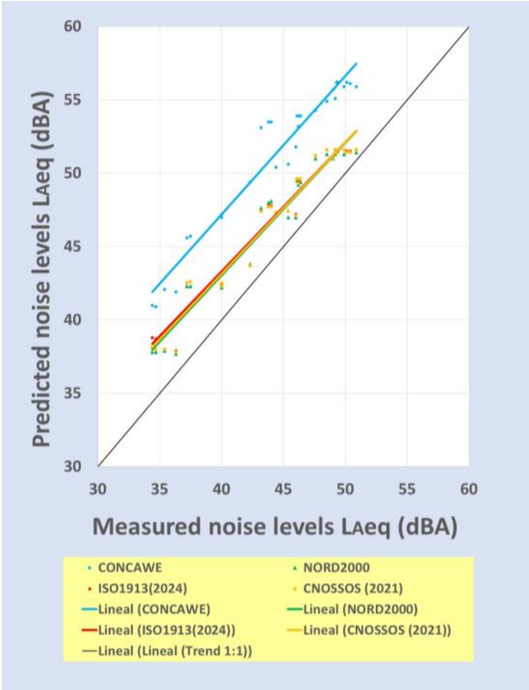


Figure 6. Comparative Analysis Between Monitoring and Sound Prediction for hard ground (G=0)

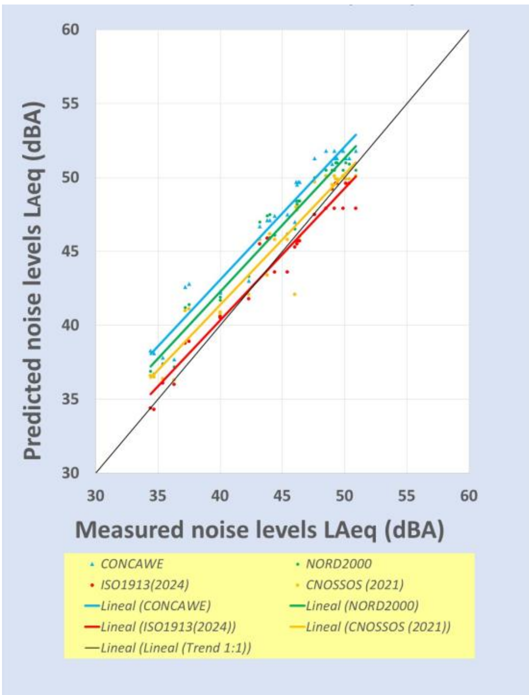


Figure 7. Comparative Analysis Between Monitoring and Sound Prediction for mixed ground (G=0,5)

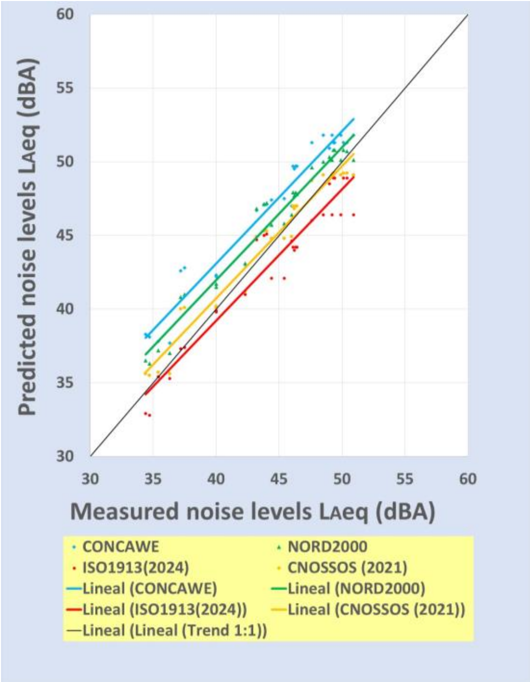


Figure 8. Comparative Analysis Between Monitoring and Sound Prediction for porous ground (G=0,71 - CLC)

4.3 Noise reduction of Mitigation Plan

Figure 9 compares the total noise with and without the implementation of low-noise modes in order to evaluate the effectiveness of the Noise Mitigation Plan strategy.

