Sound & Vibration 2025, 59(1), 1716.
https://doi.org/10.59400/sv1716

Article

Sound power of onshore wind turbines and its spectral distribution

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CITATION

van den Berg F, Koppen E, Boon J, Ekelschot-Smink M. Sound power of onshore wind turbines and its spectral distribution. Sound & Vibration. 2025; 59(1): 1716. https://doi.org/10.59400/sv1716

ARTICLE INFO

Received: 10 September 2024
Accepted: 7 November 2024
Available online: 22 January 2025

Abstract: Wind turbines (WTs) have grown substantially in size and electric capacity over the past decades. The sound power of WTs was reported to increase over time in relation to their electric power and thus over time WTs have become louder. Because of the expected ongoing growth of onshore wind energy, a greater number of people will be living close to wind farms. This sustains the need for sound reduction. Sound reduction measures, such as serrations, reduced tip speed and low noise modes, may counteract the development of higher sound power levels from ever bigger WTs. To investigate this, the sound production of WT types over the last decades is analyzed in relation to their size and electric power and the application of sound reduction measures. The analysis includes the broad band A-weighted and low frequency sound power levels as well as more detailed spectral distributions. Results show that the sound power level of wind turbines above 3 MW on average increases less with size than smaller turbines did. This is due to a lower increase in blade tip speed. The application of trailing edge serrations (TES) on average leads to a reduction in sound power level of 2.4 dB which may be slightly less at residential locations. Though TES tend to reduce the higher frequencies, the average spectral distribution of the sound did not change significantly over time, probably because of the relatively large differences between individual WT types. As a consequence, the relative low frequency content of WT sound on average has not changed.

Keywords: wind turbine; sound power; acoustic production; serrations; environmental sound level

1. Introduction

Since the 1980's onshore wind turbines (WTs) have developed tenfold in size: from about 20 m rotor diameter to present diameters of around 200 m. Maximum electric power (P_{max}, here used as synonym for rated power) in that period has grown ten times faster: from about 50 to 5000 kW. A similar trend was observed in sound power level with an increase proportional to log(P_{max}). In mid-2024 Europe had 278 GW of wind power capacity (of which 35 GW offshore), most of it in the EU (225 GW, 20 GW offshore) [1]. The EU's target for 2030 is 425 GW, but Wind Europe expects 350 GW will be realized in the EU and 450 GW in Europe [1]. Thus, over the period 2024–2030 onshore wind energy in the EU is targeted to grow with 75%, though expected grow is 44%.

The main objective of wind energy is to replace fossil energy. However, the presence of one or more wind turbines may have a negative impact on neighboring residents. Over the years reviews show firm evidence that noise annoyance is associated with wind turbine sound level [2–4], but for other health effects such as sleep disturbance, cardiovascular and psychological or stress-related effects a relation with quantifiable impacts (sound, intermittent shadow) was inconclusive. In their review Godono et al. [5] concluded there may be a relation between disturbed sleep and exposure to WT sound and/or distance from WTs, but the nature of the relation was unclear. In a field study Radun et al. [6] found that the level of WT sound (up to 40 dB day or nighttime L_{Aeq}, equivalent to 46.4 dB L_{den}) was associated with annoyance, but not with other reported health effects. This was in contrast to road traffic, where the odds for health effects were found to increase with levels of road traffic sound. Nevertheless, the impact of wind farms and socially perceived health concerns are important determinants of the opposition to wind farms [7]. In many countries wind farm planning and operation has led to a lack of social acceptance and in Europe has become “a key challenge for the deployment of wind energy”, which “could limit the overall wind resource we are able to exploit to meet climate change targets” [8].

To limit noise exposure of neighboring residents, noise and/or distance limits are set that differ between countries. In European countries or regions noise limits are different in many respects (relative to background or absolute value, statistical or equivalent sound levels over different time periods T or L_{den}, area type), but expressed in maximum allowable nighttime level (L_{Aeq}) range from 35 to 45 dB(A) [9]. In 8 of the 12 countries/regions studied there were additional distance limits [9]. Elsewhere nighttime noise limits are in a similar or higher range: in Australia 35 to 40 dB(A), in Canada 40 to 46 dB(A) and in the USA 35 to 50 dB(A) (with one exception at 70 dB(A)) [10].

In public debates on wind energy plans it is often mentioned that higher wind turbines must be louder and should therefore be placed at a larger distance from residences. In contrast, over the last years developers did not observe a clear increase in sound power level and thus saw no need to place wind turbines at larger distances. Earlier studies showed that the sound power level at maximum electric power ($L_{WA,max}$) of wind turbines from less than 100 kW up to 3 MW did increase with size. Relations found between $L_{WA,max}$ and P_{max} were close to $L_{WA,max} \propto 10 \times \log(P_{max})$ [11–13]. Individual turbine types could deviate from this relation up to about ± 3 dB. These studies date from almost a decade ago or longer and described trends in wind turbine sound for wind turbines up to about 4 MW. There is reason to think that larger and more powerful wind turbines may deviate from this trend. One reason is that there is a continuous effort to reduce aerodynamic noise, e.g., by applying and improving serrations at the trailing edge of the blades. Another reason is that the operational design may change as the blades of a higher turbine are at greater heights where wind speed on average is higher.

This study aims to show whether developments in onshore wind turbine technology have affected the relation between size and sound power or the spectral content of WT sound that was found in earlier studies. To this aim an analysis was performed, based on data from a large number of wind turbines taken from the WindPRO wind turbine catalogue. New in this study is the effect of noise reductions methods on sound level and frequency content where this study also looks at the consequences at residential distances. The focus here is on the development of sound power levels of three-bladed, horizontal axis onshore wind turbines and their spectral distribution, not on tonal sound or amplitude modulation for which no data are available in the dataset.

In section 2 a short overview is given of the dominant sound sources in modern wind turbines and how these are related to the size or other characteristics of a WT, as well as special characteristics of WT sound and possibilities to reduce the sound. Section 3 gives a description of the origin and nature of the data used in this analysis. In section 4 it is shown how WT rotor size, speed and electric power capacity have developed over time. In section 5.1 the sound power level and its low frequency content is compared to earlier studies from the period 2007–2015 and in section 5.2 this comparison to earlier studies is extended to the spectral distribution. Sections 5.3 and 5.4 consider the effect of sound reduction measures of serrations and noise modes respectively on sound level and on spectral content. Finally in section 5.5 the effect of spectral content of WT sound and of serrations at residential locations is considered, and a discussion of the results and concluding remarks of this study are given in section 6.

2. Wind turbine sound: Sources, characteristics and mitigation

The main audible components of wind turbine sound are due to aerodynamic sources on the blades of the WT. Mechanical sound sources usually contribute far less, although tonal sounds from mechanical origin may not be negligible. Of the aerodynamic sources trailing edge sound and in-flow turbulent sound are the most important audible components. Descriptions are available in many papers and reports [14,15] and are summarized in section 2.1 to give a theoretical understanding and explanation of the results of this study.

2.1. Dominant aerodynamic sources

The rotational speed of a modern, three-bladed, horizontal-axis and pitch-controlled wind turbine is proportional to the incoming wind speed V_{wind} until a maximum is reached determined by the capacity of the generator. At wind speeds below that maximum the rotor speed is proportional to the wind speed and optimized for electric power yield. Above the maximum rotational speed, the pitch of the blades is changed to keep electric power production constant in order to not overload the generator. **Figure 1** shows schematically the flow of air around a blade.

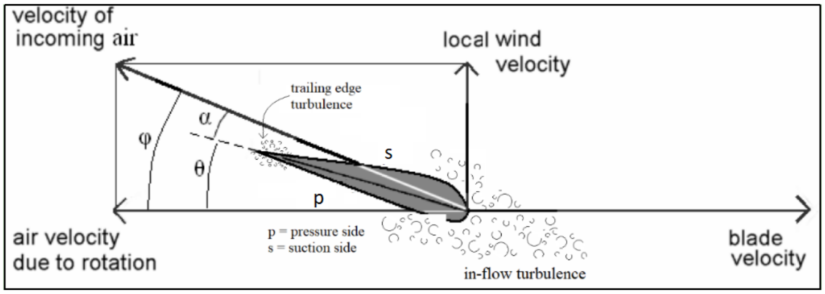

Figure 1. Cross-section of a wind turbine blade with flow (including in-flow turbulence) impinging at flow angle φ, and turbulence arising at trailing edge; θ = blade pitch angle, $\alpha = \varphi - \theta$ = angle of attack on blade.

Note: Based on figure III.2 in Van den Berg [16].

Trailing edge sound is produced by the turbulent layer of air that develops at the surface of a rotor blade towards the downstream (trailing) edge. This sound is relatively high pitched and is the dominant audible sound from modern turbines at close range. Trailing edge sound level is proportional to 50 × logV_{in}, where V_{in} is the velocity of air relative to and impinging on the blade. Air speed relative to the blade is the resultant of wind speed (in operational mode typically in the range of 5 to 15 m/s) and local blade speed which increases towards the blade tip to reach values up to about 90 m/s, equivalent to Mach 0.25. The strong dependence of sound level on incoming air velocity is the reason that most sound is produced near the tip (not at the very tip). At the tip itself the turbulent air will flow sideways from the pressure to the suction side of the blade, leading to a continuous vortex streaming from the tip in the downwind direction. Tip sound is similar to, and therefore not easily distinguished from, trailing edge sound. Though not negligible, it is not considered a main component of wind turbine sound.

