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## Wind turbine noise in practice – A decade of measurement experience

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Noise from wind turbines is a highly debated topic. Results from noise calculations and measurements are often subject to criticism, either during the planning process or in post-construction compliance tests. In the last decade, Akustikkonsulten has carried out measurements on more than 100 wind farms across the Nordic region. Most of these measurements have involved accredited noise emission measurements, in accordance with the method in IEC 61400-11, combined with calculations of noise immission with the method Nord2000. In addition, many short- and long-term noise immission measurements have been carried out. In the Nordic countries, noise immission measurements are primarily based on the method in Elforsk 98:24, with some deviations depending on national requirements. This paper summarizes results and experiences from these measurements, conducted with standardised and established measurement methods, aiming to provide a statistical review of the results.

Results from many noise emission measurements are presented, categorized by turbine size: small wind turbines (<4 MW) and large wind turbines ( $\geq 4$  MW). Both total sound power level and low-frequency noise levels (20–200 Hz) are included. Furthermore, noise immission, as equivalent sound pressure level in dBA, is presented as the difference between measured and calculated levels. In some cases, the same difference for low-frequency noise (31.5–200 Hz) is also shown. To our knowledge, no such extensive quantified compilation of measurement data has previously been published, especially not for the Nordic region with its forested areas and hilly terrain.

The main conclusion is that, in general, smaller and larger wind turbines show no significant deviations in noise emission or low-frequency noise. Larger deviations are more closely related to turbine type rather than turbine size. The results also indicate that, most of the time, calculations and measurements show good agreement.

## 1 Introduction

Noise from wind turbines continues to receive attention in the Nordic countries, particularly during environmental permitting and in post-construction compliance assessments. The discussion often revolves around whether noise predictions are sufficiently accurate and whether measured sound power levels truly reflect the behaviour of modern wind turbines. The Nordic region also presents unique challenges, as many wind farms are located in forested areas and hilly terrain where sound propagation differs compared with flat and open landscapes.

Over the last decade, Akustikkonsulten has carried out accredited noise emission measurements at more than one hundred wind farms throughout the Nordic region. These measurements were performed according to the method in the international standard IEC 61400-11 [1, 2, 3] and noise propagation to dwellings was calculated using the Nordic prediction method Nord2000 [4], which is the established prediction model in the region. This combination, accredited noise emission measurements together with Nord2000 calculations, is also the established approach for demonstrating compliance with environmental noise limits. In several projects, short- and long-term noise immission measurements at dwellings have also been carried out, primarily following the measurement method in Elforsk 98:24 [5]. This provides complementary information on sound propagation under Nordic field conditions.

The aim of this paper is to present a statistical overview of noise from modern wind turbines in the Nordic region, covering both total A-weighted sound power levels and low-frequency noise. The analysis is based on 320 accredited measurements according to IEC 61400-11 grouped into six rated power classes (1–<2 MW, 2–<3 MW, 3–<4 MW, 4–<5 MW, 5–<6 MW, and  $\geq 6$  MW). In addition, the paper presents the difference between calculated and measured noise immission at dwellings, for both equivalent A-weighted sound pressure levels and low-frequency sound pressure levels in the 31,5–200 Hz range. The results provide new insight into how wind turbine size relates to sound power levels and to the accuracy of the propagation model Nord2000 under Nordic field conditions.

## 2 Methods

All noise emission measurements were carried out in accordance with IEC 61400-11, which specifies microphone positioning, operating conditions and background corrections. The standard also defines the calculation of apparent sound power levels, including 1/3-octave band spectra from 20 to 20 000 Hz. The method is widely used internationally and provides comparable emission data between different wind turbine models. Three different editions of the standard were used in the dataset: 55 measurements were carried out using the 2006 edition [1], 50 measurements using the 2012 edition [2], and 227 measurements using the current 2018 edition [3]. Briefly, measurements according to IEC 61400-11 are performed at a distance equal to the total height of the wind turbine, downwind within  $\pm 15^\circ$  from the test object. The microphone is placed on a cylindrical ground board with both primary and secondary wind screens, and wind speed as well as other meteorological parameters are measured using a 10 m mast. Each measurement shall include at least 30 minutes with the wind turbine in operation and 30 minutes with the wind turbine stopped, to determine background noise.