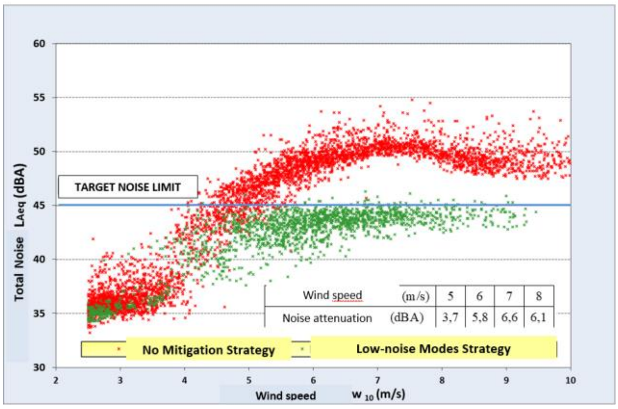


Figure 9. Total noise ($L_A$eq) during the night period and target sound level with the application of low-noise strategies at measurement position 1

The results demonstrate the effectiveness of the proposed corrective measures for reducing sound levels, especially at measurement point 1, where the average reduction is 6.2 dBA for the maximum emission of the wind turbine. At measurement point 2, the average acoustic attenuation is around 2.9 dBA and deviates by about 2 dBA from the expected sound levels. These deviations could be explained by insufficient model validation or could be associated with the implementation of low-noise strategies and the deviations found when they come into operation [30] .

Once the noise attenuation of the low-noise is confirmed, the next step is to consider the impact of the precision of the noise prediction in the design of the mitigation plan, especially during the early permitting phase when all studies are based on simulations. For this purpose, new noise reduction strategies were designed using the most accurate models (ISO9613 for G=0.5 and CNOSSOS for G=0.7) and compared against the original reduction strategy at measurement position 2. The following graph shows the accumulated electrical power as a function of wind speed for the four wind turbines with the highest contribution at that location.

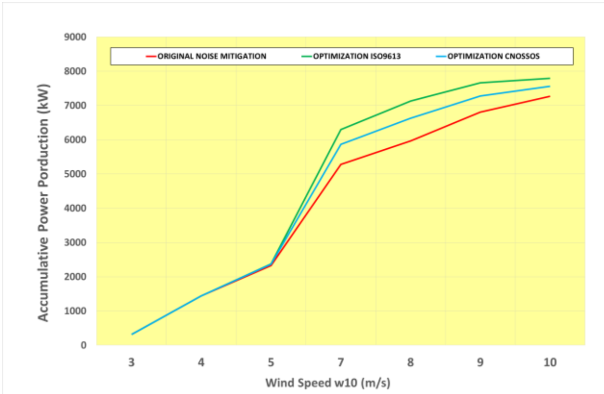


Figure 10. Accumulated electrical power (kW) for the four wind turbines with the highest contribution according to different prediction models

The results show that more accurate prediction models could lead to improvements in the electrical production of these wind turbines by up to 12% in the case of the ISO9613 standard and up to 7% in the case of the CNOSSOS model for these four wind turbines and for that wind direction. The real optimization of electrical production will evidently depend on each case study, including the frequency and distribution of wind speeds and directions, but undoubtedly, the use of more accurate sound prediction models validated with in-situ monitoring data will potentially allow designing a noise reduction strategy that optimizes the installation's production.

5. CONCLUSIONS

This study has developed a specific system for assessing the acoustic impact of wind farms, using a prediction and acoustic monitoring method, which has been validated in a practical case with complex topography. According to the results obtained for the case under study, the following can be confirmed:

- The prediction model according to CNOSSOS-EU with a ground absorption value G equal to 0,7 and the ISO9613 standard G=0,5 are the calculation standards with the least deviations from the monitored values.
- The results of the monitoring campaigns have shown that the design of low-noise strategies with prediction models is effective for managing the noise generated by wind turbines.
- The use of more accurate and validated prediction models potentially allows for the selective optimization of wind turbine electrical production, ensuring regulatory compliance.

The application of this methodology has allowed to estimate the noise immission level of the wind farm under study with a high degree of precision (average deviation less than 0,5 dBA) and would allow optimizing the electrical production of the four wind turbines with the highest contribution in a range of between 7 and 12%.

In the future, it is recommended to compare the conclusions derived from this study by expanding the validation cases under different variables (topography, distances, height and power of wind turbines, and land uses) as well as verifying the real optimization of production of a wind farm by evaluating long-term averages that consider different wind speeds and directions.

6. REFERENCES

[1] AEE (2024). Anuario 2024. Asociación Empresarial Eólica, 152 pages.

[2] Tonin, R. (2012). «Sources of Wind Turbine Noise and Sound Propagation», Acoust. Aust., 40, 20-27.

[3] Evans, T., Cooper, J., y Lenchine, V. (2013). Wind Turbine Control Methods - National Instruments. From http://www.ni.com/white-paper/8189/en/

[4] Cooper, J., Evans, T., y Najera, L. (2012). «Comparison of compliance results obtained from the various wind farm standards used in Australia», Acoust. Aust., 40, 37-44.

[5] Delaire, C., Griffin, D., y Walsh, D. (2011). «Comparison of predicted wind farm noise emission and measured post- construction noise levels at the Portland Wind Energy Project in Victoria, Australia», Proc. 4 th Int. Meet. Wind Turbine Noise. Rome, Italy, 1-24.