When the angle of attack increases from its optimal value after maximum power output is reached, the turbulent boundary layer on the suction (low pressure) side grows in thickness. For high angles of attack this eventually can lead to ‘stall’: a dramatic increase of drag and of boundary layer thickness at the suction side, causing an increase in sound level and a decrease of lift and power performance of the blade.

Apart from this turbulence near the rear edge of the blade, there is also turbulence present in the atmosphere and the interaction of this atmospheric turbulence hitting the blade surface produces in-flow turbulent sound, also known as leading edge sound. It is relatively low-pitched and because high frequencies are more strongly attenuated by the atmosphere, in-flow turbulent sound becomes more dominant at larger distances (where at the same time the overall sound level decreases due to geometrical spreading). The increase is proportional to 50 × logV_{in} for leading edge noise resulting from small scale atmospheric turbulence (turbulence size less than the blade width). For larger size turbulence it depends on the strength of atmospheric turbulence and may increase up to 60 × logV_{in}.

Thus, the sound spectrum of a modern wind turbine is predominantly the sum of two (overlapping) regions corresponding to the two mechanisms mentioned: higher frequency trailing edge sound and lower frequency in-flow turbulent sound. Several numerical models can be used, separately for each mechanism, to calculate the sound emitted by each blade section. **Figure 2**, based on data extracted from wind turbine noise model predictions of a reference 2.3 MW wind turbine from Bertagnolio et al. [17], gives an example of the calculated A-weighted sound level in 1/3 octave bands at a position 100 m downstream from a typical 2 MW wind turbine.

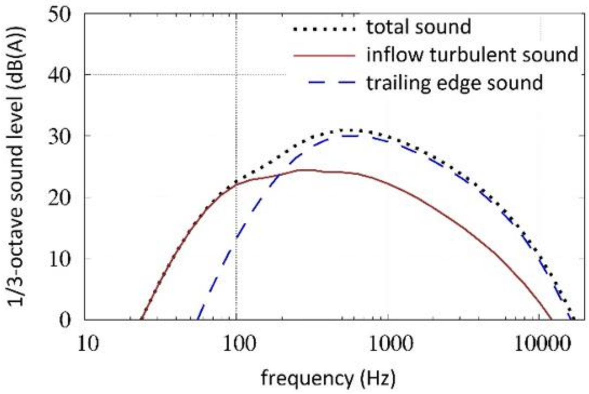

Figure 2. 1/3-octave band sound pressure levels due to turbulent inflow and trailing edge noise, 100 m downstream from a 2 MW wind turbine.

Note: Based on data in Bertagnolio et al. [17].

The sound is not radiated evenly in all directions around a WT. A downwind receiver at sufficient distance has an almost perpendicular view on the rotor. At the same distance sideways of the WT less sound is radiated (and there is also a periodic variation in level causing the swishing character). At the same distance upwind the situation is similar to the downwind side, though the sound level may be slightly lower. The basic condition for measurements according to IEC 61400-11 is to measure in the downwind position at a distance equal to maximum tip height, but other radial positions at the same distance can be added.

2.2. Other noise characteristics

In measurements a third sound component may be detected when there are variations in local wind speed due to a substantial change in wind speed with height, the wake of another wind turbine or the presence of the turbine tower or other obstacle. This 'thickness sound' is visible as regularly occurring peaks at infrasound (< 20 Hz) frequencies [16]. It is not relevant for residents as it is far below the perception threshold at residential distances.

Two characteristics of WT sound deserve special attention, as they increase residential annoyance: amplitude modulation and tonality. Amplitude modulation (AM) of WT sound is a rhythmic variation in sound level that is easily detectable by human hearing and perceived as 'swishing', 'swooshing' or 'thumping'. 'Normal' AM is always present in the forward direction of the blades, which is sideways of the rotor, i.e., in the rotor plane [14]. 'Other' or 'Excessive' AM is not always present, but occurs more or less often when there are substantial differences in incoming air flow such as in a stable atmosphere or in the wake of other turbines or hills or buildings [18,19]. Several studies show that AM is associated with increased annoyance [18,20] and may be relevant for sleep disturbance [21].

Tonality in WT sound is important as human hearing is sensitive to tonal sound. As it is with other noise sources, tonality in sound makes a sound more conspicuous. Tonal sound usually is a result of mechanical vibrations from machinery in the WT (gearbox, generator) that transmit to the tower and/or rotor blades and are radiated from their surfaces as sound [22,23]. There are many publications that deal with the detection and assessment of tonal components, but information on the prevalence of tonal components in WT sound is not (publicly) available.

2.3. Sound reduction methods for aerodynamic noise

Methods to reduce the sound of WTs aim at changing the aerodynamic flow over and just after a blade and can be divided in three approaches (which are mutually dependent): control settings, blade add-ons, and blade geometry [24]. Van Treuren listed the following technical measures [25]:

1) trailing edge serrations (TES)
2) low-noise airfoils/optimization of blade designs
3) trailing-edge brushes
4) porous blade surfaces
5) blade tip treatments
6) reduction of rotor speed
7) blade add-ons (such as vortex generators or coatings)
8) boundary layer suction
9) pitch control systems to control rotor speed

Some of these measures (2, 4, 5, 8) concern the design of the rotor blades and are thus inherent to a WT type. Other measures (1, 3, 6, possibly 4, 5 and 7) are measures that can be added to a WT, even after construction. Individual pitch control systems (9; IPC, where individual refers to the individual blades) are now applied to WTs: not specifically to control speed, but to change the pitch (and angle of attack) within a rotation to reduce the more or less abrupt changes in blade loading (because of such changes in incoming wind) by fast alignment of the blades to the flow. As this is likely to prevent local stall (a cause of ‘excessive’ AM), it is also likely to reduce or prevent ‘excessive’ AM.

In the present dataset two different measures can be distinguished. One is to reduce the blade speed and thus lower sound production. This is used in ‘low noise’ modes, often to meet noise limits in specific conditions. Another measure is the application of noise reducing extensions on or adaptations of the blades. In practice trailing edge serrations (TES) are attached to the blades. TES thus reduce trailing edge sound but have no effect on leading edge sound. Other sound reduction methods or designs, if applied, are implicit in each type but cannot be separated out of the dataset and hence cannot be analyzed.

There are also possibilities to reduce the effect of WT sound on residential locations with measures in the sound propagation path and/or at or near residential positions, but these are outside the scope of this study.

2.4. Relation with size

According to the Betz law an ideal wind turbine extracts an optimum amount of energy from wind at a tip speed ratio λ_{opt} that is equal to $4\pi/N$ with N the number of blades; λ is the ratio of blade tip speed V_{tip} and undisturbed wind speed V_{wind}. For a three-bladed turbine theoretically $\lambda_{opt} = 4\pi/3 \approx 4.2$, so $V_{tip} \approx 4.2 \times V_{wind}$. In practice λ_{opt} is higher and also depends on blade design, for most wind turbines approximating 5.4 up to 6 [26,27]. For variable speed wind turbines V_{tip} increases with V_{wind} until maximum electric power is reached and then is constant for higher V_{wind} until the turbine is stopped to prevent storm damage. In practice, the tip speed at maximum electrical power, averaged over a large number of wind turbines and diameters ranging from 40 to 126 m, historically increased from 62 to 86 m/s or with 0.28 m/s per m diameter [28].

For modern, pitch regulated wind turbines sound power increases strongly with wind speed until rotational speed reaches a maximum value. At higher wind speeds sound power may still increase slightly. One reason is that wind speed relative to the blade still increases, the other is that at the suction side of the trailing edge the turbulent layer thickness increases, which implies a higher sound production [14]. Although the 'log' relation $L_{WA,max} \propto 10 \times \log(P_{max})$ suggests there is a relation between sound power level and turbine size/electric power, there is no direct relationship between both. Wind turbine sound produced from aerodynamic sources is related to flow speed, not to rotor size. However, to compare the present results to results from earlier researchers, who have used a log relation to fit sound power to electric power, such a relation is also used here.

3. Data selection

The main body of data was provided from the WindPRO database by EMD International A/S early in 2023. The WindPRO catalogue contains over 1000 wind turbine types which were all supplied by WT manufacturers only (OEM: Original Equipment Manufacturers) and is accessible for WindPRO users. All measurements are based on the industry standard IEC 61400-11 [29]. Keith et al. [30] used the same standard to verify sound power levels of ten WTs in operation and found the results in agreement (equal within measurement uncertainty) with the data provided by the manufacturers.