Noise immission at dwellings was measured according to the method in Elforsk 98:24. This Swedish guidance document from 1998 is largely a translation of an international method published by the International Energy Agency in 1997 [6], with some modifications. Elforsk 98:24 has also been used, with some modifications, in other Nordic countries, although IEC TS 61400-11-2 [7] is now referenced in the Norwegian guidelines. Elforsk 98:24 can be used to determine both equivalent A-weighted sound pressure levels and low-frequency sound pressure levels in the 31.5–200 Hz range under outdoor conditions at receptor positions. Measurements shall be performed for downwind conditions within  $\pm 45^\circ$  from the nearest wind turbine or group of wind turbines. Similar to IEC 61400-11, each measurement should include at least 30 minutes with the wind turbine(s) in operation and 30 minutes with the wind turbine(s) stopped, for determining background noise. Elforsk 98:24 is used for both long-term and short-term measurements.

Noise propagation was calculated using the Nordic prediction model Nord2000, which includes terrain effects, ground impedance, atmospheric refraction and wind-dependent sound speed gradients. The model is recommended in national guidelines for wind turbine noise in Sweden as well as in other Nordic countries. Assumptions applied in the calculations, for example meteorological parameters and ground factors, follow the recommendations in IEC TS 61400-11-2. In most cases, ground factor D was used for forested areas and ground factor H for water surfaces. Normally, a wind speed of 8 m/s at 10 m height and downwind conditions is assumed when evaluating compliance with noise limits in environmental permits. In some of the presented cases, day-specific wind directions have also been applied to enable a direct comparison with measured noise immission under the same wind direction. For each wind farm, measured sound power levels are used for the wind turbines that were tested. For the remaining wind turbines, the highest measured level from the tested wind turbines is applied. Nord2000 can calculate both equivalent A-weighted sound pressure levels as well as low-frequency sound pressure levels in the 31.5–200 Hz range.

The wind turbines in this paper cover a broad range of sizes and geometries. Table 1 summarises the mean hub height, total height, rotor diameter and rated power for each class. The smallest wind turbines (1–<2 MW) have hub heights around 64–80 m and rotor diameters of 70–82 m, whereas the largest wind turbines ( $\geq 6$  MW) reach total heights up to 240 m and rotor diameters up to 170 m. The dataset includes 65 different wind turbine models installed at 110 wind farms.

Table 1: Rated power classes

	Rated power class					
	1-<2 MW	2-<3 MW	3-<4 MW	4-<5 MW	5-<6 MW	≥6 MW
Hub height [m]	86	96	111	122	128	121
Total height [m]	130	145	173	194	207	203
Rotor diameter [m]	88	97	124	142	159	166
Rated power [MW]	1,7	2,2	3,5	4,2	5,5	6,3
n (wind turbines)	10	42	90	105	36	37

### 3 Results

#### 3.1 A-weighted sound power level

Figure 1 shows a scatter plot of sound power levels measured at a total of 320 wind turbines in accordance with IEC 61400-11. Each grey symbol corresponds to a single measurement. The results represent the highest sound power level among all measured wind-speed bins as defined in the standard, typically corresponding to a wind speed of around 10–11 m/s at hub height for the measured wind turbines. This maximum sound power level is also the value normally used in noise immission calculations when evaluating compliance with noise limits in environmental permits. Most measurements also represent the highest available operational noise mode for each wind turbine model assessed.