[6] Institute of Acoustics (2013). A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise 40 pages.

[7] Chiles, S. (2010). «NZS 6808 :2010 Acoustics – Wind farm noise», New Zeal. Acoust., 23, 20-22.

[8] Dickinson, P. J. (2009). «Nonsense on s tilts», Acoust. Aust. 2009. Adelaide, Aust., Adelaide, 8.

[9] Tickell, C. (2006). «Wind Farm Noise Assessment in Australia and Model Comparison», Can. Acoust., 34, 37-44.

[10] Rosão, V., Leonardo, R., & Santos, P. (2021). Necessary adjustments in ISO 9613-2 and CNOSSOS (industries) methods for noise forecasting in Wind Farms. Proceedings of Euronoise 2021. https://documentacion.sea-acustica.es/publicaciones/Madeira21/ID214.pdf

[11] Ontario Ministry of the Environment (2008). Noise Guidelines for Wind Farms 20 pages.

[12] ISO (2024). International Standard ISO 9613-2:2024 - Acoustics — Attenuation of sound during propagation outdoors — Part 2: Engineering method for the prediction of sound pressure levels outdoors Edition 2, 2024-01

[13] Manning, C. J. (1981). The propagation of noise from petroleum and petrochemical complexes to neighboring communities Technology. Recuperado a partir de http://www.concawe.be/Content/Default.asp?PageID=569

[14] Plovsing, B. (Delta A. and V. (2010). Proposal for Nordtest Method: Nord2000 – Prediction of Outdoor Sound Propagation 1-176 pages. DOI: AV1106/07

[15] European Commission. (2015). Commission Directive (EU) 2015/996 of 19 May 2015 establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council. Official Journal of the European Union, L 168, 1-823 and further modifications.

[16] European Commission Working Group Assessment of Exposure to Noise (2007). Position Paper: Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure 129 pages.

[17] R. Nota et al. (2005). HARMONOISE - Engineering method for road traffic and railway noise after validation and fine-tuning.

[18] EAA (2006). Corine Land Cover — Copernicus Land Monitoring Services, from http://land.copernicus.eu/pan-european/corine-land-cover

[19] AMEC Environment & Infrastructure (2012). Provision of Second Round Noise Maps for Northern Ireland. 3D modelling report 89 pages.

[20] Northern Ireland EPA (2009). Guidance Note for Strategic Noise Mapping 126 pages.

[21] Grilo, Álvaro. (2024). Design, Monitoring, and Validation of Noise Mitigation Strategies in Wind Farms. Proceedings of the Ibero-American Congress on Acoustics, Santiago de Chile, 2024.

[22] Cooper, J., y Evans, T. (2013). «Accuracy of noise predictions for wind farms», Proc. 5 th Int. Meet. Wind Turbine Noise. Denver, US., 17.

[23] Öhlund, O., y Larsson, C. (2013). «Sound propagation from wind turbines under various weather conditions», Proc. 5 th Int. Meet. Wind Turbine Noise. Denver, US., 13.

[24] Siponen, D., Napoli, C. Di, Eurasto, R., Uosukainen, S., y Nykänen, H. (2013). «The new good-practice-guide to help assessment of wind turbine noise in Finland», Proc. 5 th Int. Meet. Wind Turbine Noise. Denver, US., 10.

[25] Teague, P., Leonard, A., Engineers, V., y Town, K. (2011). «Prediction, Validation, Assessment & Compliance of Wind Farm Noise in Australia», Proc. 4 th Int. Meet. Wind Turbine Noise. Rome, Italy, 19.

[26] Søndergaard, B. (2012). «Noise from Wind Turbines Measurement and prediction including low frequency noise», Jt. Balt. Acoust. Meet., BNAM2012, Odense, Denmark, 8.

[27] Evans, T., y Cooper, J. (2012). «Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms», Acoust. Aust., 40, 28-36.

[28] King, E. A., & Ní Bhraonáin, L. (2022). Evaluating the potential impact of noise annoyance from Offshore Wind Turbines in Ireland. Proceedings of the 10th Convention of the European Acoustics Association Forum Acusticum 2023, 3101–3106. DOI: 10.61782/fa.2023.0634

[29] Kokowski, P., Libiszewski, P., Kaczmarek, T., Gałuszka, M., Pękala, P., & Gjaestland, T. (2024). On-line wind farm noise control. Proceedings of the 10th Convention of the European Acoustics Association Forum Acusticum 2023. DOI: 10.61782/fa.2023.1292

[30] Evans, T., y Cooper, J. (2011). «Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms», Acoust. Aust. 2011, Gold Coast, Aust., 1-8.