Selected for this study were 1) all onshore wind turbine types of 2 MW and more (suitable for a 50 Hz grid), and 2) all wind turbine types placed in the Netherlands to compare with older and smaller (< 2 MW) turbines. For the second selection a list of types was provided by Bosch & van Rijn. The two selections overlap for the ≥ 2 MW types. Some types in the WindPRO database have no noise data and were therefore excluded. The resulting wind turbines add up to a total of 238. Some of the largest turbine types have not been built yet, which means the noise data are in some cases based on an estimate and not on actual measurements; in these cases, the sound data (and especially spectral data) may be less reliable. Not for all the turbine types a complete dataset was available. Some of the missing data could be supplemented based on manufacturers documentation. Additionally, a set of 8 complementing wind turbine types up to 6.3 MW was added based on manufacturers documentation available from Arcadis. Wind turbine types over 6.3 MW in the Arcadis data set were not used, since due to the very limited number of turbines in this class, data may be directly traceable to a specific turbine type or manufacturer; in such cases it was not allowed to present data derived from manufacturers documentation due to nondisclosure agreements. Wind turbine types over 6.3 MW from the WindPRO database were included in the analysis since these data already were public. Exceptions to this are the analyses regarding the overall sound power level compared to the low frequency sound power level and regarding the effect of serrations. For these analyses all turbine types over 6.3 MW were excluded, because it is not clear how representative the comparison would be due to the very limited number of such large turbine types.

Of the resulting 246 turbine types, 51 types include noise data both with and without trailing edge serrations (TES). A total of 76 types with TES are included in the database. In this paper, a turbine type available with and without serrations is only in sound analyses considered as two separate types. As illustrated in **Table 1**, this has led to a database consisting of 297 wind turbine types regarding sound power level and 246 wind turbine types with regard to other turbine characteristics (rated power, diameter, speed).

Table 1. Number of wind turbine types in present analysis in relation to presence of trailing edge serrations (TES).

types in database		**presence of TES**		**types differing in sound power**
		yes	**no**	
non-TES only	170		170	
				non-TES: 221
TES + non-TES	51	51	51	
				TES: 76
TES only	25	25		
total	246	76	221	297

Note: Shading according to presence or absence of TES.

Data description

The dataset provides data on a number of wind turbine parameters, including: rated power, rotor diameter, rotational speed (rpm) at rated power and apparent sound power level (L_{WA}) at varying wind speeds. All sound data in the dataset and the present paper are in A-weighted decibel and sound levels are expressed in dB(A). Differences in level are given in decibel (dB). Nominal wind speed is where electric power reaches its full capacity (rated or maximum power). From the available parameters, blade tip velocity and swept rotor area were calculated. In the database sound spectra were available for 123 turbine types at nominal wind speed in 1/1-octave bands ranging from 63 to 8000 Hz. For these types the maximum low frequency sound power level ($L_{WA,LF}$) was calculated as the sum of the 63 and 125 Hz octave band levels. The range in size of the wind turbines and in their parameters is large. For example, the smallest turbine has a rated power of 80 kW, while this is 7580 kW for the largest. To be consistent, the octave band levels at maximum sound power level ($L_{WA,max}$) produced by each turbine was used for analysis. Not all parameters are specified for all turbines. Therefore, each figure in the text below includes a specification of the number of available data points, i.e., turbine types. All WT types in the dataset are listed in a Supplementary file ‘List of Turbines’ together with data on power and rotor diameter, and with an indication whether data are available concerning rotor speed, sound power (total and low frequency), spectral content, serrations and noise modes.

The dataset includes information on the presence of two sound reduction measures (TES and Noise modes) and this will be used in the analysis. Other measures aiming at sound optimization or reduction can be part of the WT design and a cause of differences between turbine types, but they are not visible in the dataset. Also, tonality and AM are not included in the dataset and hence cannot be included in the analysis.

Earlier studies [11,12] have used 2 MW as the boundary between smaller and bigger wind turbines. The same boundary will be used when results from the present study are compared to results from these earlier studies. However, as results will show, with regard to sound production there is in fact no sharp boundary but a transition zone between 2 and 3 MW. When the development of earlier (smaller) is compared to later (bigger) wind turbines without reference to earlier studies, this transition zone will be excluded.

4. Development of rotor size

Size can be expressed as diameter or swept area of the rotor, as height of the turbine (including or excluding blade length) or as electric power capacity. Rotor size is related to electric power as a larger rotor catches more wind to be converted to electric energy. **Figure 3** shows the relation between the area that is swept by the rotor blades (short: the 'rotor area', A_{rotor}) and the electric power capacity ($P_{\max}$). The correlation coefficient (c.c.) between A_{rotor} and $P_{\max}$ is high (squared c.c.: $r^2 = 0.96$), which means that the electric power capacity is to a high degree (96%) related to the rotor area. The best linear fit in a least squares approximation to the data points equals $P_{\max} = 0.284 \times A_{\text{rotor}}$, where it was assumed that this relation includes the origin (point 0,0). Thus, on average every square meter rotor area yields a maximum electric power of 284 W. Though the technology is quite different from solar energy, coincidentally this is in the same order of magnitude as the 218–228 W/m^2 peak power produced by the best performing home solar panels [31].

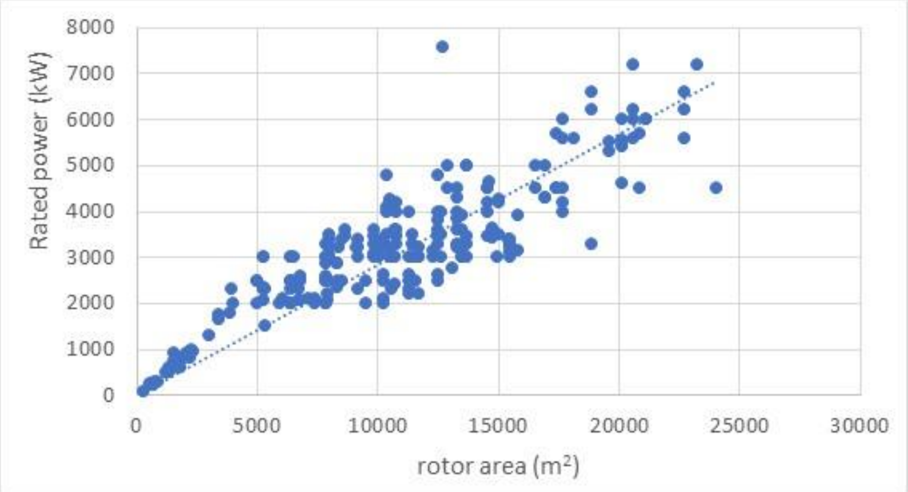

Figure 3. Rated power plotted versus swept area of rotor for 246 turbine types and best linear approximation (dotted line).

Earlier studies showed that the acoustic or sound power level of a wind turbine appeared to be proportional to the logarithm of the electric power: $L_{WA} \propto \log(P_{max})$. Thus, because of the linear relation between P_{max} and A_{rotor}, the sound power level was expected to be proportional to the rotor area: $L_{WA,max} \propto \log(A_{rotor})$. **Figure 4A** shows the relation between maximum sound power level $L_{WA,max}$ and rotor area and a best logarithmic fit to the data. To see if the actual data indeed approach a logarithmic fit, a local best fit is applied (LOWESS or Locally Weighted Scatterplot Smoothing) to obtain a smooth line without any assumption about the form of the best fit. This local fit is comparable to a moving average: it is based on a division of all data points in subsequent bands and a low-order polynomial fit is calculated for each band. The fit shows that there is a transition from a steeper gradient below about 7000 m^2 (≈ 90 m diameter) to a less steep gradient above about 10000 m^2 (≈ 110 m diameter). The data points for only the larger turbine types (≥ 3 MW: **Figure 4B**) show that, although over time the sound power level of earlier wind turbines (< 3 MW) on average increased with about 10 dB, the average increase over the entire rotor area range of the larger types (≥ 3 MW) is about 1.5 dB. Individual differences between the larger types are large (up to 8 dB) and not related to size. This is reflected in the low correlation coefficient ($r^2 = 0.05$), indicating that geometric size has almost no influence on the sound power level for wind turbines ≥ 3 MW.

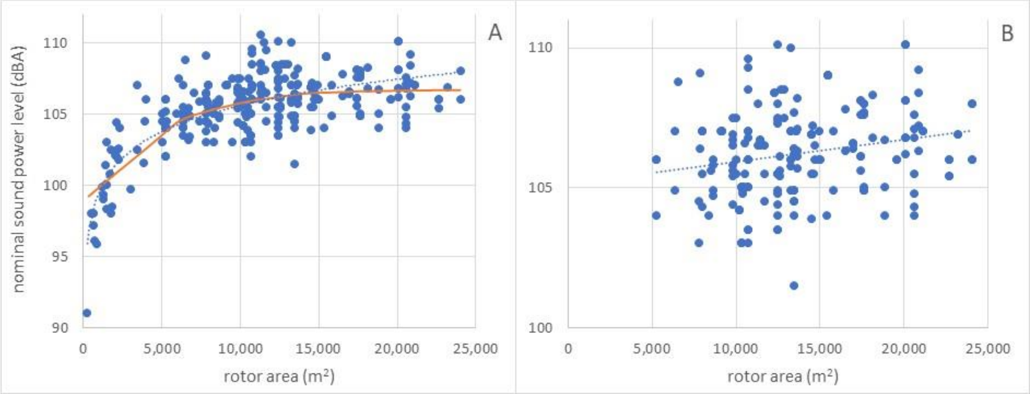

Figure 4. Maximum sound power plotted versus swept area of rotor for 297 turbine types (A, left) and 195 types ≥ 3000 kW (B, right): **(A)** best logarithmic fit (dotted lines) and best local fit (solid red line); **(B)** best linear fit (dotted line). Mind the differences in vertical axes.