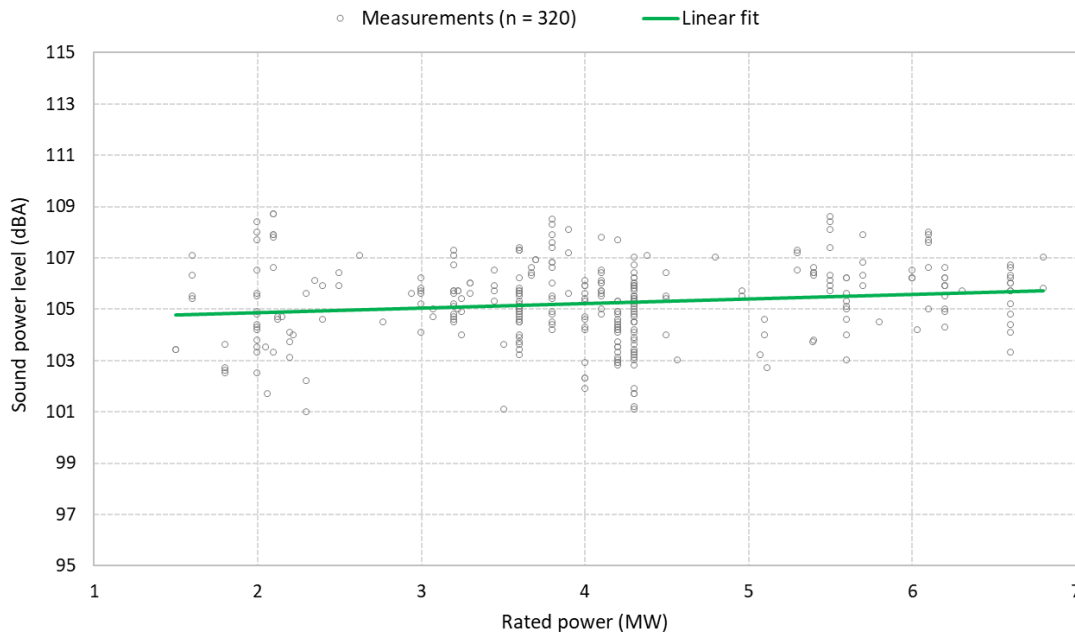


Figure 1: Sound power level from 320 measurements according to IEC 61400-11 including 65 wind turbine models and 110 wind farms in the Nordic region.

The scatter plot of all 320 measurements shows that the A-weighted sound power level ( $L_{wA}$ ) remains very stable across wind turbine sizes. Although the wind turbines vary greatly in geometry and manufacturer, the measured mean sound power level lies around 105–106 dBA for all measured wind turbines. The linear fit across all measurements is nearly flat, indicating that rated power does not meaningfully influence total A-weighted sound power level. The spread within each rated power class is typically 2–3 dB, which is larger than the difference between the classes themselves.

To further illustrate the statistical distribution, Figure 2 presents the arithmetic-mean sound power level for each rated power class, together with the p95–p5 percentile range, showing how the variation within each rated power class compares to the differences between them.

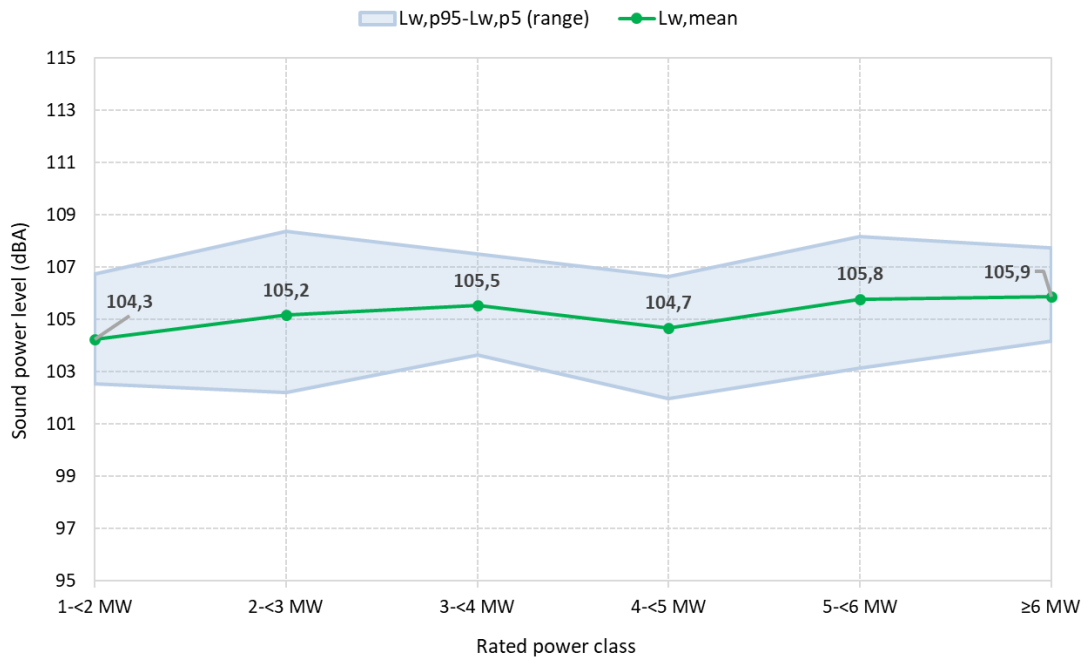


Figure 2: Mean sound power level from 320 measurements according to IEC 61400-11 divided into six classes based on rated power.