As blade tip velocity is the most important factor in sound production, a possible reason for the low correlation between the size of the larger turbine types and their sound power level is that blade velocity is less clearly related to turbine size. **Figure 5** shows that rotational speed decreases with size for most turbine types and is highly correlated to size ($r^2 = 0.59$) when one exceptional turbine (18 m diameter, 120 rpm at rated power) is neglected. The data points in **Figure 5** are divided in diameter classes < 95 m and ≥ 115 m (corresponding to averages of 2 and 3 MW). This shows that for the smaller turbine types there is a clear tendency that with increasing diameter wind turbines rotate at lower rotational speeds and this decrease continues at a lower pace for the larger turbine types.

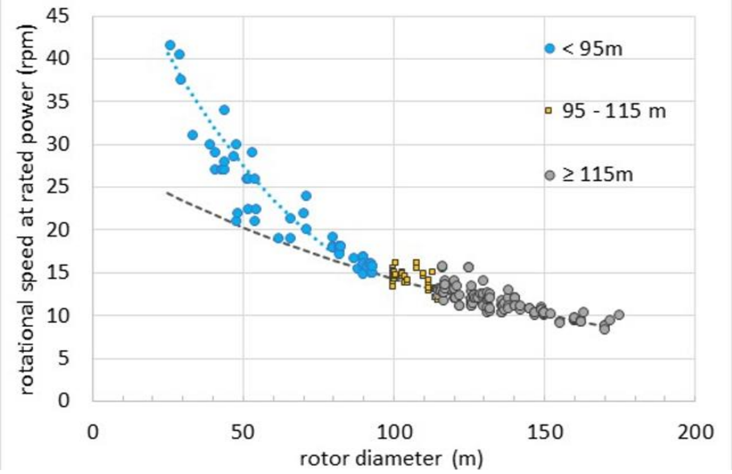

Figure 5. Maximum rotational speed (in rotations per minute or RPM) of 221 turbine types in 3 diameter classes plotted versus rotor diameter; best exponential fit for < 95 m (blue dotted line) and extended best exponential fit for > 115 m (grey dashed line).

Note: Exceptional turbine (18 m diameter, 120 rpm) excluded.

A consequence of a lower rotational speed is not necessarily a lower blade tip speed as this also depends on rotor diameter. Most of the sound of a wind turbine is produced near the blade tips, and **Figure 6A** shows that for smaller turbines blade tip speed on average clearly increased. However, for turbines over about 95 m diameter, tip speed increases more slowly with rotor diameter. The local fit in **Figure 6A** shows a transition from a steeper to a less steep gradient when the diameter is about 95 m (corresponding to about 2 MW). For the larger turbine types (3–6.3 MW; **Figure 6B**) the average tip speed increases (from 78.4 to 82.0 m/s) with 3.6 m/s or 4.45%. Theoretically, this would lead to a 0.95 dB (= 50 × log(1.0445) increase in sound power level.

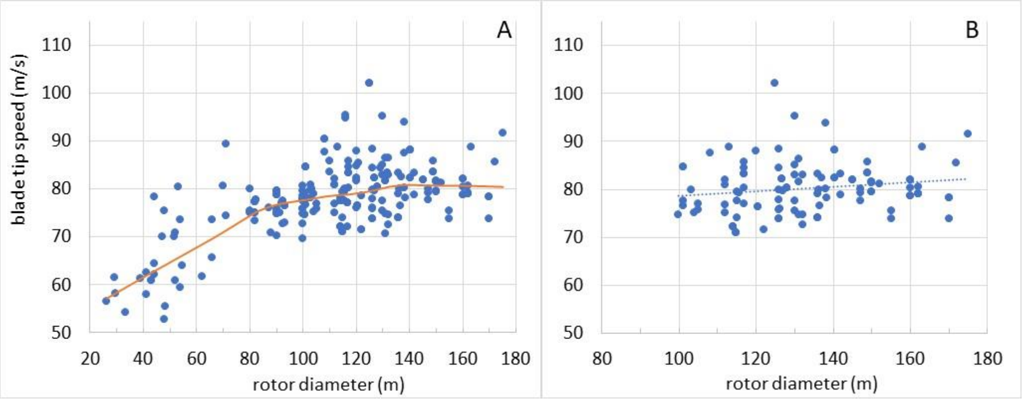

Figure 6. Blade tip speed versus rotor diameter; **(A)** for all rated powers (221 types); **(B)** for rated power ≥ 3000 kW (108 types). Best local fit (left: solid red line) and best linear approximation (right: dotted line).

Note: Exceptional turbine (18 m diameter, 113 m/s) excluded.

5. Development of sound power

5.1. Development of sound power level

The relation between maximum sound power level and maximum electric power is plotted in **Figure 7**. Over the entire range the best logarithmic approximation to the data points is:

$$L_{\mathrm{WA,max}} = 6.8 \times \log(P_{\mathrm{max}}) + 82\ \mathrm{dB(A)} \rightarrow \text{(all turbine types)}$$

where P_{max} is in kW.

The local fit shows to what degree the actual data are comparable to a logarithmic fit. It shows that between 2 and 3 MW a transition is apparent from a steeper to a less steep slope. In fact, above 4.5 MW the average becomes almost a constant 106.7 dB(A), likely as a consequence of the nearly constant average blade tip speed for the biggest turbine types (> 135 m: see local fit in **Figure 6A**). Including only turbine types below 2 MW, the best logarithmic fit is:

$$L_{\mathrm{WA,max}} = 8.9 \times \log(P_{\mathrm{max}}) + 75\ \mathrm{dB(A)} \rightarrow \text{(turbine types} < 2\ \text{MW)}$$

For types ≥ 2 MW the local fit closely fits a logarithmic function:

$$L_{\mathrm{WA,max}} = 3.0 \times \log(P_{\mathrm{max}}) + 95\ \mathrm{dB(A)} \rightarrow \text{(turbine types} \geq 2\ \text{MW)}$$

The correlation between sound power level and rated power is strong ($r^2 = 0.72$) for the turbine types below 2 MW, but very weak ($r^2 = 0.06$) for the larger types. This means that for the larger types the maximum electric power is not at all a good predictor of the maximum sound power level. Over the entire electric power range from 2 to 7.6 MW the average increase in sound power is only 1.7 dB, whereas the differences between turbines types can be up to 8 dB. For turbines with rated power increasing from 3 to 6.3 MW, the increase predicted from the increase in blade tip speed is 0.95 dB. According to the expression for $L_{\mathrm{WA,max}}$ above, the increase in sound power level is 0.97 dB.

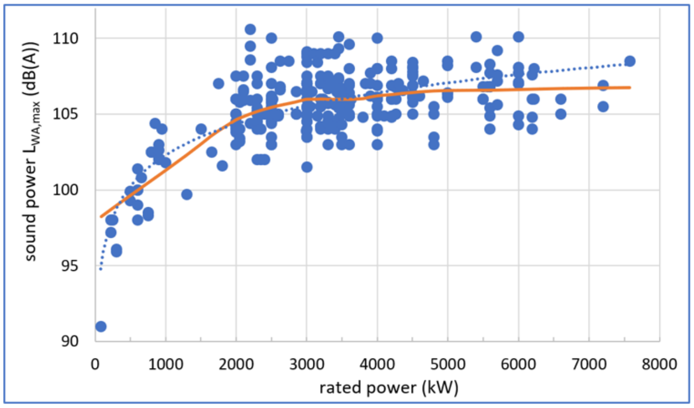

Figure 7. Maximum sound power level plotted versus rated power for all 297 turbine types; best overall logarithmic approximation (dotted line) and local fit to data (solid red line).

Møller and Pedersen [12] concluded that with the increase of wind turbine size the contribution of the low frequency part increases relative to the contribution of all frequencies combined. This can be analysed here by comparing the contribution of the two low frequency octave bands (63 and 125 Hz) that are available in the present data to the overall sound power level. The sum of these frequency bands ($L_{\mathrm{WA,LF}}$) is calculated for the same conditions as the sound power level at rated power ($L_{\mathrm{WA,max}}$).

The result is shown in **Figure 8** for the entire range of turbine types with sufficient data. The difference between $L_{\mathrm{WA,max}}$ and $L_{\mathrm{WA,LF}}$ is 11.9 ± 0.5 dB for turbines < 2 MW and 11.6 ± 0.2 dB for turbines > 3 MW: a small and nonsignificant difference. According to the logarithmic fits for the smaller types (< 2 MW) the increase of sound power level with rated power was somewhat larger for the LF level when compared to the broad band level: the difference over a tenfold increase in rated power amounts to 1.4 dB with a moderately strong correlation ($r^2 \approx 0.65$). For the larger turbine types the difference is less (and in fact reversed), but irrelevant due to the very weak correlation ($r^2 < 0.06$).

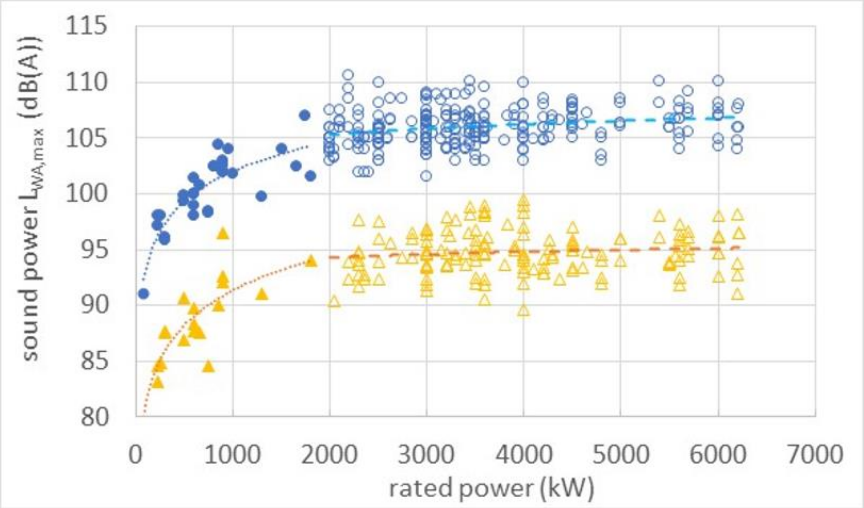

Figure 8. Maximum sound power level (circles) and maximum low frequency sound power level (triangles) versus rated power; best logarithmic approximations (dotted/dashed lines) based on 30 ($L_{\mathrm{WA,max}}$) and 18 ($L_{\mathrm{WA,LF}}$) turbine types < 2 MW and similarly 262/144 for ≥ 2 MW.

The blade tip speed of a modern pitch-controlled wind turbine is proportional to wind speed (section 2.4), but above a maximum value the pitch of the blades is changed to keep electric power production constant. **Figure 9** shows the relation between sound power level and wind speed for all turbine types with or without serrations. For both groups the increase of sound power level with wind speed is close to the expected slope of 50 × log(V_{wind}) for wind speeds from 5 to 8 m/s (plotted as a dashed line in **Figure 9**). At higher values the average sound power converges to a constant value.

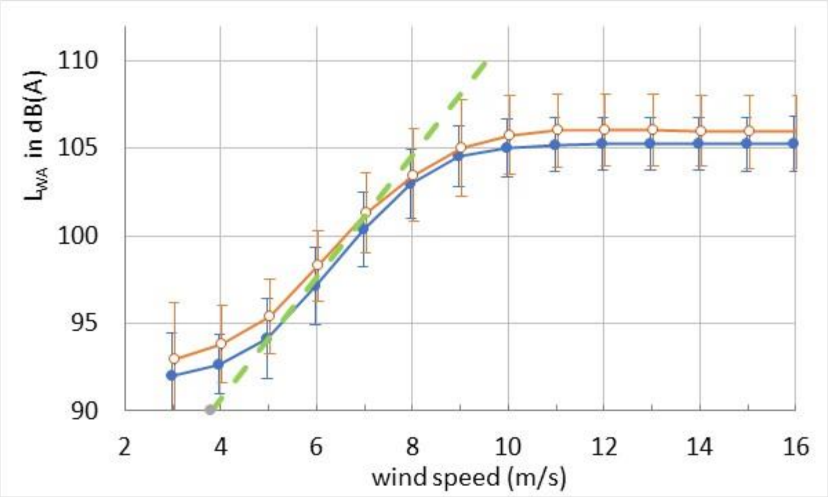

Figure 9. Sound power level L_{WA} in relation to incoming wind speed V_{wind} averaged for wind turbine types with (filled blue circles) and without (open orange circles) serrations. Green dashed line shows proportionality 50 × log(V_{wind}). Based on data from 76 turbine types with and 221 without serrations. Curves shifted 0.03 m/s right or left to separate standard deviation error bars.

5.2. Sound power spectra

All available sound power octave band spectra of wind turbines in the database are shown in **Figure 10A**, including the (arithmetic) average. The spectra are at nominal wind speed. In **Figure 10B** each of these spectra is normalized to the sound power $L_{WA,max}$ of each wind turbine type; the advantage of normalized spectra is the independence of the broad band sound level and thus they represent only spectral shape. Normalized spectral levels fall into a bandwidth of 6 up to 12 dB at most frequencies except at the highest frequency. The larger spread at 8 kHz may be a consequence of the distance between rotor and measurement site in combination with the high atmospheric attenuation at 8 kHz for which (according to IEC 61400-11 [29]) no correction is applied when determining the sound power level from measurements. This attenuation depends on temperature and relative humidity and varies, in the range of 0 °C–20 °C and 80%–100% relative humidity, from 0.06 to 0.15 dB/m [32]. Thus, the attenuation for sound coming from maximum tip height (hub + blade length), which is in the range of 140 to 250 m (with sound path length $140\sqrt{2}$ to $250\sqrt{2}$ m), can vary from 11.8 to 52.5 dB depending on turbine height and weather conditions.

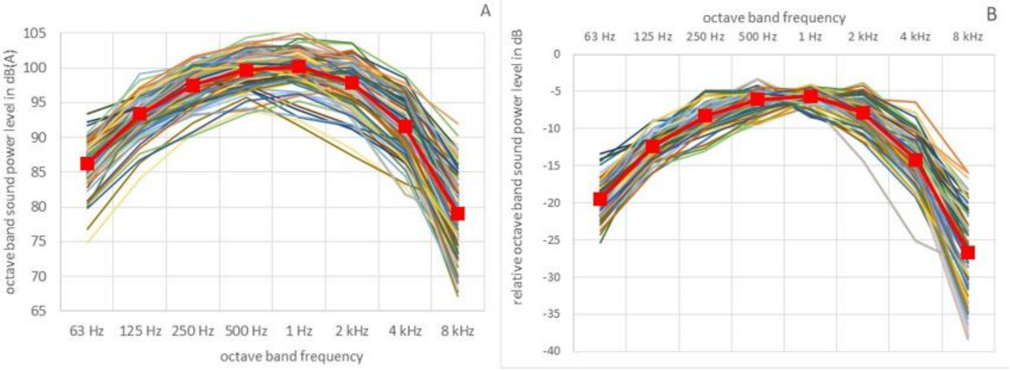

Figure 10. Individual sound power octave band spectra; **(A)** at rated power; **(B)** normalized to individual sound power level $L_{WA,max}$. With arithmetic means (bold red lines with markers).

Note: Based on data from 123 turbine types.

In **Figure 11** the average normalized octave band spectrum of all turbines with sufficient spectral data (including with or without serrations) is compared to those from earlier studies. The standard deviations are derived from figure 14 in Møller and Pedersen [12] and figure 3 (for 1/3 octave levels) in Sondergaard [11] (who only shows these for turbines > 2 MW, therefore not shown in **Figure 11A**). Standard deviations (s.d.) of the differences in **Figure 11B** are calculated as the square root of the sum of both individual squared s.d.'s. Although in the present study the levels at 500 or 1000 Hz are somewhat higher compared to earlier studies, the differences at all frequencies are not significant. Also, in the present study the spectral differences between turbines with rated power below and above 2 MW is within 2 dB, but again these differences are not significant.

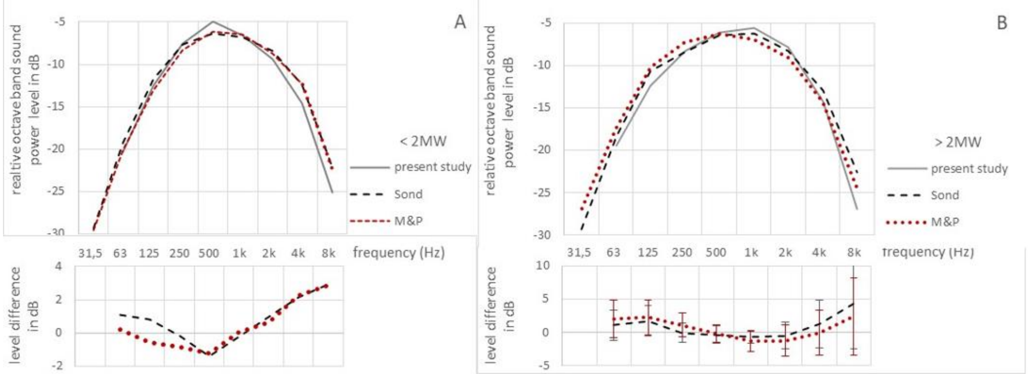

Figure 11. Average normalized sound power octave band spectra in the present study compared to spectra from Sondergaard [11] and Møller and Pedersen [12]. Above: **(A)** for wind turbines < 2 MW; **(B)** > 2 MW. Below: differences between earlier and present spectral levels, at right with 1 s.d. error bars; positive difference means present value is lower. Present study based on 9 turbines < 2 MW and 114 > 2 MW, the latter include 25 turbines with serrations.