As shown in Figure 1, the overall distribution of measured A-weighted sound power levels remains highly consistent across the full range of wind turbine sizes. When the measurements are grouped into rated power classes as in Figure 2, the same picture becomes even clearer. The mean A-weighted sound power levels differ by only about 1 dB between the 3–<4 MW, 4–<5 MW, 5–<6 MW and ≥6 MW classes. Smaller wind turbines below 2 MW show slightly lower levels, and the 2–<3 MW class lies in between. For modern multi-megawatt wind turbines, however, the total A-weighted sound power level appears essentially constant, independent of wind turbine size. This indicates that aerodynamic optimisation, reduced rotational speed and load-control strategies outweigh any simple geometric scaling effect.

The class-mean values also show how tightly clustered the measurements are, even for wind turbines with the same rated power. Within-class variation is modest, and the overlap between neighbouring classes is substantial, illustrating that turbine-to-turbine differences dominate over differences related to rated power. With 320 accredited measurements representing 65 wind turbine models and 110 wind farms, the dataset provides a robust statistical basis, and the overall distribution is consistent across the entire dataset. The percentile bands included in Figure 2 further illustrate this pattern by showing that the variability within each rated power class exceeds the small differences between the class-mean values themselves.

### 3.2 Low-frequency sound power level (20–200 Hz)

Figure 3 shows the mean unweighted sound power level per 1/3-octave band in the range 20–200 Hz for the same 320 accredited measurements presented in chapter 3.1. The curves represent arithmetic-mean values and provide a direct comparison of the low-frequency spectral characteristics between the rated power classes. The figure illustrates how the unweighted sound power level varies with frequency and how low-frequency emission behaves across different wind turbine sizes.

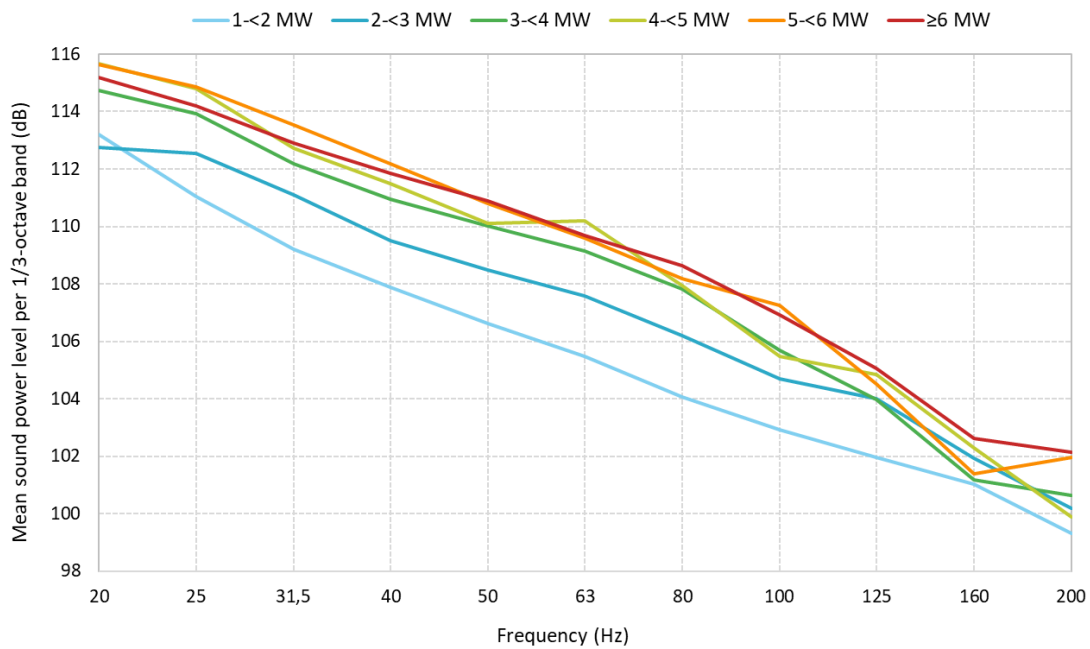


Figure 3: Mean sound power level between 20–200 Hz from 320 measurements according to IEC 61400-11 divided into six classes based on rated power.

The low-frequency spectra in Figure 3 show a clearer relationship with wind turbine size, but only up to a point. The smallest wind turbines (1–<2 MW) have noticeably lower sound power levels across almost the entire frequency range. Low-frequency sound power levels then increase from the 2–<3 MW class to the 3–<4 MW class, which is consistent with the increase in rotor diameter and associated aerodynamic loading. From 3 MW and upwards, however, the spectra converge. The 4–<5 MW, 5–<6 MW and ≥6 MW classes follow almost identical curves, and the differences between these classes are small and within the normal variation observed for modern wind turbines.

Across all rated power classes, the standard deviation within each class is approximately 2–3 dB for most 1/3-octave bands. This variability is consistent with the expected combined influence of wind turbine-specific characteristics and variations in inflow conditions. The absence of larger systematic differences suggests that no single factor dominates the observed spread. Consequently, although low-frequency sound power levels increase from smaller wind turbines to the mid-sized range, they show no clear systematic increase beyond about 3 MW, with the largest wind turbines exhibiting levels comparable to those of 3–6 MW.

This stabilisation may be explained by how modern large wind turbines are operated. While dipole theory suggests that low-frequency source strength should increase with rotor diameter, several practical factors counteract this trend. Larger wind turbines operate at lower rotational speeds, reducing low-frequency pressure fluctuations, and aerodynamic optimisation, serrated trailing edges and pitch control could also limit low-frequency generation. Small site-to-site variations, which may include differences associated with Nordic forested or hilly terrain, could also contribute to the observed 2–3 dB spread within the rated power classes, but the available data do not allow firm conclusions.

Together, Figure 3 demonstrates that the dominant changes in low-frequency sound power level occur between the smallest rated power classes, whereas low-frequency sound power level for wind turbines above approximately 3 MW is essentially similar.

### 3.3 Noise immission at dwellings

Figure 4 presents the difference between measured and calculated equivalent A-weighted sound pressure level at dwellings for 21 cases, expressed as the difference between the Elforsk 98:24 measurements and the corresponding Nord2000 calculations. Each vertical symbol represents one comparison, with positive values indicating that the measured level exceeded the calculated level, and negative values indicating the opposite. All calculations are based on sound power levels determined from measurements in accordance with IEC 61400-11.