5.3. Effect of serrations on sound power level

The database includes 74 turbine types with trailing edge serrations (TES) and 218 without serrations (non-TES) with relevant data. In **Figure 12** these selections are plotted separately and this shows that serrations do have an effect on sound power level. When compared to all types together (**Figure 7**), the non-TES types on average have a higher, the TES types a lower maximum sound power level. **Figure 12** also shows that TES only have been applied to the larger, more recent turbines (> 2 MW).

Based on the logarithmic fits in **Figure 12** the average effect of TES (= difference between non-TES and TES sound power level fits) increases with rated power from 1.2 to 2.3 dB. This increase in effect is in part due to a larger share of TES turbines at higher rated powers. The average difference over each 1 MW interval is 1.5 dB.

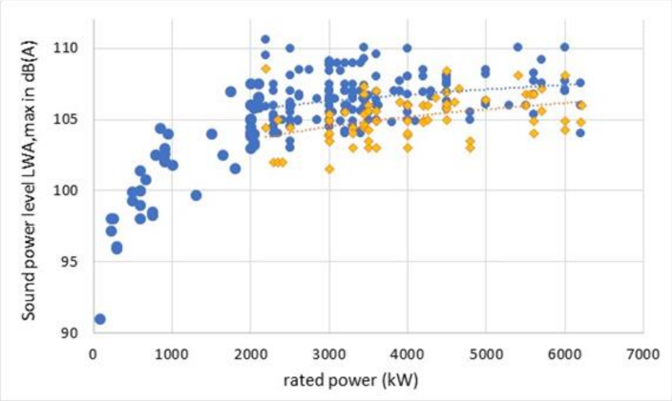

Figure 12. Maximum sound power level of turbine types with serrations (orange diamonds) and without (blue circles) versus rated power, with best logarithmic approximations (dotted lines) based on 218 (without) and 74 (with serrations) turbine types.

A detailed view of the spectral differences between non-TES and TES wind turbines can be based on detailed spectral data that are available for 11 turbine types each with and without serrations, of 2 manufacturers. **Figure 13** shows the averaged 1/3 octave band spectra and the average value of individual differences (same turbine with/without TES). The broad band level difference is 2.4 dB (s.d. 0.5 dB), determined by frequencies > 200 Hz where trailing edge sound is dominant. For spectral bands in this range up to 2.5 kHz the effect of TES is significant (chance of effect being zero or less < 5%) over all turbine types and amounts to 1.5 to 3.1 dB. At lower and higher frequencies, the differences in level are not significant.

Figure 13 implies that serrations have less effect on the low frequency part of wind turbine sound. Without serrations the difference between broad band ($L_{\mathrm{WA,max}}$) and low frequency power sound level ($L_{\mathrm{WA,LF}}$) is 11.4 ± 0.25 dB, with serrations this is 11.0 ± 0.8 dB, close to the overall value of 11.4 ± 0.15 dB (**Figure 8**). Because serrations predominantly have effect on the higher frequency trailing edge sound, they are likely to change the spectral balance of the emitted sound: with serrations the low frequency part is expected to be slightly higher relative to the broad band level.

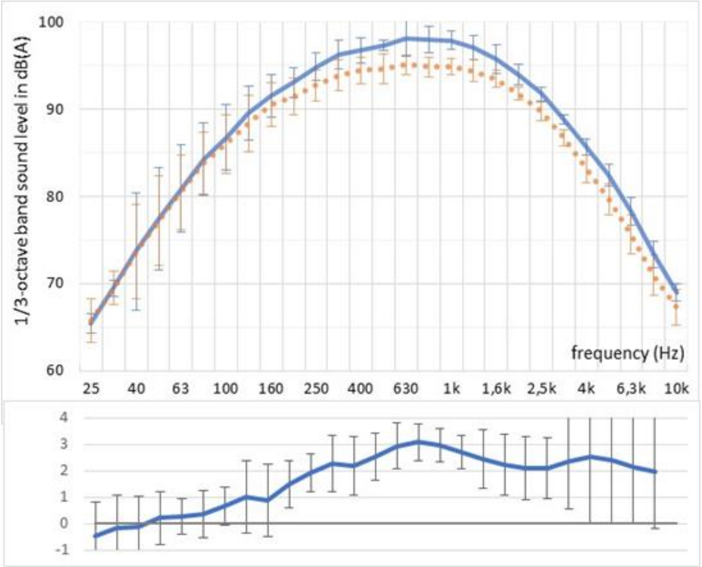

Figure 13. 1/3 octave band spectra of 11 turbine types with serrations (TES, dotted red line) and without (non-TES, solid blue line). Below: difference between non-TES and TES spectral levels in dB. Vertical bars: standard deviation.

5.4. Effect of noise mode

Several turbine types have a ‘noise mode’ where the rotational speed can be reduced with the aim to reduce sound emission. A noise mode is usually set in steps of about 1 dB with a variation in number of steps depending on the manufacturer. Here a noise reduction of 3 dB (± 0,5 dB) is chosen to compare its effect to the standard (0 dB) mode. For this comparison 15 turbine types from 5 manufacturers were available with spectral data for a standard mode and a 3 (± 0.5) dB noise mode, all with a rated power between 3 and 6.3 MW. The average sound power level $L_{\mathrm{WA,max}}$ for the two groups was 105.5 and 102.6 dBA, with an average noise reduction of 2.7 dB. The noise reduction appears to have a small effect on spectral distribution: for 1/3 octave band frequencies from 20 to 100 Hz the reduction is somewhat lower (2.4 dB) compared to higher frequencies (3.0 dB), though the difference is not significant. Leading edge noise thus is reduced somewhat less than trailing edge noise. One could expect an opposite effect, because with the increasing pitch angle the turbulent layer thickness at the suction side of the trailing edge increases, which would imply more sound production. However, results show there is no evidence for this effect.

Using a noise mode has a price in loss of power production. For all available noise modes of 19 wind turbines the loss in rated power, relative to the standard mode, is shown in **Figure 14**. The reduction in rated power is 4.8% per dB noise reduction and for noise reductions up to 5 dB both are strongly correlated (r^2 = 0.79).

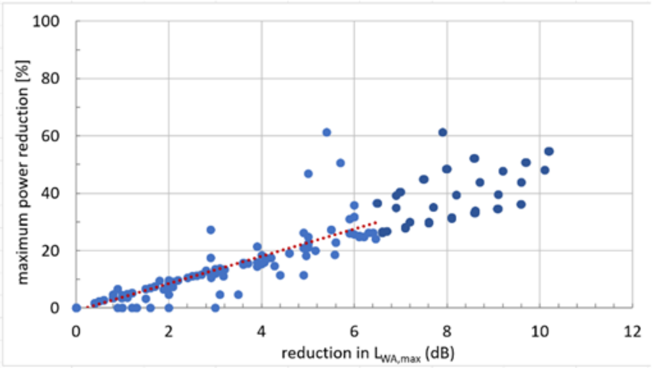

Figure 14. Loss in rated power in relation to sound reduction through use of noise mode settings, based on 19 turbine types.

5.5. Effect of serrations and spectral content at residential locations

The analysis in section 5.3 concerns the effect of trailing edge serrations on the sound power level of wind turbines at the source, without any influence of the environment. At residential locations the sound level will be lower because of geometrical spreading, but also the spectral content will change as higher frequencies will be attenuated more than lower frequencies. To assess such propagation effects, the immission sound levels within two kilometres of five types of large wind turbines (3.3 to 6.2 MW) with and without serrations have been calculated. The ISO 9613 calculation model is used with a ground factor of 0.5 in a downwind situation, over flat ground at typical temperate weather conditions. Immission height is 1.5 (‘ear at ground floor’) and 4 m (ditto first floor). The turbine types were selected for differences in ‘spectral balance’: the relative strength of the low frequency content, based on the difference between the sound levels of the 1000 Hz and 63 Hz octave bands. A low difference means a relatively high LF content. The turbine types, marked as A through E, will be denoted as ‘highest’ and ‘lowest’ with respect to relative LF content; the middle three types have intermediate values. **Table 2** shows these differences as well as the sound power level of the five types with and without serrations. The third column shows the spectral balance according to the difference L_{1kHz}–L_{63Hz}: adding serrations changes the spectral balance order of the intermediate three turbine types. The differences in the spectral balance as a result of adding serrations is in the lower third of column 3; this shows that serrations increase LF content with varying magnitude. In **Table 2** also immission levels are shown at two specific distances (500 and 1000 m) and distances where a specific sound level (30 and 40 dB(A)) is reached. The distance where a level of 40 dB(A) is reached depends on the sound power level of the turbine, but with serrations this distance is reduced. The effect is greater for a 30 dB(A) immission level, where distance is reduced with up to 260 m (20% relative to same turbine without serrations).