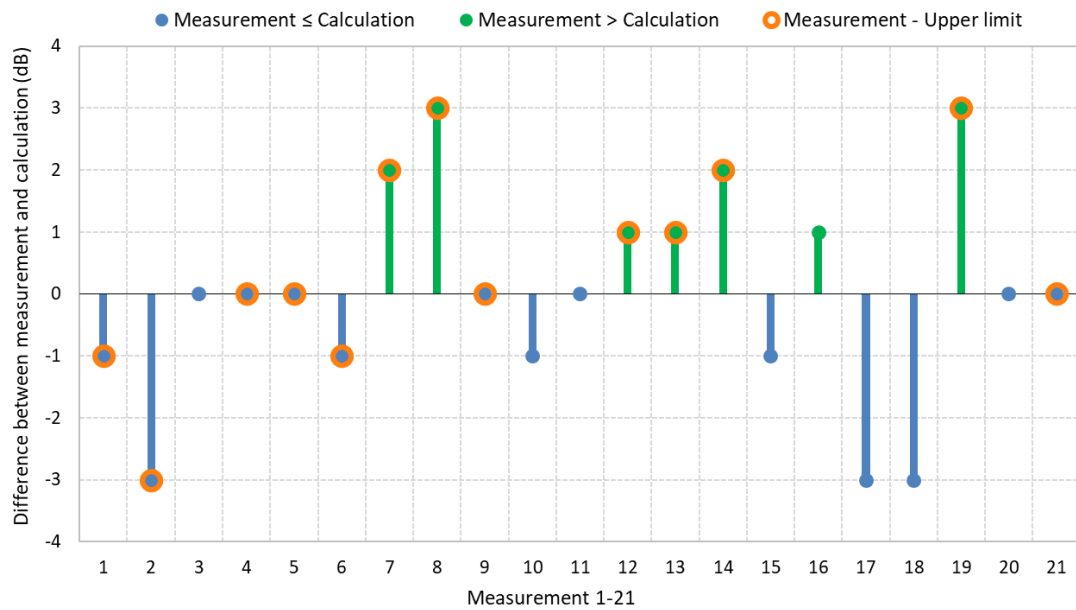


Figure 4: Comparison of the difference in equivalent A-weighted sound pressure level between measurements performed according to Elforsk 98:24 and calculations using Nord2000.

The comparison between measured and calculated A-weighted sound pressure levels at dwellings shows generally good agreement. Differences between measurement and Nord2000 calculation typically fall within  $\pm 2-3$  dB, which is consistent with the normal variability seen in Nordic environments. Several cases show negative differences, where Nord2000 predicts slightly higher levels than measured. In other cases, the measured levels exceeded the calculated values. For some of these cases, background noise contributes to the measured sound pressure level, meaning that the result represents an upper limit of the wind turbine noise rather than the wind turbine noise alone. Measurements where the A-weighted sound pressure level should be interpreted as an upper limit are marked with an orange circle in Figure 4.

Figure 5 presents the frequency-dependent difference between measured and calculated noise immission for illustrative examples. The curves show the deviation per 1/3-octave band in the range 31.5–200 Hz, allowing a direct comparison of how well Nord2000 reproduces the measured low-frequency spectra at dwellings.

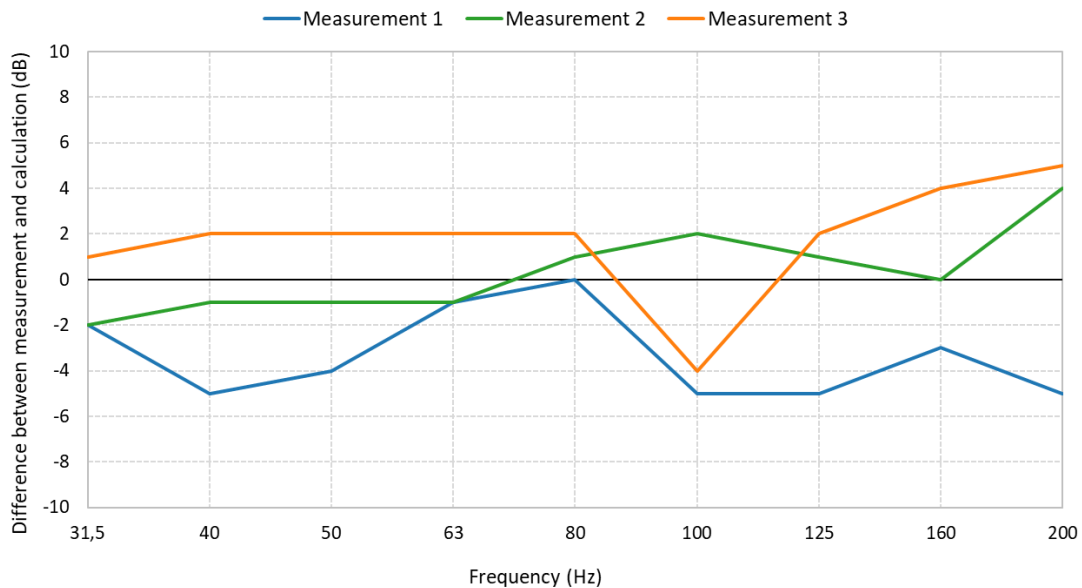


Figure 5: Comparison of the difference in outdoor equivalent A-weighted sound pressure level (31.5–200 Hz) between measurements performed according to Elforsk 98:24 and calculations using Nord2000.