Table 2. Effect of serrations and of low frequency content of sound power level on immission levels at distance from five wind turbine types (A through E) of 3 to 6 MW.

		sound level difference 1000 Hz/63 Hz	**relative LF content**	**sound power level in dB(A)**	**immission level at 500 m**	**immission level at 1000 m**	**distance to 40 dB(A)**	**distance to 30 dB(A)**
no serrations (non-TES)	A	14.6	highest	108.0	40.8	33.1	540	1280
	B	16.7	high	107.6	40.3	32.9	520	1280
	C	17.0	medium	108.1	40.9	33.2	540	1300
	D	17.5	low	106.9	39.5	31.8	480	1160
	E	19	lowest	105.8	38.5	30.8	430	1060
with serrations (TES)	A	11.9	highest	106	38.9	31.4	450	1130
	B	13.3	medium	104.8	37.6	30.2	390	1020
	C	15.4	low	106.1	38.9	31.2	440	1100
	D	12.9	high	103.9	36.6	28.9	350	910
	E	16.1	lowest	104.4	37.0	29.5	370	960
difference non-TES minus TES	A	2.7	increased	2.0	1.9	1.6	90	150
	B	3.4	increased	2.8	2.7	2.6	130	260
	C	1.6	least increased	2.0	2.0	2.1	100	200
	D	4.6	most increased	3.0	2.9	2.9	120	250
	E	2.9	increased	1.4	1.4	1.2	60	100

Figure 15 compares the attenuation without and with serrations relative to the immission level at 200 m from the unserrated wind turbine (which is set at 0 dB). Attenuation is less when LF content of the sound power level is higher, but without serrations the differences between turbine types over this distance range do not exceed 1 dB. With serrations the levels are lower and differences between turbine types are larger, up to 2 dB.

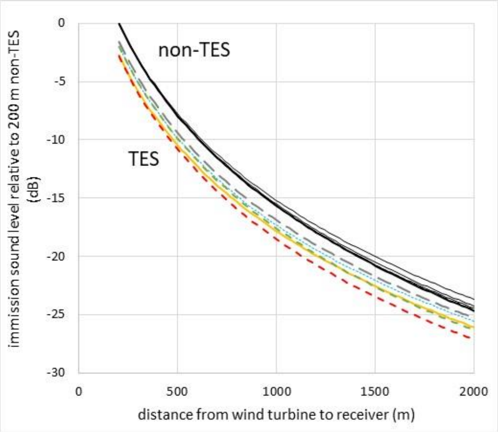

Figure 15. Attenuation (with reference 0 dB at 200 m of non-TES turbine type) at distances up to 2 km from five wind turbine types without (black lines) and with trailing edge serrations (color scheme in **Figure 16**).

The effect of serrations over the distance range of 200 m to 2 km is depicted in **Figure 16** for the 5 turbine types for a receiver height of 1.5 m. Differences between immission levels at receiver heights of 1.5 and 4 m amount to less than 0.25 dB. The effect depends on the spectral balance of the unserrated sound power level and on the spectral effect of the serrations. In three cases (B, C, D) the sound reduction from the serrations changes less than 0.3 dB over the entire distance range. In the other cases (A, E) the serrations are less effective with increasing distance and at 2 km reduce sound 0.9 dB less compared to the source.

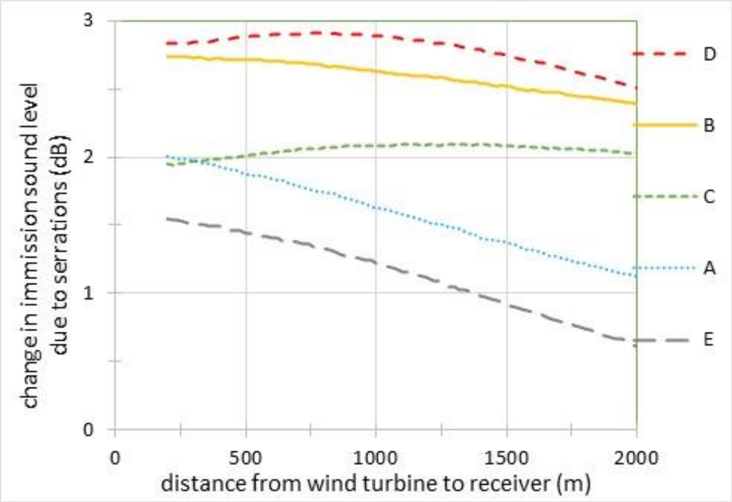

Figure 16. Effect on immission sound level of adding serrations to five wind turbine types (A through E, see **Table 2**) as a function of distance to the turbine for receiver height of 1.5 m.

6. Discussion and conclusions

The present study gives an update of similar studies in 2011 and 2015 [11,12] that show the development of wind turbine sound power, including its spectral distribution, with wind turbine size. It also considers aspects of wind turbine sound that were not included in the earlier studies: the effect of sound reduction measures (trailing edge serrations and noise modes) and their effect at residential distances.

This study includes all wind turbine types with rated power ≥ 2 MW and a smaller number of turbines < 2 MW that were available in the WindPro catalogue early in the year 2023. The average behavior of these turbine types is described where it must be kept in mind that individual types can differ up to about 3–4 dB from the average. The WindPro dataset includes sound data obtained in accordance with the measurement standard IEC 61400-11 [29], but for some new types the sound data seem to be derived from calculations. For each wind turbine type individual turbines may deviate (slightly) from the type specifications, but this is not relevant in the statistic approach in this study.

The results show that over a time of several decades sound power level averaged over all wind turbine types appears to increase with rated electric power. This can be expressed as a log-relation: $L_{WA,max} \propto y \times \log(P_{max})$, where the constant y is the slope in this proportionality (theoretically the sound power level is related to blade tip speed, not to rated power, but historically a logarithmic fit was used). This increase has changed over time: there is a transition zone from a higher slope for turbine types < 2 MW to a lower slope for types ≥ 2 MW. In 2008 Van den Berg et al. [13] found a slope of 9.9 and 10.0 for sound power levels at 7 and 8 m/s respectively (i.e., near rated power), based on 78 turbine types ranging from 75 to 3000 kW. A few years later, Møller and Pedersen [12] found a slope of 11.0 (according to their figure 13) based on 44 wind turbines ranging from 450 to 3600 kW. Finally, in 2015, Søndergaard [11] found a slope of 8.9 based on wind turbines (no number mentioned) ranging from about 300 kW to 3000 kW. For the development of wind turbines from 3 to 6.3 MW these relations mean that an increase of sound power level of 2.9–3.5 dB was expected (based on a slope of 8.9–11.0). In contrast, the present study shows the actual average increase is 1.0 dB (with a slope of 3.0).

One reason for the later development appears to be the use of trailing edge serrations (TES) on turbine types of 2 MW and above. Averaged over all turbine types with or without TES they lead to a sound reduction of 1.5 dB. Focusing on detailed data from turbine types that can be equipped with or without serrations, adding serrations give an average sound power reduction of 2.4 dB (s.d. 0.5 dB). The increased use of TES has led to a lower overall increase with rated power. However, also the larger turbine types that do not use TES have a lower slope than found before: 4.4 instead of 8.9–11.0. And also for the larger turbine types with TES the slope is 5.6, again lower than 8.9–11.0. A reason for this appears to be a slower increase of blade tip speed with size. The transition to a smaller increase in sound power level is accompanied by a similar transition in blade tip speed. For the larger turbine types (3–6.3 MW) the average tip speed increases with 3.8 m/s or 4.5%. This increase in tip speed leads to an expected increase in sound level of 1 dB which is exactly the increase found over this range of diameters. **Table 3** gives an overview of the sound power levels of turbine types between 1 and 7 MW and its spectral composition in absolute and relative or normalized ($L_{WA,max}$ subtracted) terms and separately for wind turbine types without and with trailing edge serrations (TES). At 31.5 Hz less data are available compared to the other frequencies. Møller and Pedersen [12] expected for turbines in the 5 MW class a sound power level at rated power of 108.8 dB(A), but the present results show that the average sound power level of the 3–5 and 5–7 MW types without serrations (106.7–106.9 dB(A)) are about 2 dB, with serrations (105.4–105.8) about 3 dB, below their estimate.