As shown in Figure 5, frequency-dependent comparisons for three representative cases highlight the same overall pattern as in the A-weighted results. Curves above zero indicate that the measured levels exceed the calculated levels, while negative values indicate the opposite. One case shows systematic overprediction across most low-frequency bands, another aligns well with the calculations, and a third shows increasing measured levels at the higher frequencies. These differences are not related to turbine size or rated power but instead reflect normal variability in immission measurements.

Overall, Nord2000 shows an acceptable level of accuracy for A-weighted sound pressure levels when results are viewed across many sites, and the deviations observed in this study are in line with what has been reported in other studies. Both the Elforsk 98:24 measurements and the Nord2000 calculations are carried out under conservative assumptions, most importantly downwind conditions, which are known to give the highest noise immission. It is therefore important that noise immission measurements according to Elforsk 98:24 and the corresponding Nord2000 calculations are evaluated under the same operating and meteorological conditions. When this is the case, the comparison presented in this paper indicates that the two approaches provide broadly consistent results for A-weighted sound pressure levels.

The same overall agreement is seen for low-frequency noise, although the number of examples is smaller and the results should therefore be interpreted with some caution. Nevertheless, the combined outcome suggests that both methods give comparable results under the same assumptions, and that Nord2000 provides a sufficiently reliable basis for evaluating compliance with environmental noise limits.

### 3.4 Discussion

The dataset used in this study, comprising more than 300 accredited noise emission measurements from over 100 wind farms and 65 wind turbine models, represents one of the most extensive collections of standardised wind turbine noise data available. It provides a robust basis for identifying general trends that can be difficult to observe in smaller datasets. A consistent pattern emerges from the results. First, the A-weighted sound power level does not increase with wind turbine size above roughly 3 MW. This is an important observation, as larger wind turbines are often assumed to be noisier in public debate. In practice, modern aerodynamic design and operational strategies keep the total A-weighted sound power level within a narrow range.

Second, low-frequency sound power levels increase only up to mid-sized wind turbines but then stabilise. Dipole-based theoretical scaling provides a useful conceptual framework for understanding why smaller wind turbines generate less low-frequency noise. However, for modern multi-megawatt wind turbines, several physical and operational mechanisms may counteract theoretical scaling. The result is a convergence in low-frequency sound power levels for wind turbines larger than about 3 MW.

Third, the comparison between measured and calculated noise immission shows a consistent pattern for both A-weighted and low-frequency sound pressure levels. For the A-weighted sound pressure levels, most differences fall within  $\pm 2-3$  dB, which is fully in line with the normal variability of noise immission measurements. The frequency-dependent comparison in Figure 5 shows the same behaviour: one case with overprediction, one closely matching the calculation, and one case with higher measured sound pressure levels especially at the upper frequencies. These variations are modest and fall within what can reasonably be expected from individual noise immission measurements.

Finally, the observation that large wind turbines produce more MW per dB is noteworthy. Since the largest wind turbines emit roughly the same A-weighted sound power level while generating several times more electrical power than smaller models, the 'noise efficiency' of modern wind turbine design has improved significantly.

## 4 Conclusions

This paper summarises noise emission and immission data from more than one hundred wind farms in the Nordic region, based on 320 accredited noise emission measurements and a set of noise immission measurements. The main conclusions are:

- Modern wind turbines above 3 MW show no increase in A-weighted sound power level with increasing size.
- Low-frequency sound power levels increase from the small wind turbines but stabilise for wind turbines above 3 MW, with only small differences between the larger rated power classes.
- Differences between measured and calculated noise immission are small and fall within the normal variability associated with noise immission measurements.

- When Elforsk 98:24 measurements and Nord2000 calculations are evaluated under the same conservative assumptions, the agreement is typically within  $\pm 2\text{--}3$  dB.
- Nord2000 also provides broadly consistent results for low-frequency sound power level in the range 31.5–200 Hz, although the comparison is based on fewer cases.
- The results demonstrate that wind turbine size alone is not a reliable predictor of sound power level. Instead, modern wind turbine design plays a dominant role in determining both overall A-weighted and low-frequency noise characteristics.
- Large wind turbines generate substantially more electrical power per emitted dB, highlighting an improved ‘noise efficiency’ in modern wind turbine design.

These results contribute to a more data-driven understanding of wind turbine noise in Nordic environments and may support clearer communication in environmental permitting and project development.

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