Table 3. Absolute and relative sound power octave band levels in dB(A) for turbine types without and with trailing edge serrations.

power range‡	**1–3 MW**	**3–5 MW**	**5–7 MW**	**1–3 MW**	**3–5 MW**	**5–7 MW**
	without serrations (non-TES)					
Number of types‡‡	11	43	15	11	43	15
LWA,max	105.9 ± 1.7	106.7 ± 1.3	106.9 ± 1.1			
frequency in Hz	LWA,max octave band levels			relative octave band levels		
31.5†		77.0 ± 1.4	77.4 ± 2.5		−30.2 ± 1.7	−30.2 ± 2.0
63	86.5 ± 2.4	87.1 ± 2.2	86.8 ± 2.3	−19.4 ± 2.4	−19.7 ± 2.3	−20.1 ± 2.1
125	93.8 ± 1.6	94.2 ± 1.8	94.4 ± 1.1	−12.2 ± 1.6	−12.6 ± 1.4	−12.5 ± 0.8
250	96.9 ± 1.5	98.5 ± 1.9	99 ± 1.5	−9.1 ± 2.0	−8.3 ± 1.4	−7.9 ± 1.0
500	99.7 ± 1.5	100.6 ± 2.0	100.8 ± 2.0	−6.2 ± 1.5	−6.2 ± 1.3	−6.1 ± 1.3
1000	100.5 ± 2.1	101.1 ± 1.8	101.4 ± 1.7	−5.4 ± 0.6	−5.6 ± 0.9	−5.5 ± 0.8
2000	98.2 ± 3.4	98.6 ± 2.5	99.2 ± 1.6	−7.7 ± 2.1	−8.1 ± 2.3	−7.7 ± 1.6
4000	92.5 ± 3.9	92.6 ± 4.2	91.9 ± 1.7	−13.5 ± 3	−14.1 ± 4.2	−15 ± 2.5
8000	79.5 ± 7.4	80.4 ± 5.6	79.9 ± 3.5	−26.5 ± 6.7	−26.3 ± 5.4	−27 ± 3.7
	with serrations (TES)					
Number of types‡‡	3	29	11	3	29	11
LWA,max	102.6 ± 1.1	105.4 ± 1.0	105.8 ± 1.0			
frequency in Hz	LWA,max octave band levels			relative octave band levels		
31.5††		77.6 ± 3.3	75.3 ± 3.6		−27.9 ± 3.9	−30.0 ±2.9
63	85.4 ± 0.7	86.1 ± 2.0	86.5 ± 1.3	−17.2 ± 1.2	−19.3 ± 1.8	−19.3 ± 1.1
125	90.9 ± 0.5	93.1 ± 1.6	93.2 ± 1.3	−11.7 ± 1	−12.3 ± 1.3	−12.6 ± 1.6
250	93.8 ± 0.4	97.0 ± 1.7	97.2 ± 1.4	−8.8 ± 0.8	−8.4 ± 1.2	−8.5 ± 2.0
500	96.6 ± 0.5	99.3 ± 1.9	99.6 ± 0.7	−6.1 ± 1.2	−6.1 ± 1.4	−6.2 ± 1.3
1000	97.0 ± 0.9	99.7 ± 1.3	100.2 ± 1.4	−5.7 ± 0.2	−5.7 ± 0.6	−5.5 ± 0.5
2000	95.5 ± 2.6	97.8 ± 1.6	98.2 ± 3.2	−7.1 ± 1.5	−7.6 ± 1.4	−7.6 ± 2.2
4000	89.0 ± 3.9	91.6 ± 2.8	90.7 ± 3.5	−13.6 ± 2.8	−13.8 ± 3.0	−15.1 ± 2.8
8000	73.5 ± 3.8	78.4 ± 6.5	77.8 ± 2.8	−29.1 ± 2.8	−27.0 ± 6.5	−28.0 ± 2.7

‡ 1–3 MW includes 1 MW and excludes 3 MW, etc. ‡‡ numbers do not apply for 31.5 Hz.
† based on 4 and 8 types, respectively; †† based on 11 and 9 types, respectively.

Møller and Pedersen [12] analyzed data from 48 wind turbines, of which 11 at a rated power > 2 MW, and found that the increase of the low frequency part of the maximum sound power level $L_{\mathrm{WA,LF}}$ was slightly but significantly higher than the broad band level L_{WA}. On average $L_{\mathrm{WA,max}}$ exceeded $\mathrm{L}_{\mathrm{WA,LF}}$ with 11.6 dB for the smaller turbines and 9.7 dB for the larger turbines (taken from their figure 1 [12]). Møller and Pedersen used the 10-160 Hz 1/3-octave bands as a low frequency range, the present study uses the 63 and 125 Hz 1/1-octave bands which include the 50-160 Hz 1/3-octave bands, but not the lower 1/3-octave bands (10–40 Hz). However, the levels in the range 10–40 Hz are so low they can be considered negligible, based on the spectral distribution in the present study (17 dB below the upper part of the LF range). Søndergaard [11] repeated the analysis of Møller and Pedersen with more larger turbines and found similar excesses of $L_{WA,max}$ over $L_{WA,LF}$ (12.0 dB for small, 10.3 dB for large turbines), but the difference between smaller and larger turbines was not significant. The present study finds an excess of $L_{WA,max}$ over $L_{WA,LF}$ of 11.9 ± 0.5 dB for turbines < 2 MW and 11.6 ± 0.2 dB for turbines > 3 MW: a small and nonsignificant difference. For the smaller turbines the excess of $L_{WA,max}$ over $L_{WA,LF}$ is similar to earlier results and for larger turbines it actually appears to be larger (i.e. $L_{WA,LF}$ lower) compared to earlier results, but the difference with earlier results is not significant. Although serrations do not affect the lower frequencies, on the whole this does not lead to significant spectral differences due to the relatively large differences between turbine types.

The present study shows that the spectral content of the sound of modern three bladed, pitch regulated wind turbines has not changed significantly over time and this includes the contribution of the low frequency part. Normalized octave band levels of all individual wind turbine types are within ± 5 dB of the average values with the exception of a larger spread (± 12 dB) at the highest frequency. The larger spread at 8 kHz may be a consequence of not taking atmospheric attenuation into account when determining sound power levels, which has also been noted by Junker and Quillet [33]. For large turbines, with blade tip heights up to 250 m, the attenuation along the propagation path to the measurement position is determined by size and weather conditions and can be substantial. This may also explain the lower average 8 kHz octave band level, when compared to earlier results.

The results show that the size of wind turbines of 3 MW and above has a small effect on their sound emission. Sound emission is predominantly determined by the choice of wind turbine manufacturer or type. To mitigate sound emission, trailing edge serrations have proven to be effective. Spectral analysis shows that they are most effective at 400 to 1600 Hz and indeed reduce the higher frequency trailing edge sound, not the relatively low frequency leading edge sound. When the sound propagates to neighboring locations, atmospheric and ground absorption reduce higher frequencies more effectively than lower frequencies. As a consequence, calculations show that the effect of serrations becomes less with distance (up to 2 km): up to 0.3 dB for three turbine types and up to 0.9 dB for two others. To reduce sound emission at specific times or in specific conditions a low noise mode can be applied to a wind turbine. On average this has an effect on power sound level and—when compared to serrations—a small (not significant) effect on its spectral distribution with lower frequencies somewhat less attenuated.

The objective for noise mitigation is to reduce adverse effects on neighboring residents. However, reducing only an A-weighted sound power level may be counterproductive to this aim. One reason for this is that reducing higher frequencies (as TE serrations do) to comply with a noise limit, will lead to a decrease in higher frequencies but a relative increase of lower frequencies. At the same A-weighted sound level at the façade, a higher contribution of low frequency sound will lead to a higher indoor sound level because the attenuation of a façade is less at lower frequencies. At present this effect is limited, but with an increasing efficiency of TE serrations this might become more prominent in the future. A second reason is that, if no other constraints apply, especially for visual intrusion, reduction of wind turbine sound power but meeting the same noise limit will lead to wind turbines placed closer to residences. As a result, visual intrusion will have more impact.

Over time, neglecting these aspects may add to social resistance. Social resistance already has a major influence on the expansion of onshore wind energy and can only be addressed successfully if authorities, developers and operators include residential interests in the planning and operation of wind farms [34]. It is recommended WT manufacturers, developers and operators focus not only on reducing overall sound levels, but also on reducing the low frequency part of sound production, preventing tonal sound and limiting amplitude modulation (‘other’ AM). If also neighboring residents benefit from a reduction in sound production it will likely reduce social resistance.

Supplementary materials: All wind turbine types used in this study are listed in a Supplementary file together with rated power and rotor diameter. The list also mentions whether data are available on rotor speed, total and low frequency sound power and its spectral content, serrations and noise modes.

Author contributions: Conceptualization, FvdB and EK; methodology, FvdB; formal analysis, JB and MES; writing—original draft preparation, FvdB; writing—review and editing, FvdB, EK, JB and MES; supervision, FvdB and EK; project administration, JB and MES. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors thank Casper van Wezel, former intern at Arcadis, for the analysis of part of the data, and Steven Velthuijsen of Bosch & Van Rijn for his help in setting up this study.

Availability of data and materials: The actual data from the WindPRO catalogue are accessible for WindPRO users.

Conflict of interest: The authors declare no conflict of interest.

Abbreviations

Pmax	Rated or maximum electric power of wind turbine
LWA,max	A-weighted sound power level at rated power
LWA,LF	A-weighted low frequency sound power level at rated power

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