

Infrasound and low-frequency noise generated by high-power onshore wind turbines – case study

Aleksandra ROGOWIEC , Maciej KŁACZYŃSKI 

AGH University of Krakow, al. Mickiewicza 30, 30-059 Krakow, Poland

Corresponding author: Aleksandra ROGOWIEC, email: arogowiec@agh.edu.pl

Abstract The development of renewable energy sources in recent years has played a key role in the global transformation of energy and the diversification of conventional energy sources. Wind energy is one of the most dynamically developing renewable energy sectors. Leading wind turbine manufacturers are improving production technologies by introducing larger and larger turbines to the onshore wind energy market. Their higher unit power makes it possible to replace several smaller devices with a bigger one, but this brings with it some controversy and environmental challenges. The operation of high-power wind farms can increase infrasound and low-frequency noise (ILFN) emissions, potentially impacting the quality of life of nearby residents. This paper discusses the current environmental risks associated with the development of high-power wind turbines and potential problems with increasing ILFN emissions. The range of impact and emission of low-frequency noise generated by high-power turbines was compared with that of their smaller counterpart in terms of size and dimensions. This paper highlights the foreseeable problems in current regulations for the assessment of noise generated by wind turbines in Poland.

Keywords: high-power wind turbine, low-frequency noise, ILFN, onshore wind energy, infrasound.

1. Introduction

The growing interest in renewable energy sources in recent years has been crucial in the context of developing a balanced global energy mix. In 2023, the share of renewable energy sources in the global energy mix exceeded 30% and is still growing. The forecasts for 2030 are promising and predict an increase in energy production from renewable sources to 46%, with solar and wind energy playing a key role in this growth. It is estimated that by the end of the decade, wind energy will become the second largest source of electricity production in the world (14%), right after solar PV (16%), surpassing the hydropower (13%). Global renewable electricity production is projected to rise to over 17.000 TWh (60 EJ) by 2030, representing an increase of nearly 90% compared to 2023 [1].

Over the years, there has been a significant increase in the importance of the wind and solar energy sectors in the global energy mix. The share of energy alone has increased by approximately 6 percentage points over the past decade (from 3.4% in 2015 to 9.2% in 2025) [1]. Based on the Global Wind Energy Council report (GWEC 2025), global wind energy production in 2024 amounted to 1136 GW and is 115 GW higher than in 2023 [2]. About 278 GW or 27% of global installed wind energy resources are located in Europe (243 GW of this is onshore and 35 GW offshore) [3] and about 9.56 GW in Poland [4].

In recent years, the onshore wind energy market has seen a trend of introducing increasingly larger wind turbines. Those devices have higher unit power and have enabled the replacement of several smaller devices with a single one. This is very beneficial from an economic point of view and “small” wind turbines are increasingly being replaced by modern solutions with larger dimensions and unit power. A similar situation can be observed in the offshore wind energy sector, where the size and unit power of the wind turbines used are even greater, and the range of their acoustic impact may pose a real threat to the environment. Figure 1 illustrates a summary of the development trend in the size of wind turbines for offshore and onshore wind energy sector [2]. In 2024, proposed wind turbines in the onshore sector were rated at up to 15 MW. The trend in wind turbine size development in the coming years is upward, with planned rotor diameters expected to range from 300 to 350 m. The forces acting on this type of turbine are getting bigger, and a particularly important issue in the context of their design is the development of an appropriate foundation.

Despite the low sound pressure level generated by wind turbines in their surroundings, the low-frequency and infrasound component of wind turbine noise and amplitude modulation can pose a real

problem in the context of the impact on humans, including sleep disturbances, headaches, irritation, and annoyance. The increase in the size of wind turbines raises concerns related to the shift of the noise characteristics of wind turbines towards low frequencies. By increasing the size of the rotor (larger surface area), the rotational speed of the wind turbine is reduced and therefore the frequency of rotor operation decreases. Low-frequency components (LFN) should be taken into account in the assessment of the impact on human health, as they can pose a real threat compared to other types of noise sources that do not contain these components. Despite the classification of infrasound as noise inaudible to the human ear, studies have shown that if the sound pressure level for infrasound is high enough – typically exceeding 95 dB at 16 Hz and increasing rapidly at lower frequencies up to 140 dB at 1 Hz – these sounds can be perceived by humans, among others, as vibrations in various parts of the body [5, 6].

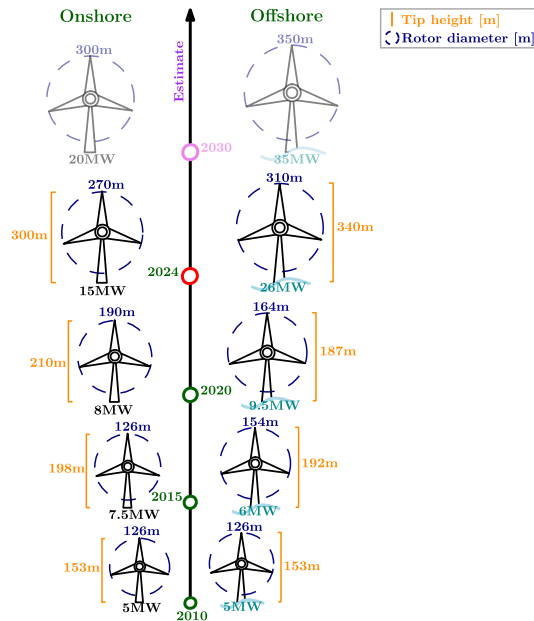


Figure 1. Trend of onshore and offshore wind turbine size, 2010-2030.

In addition to acoustic impact, wind farms can affect local fauna and the surrounding landscape. It is also worth paying attention to problems such as electromagnetic interference, light flicker, collapses, failures, and ice fragments. All these factors should be taken into account when designing and implementing new installation solutions currently available on the market. This article discusses the current environmental risks associated with the development of high-power wind turbines and potential problems with increasing ILFN emission. Additionally, it presents a case study and pilot investigation of two high-power onshore wind farms, which constitute the initial component of the first author’s doctoral research.

2. Wind turbines characteristic

2.1. Wind turbines classification

Wind turbines are complex machines with numerous parameters that accurately describe and classify them. Table 1 presents a comprehensive list of sample parameters for categorizing different types of wind turbines, along with detailed descriptions and illustrative examples.

Table 1. Wind turbine classification based on different parameters [7–10].

Parameter	Description
rotation axis	<ul style="list-style-type: none"> Horizontal Axis Wind Turbines (HAWT) most often used in commercial solutions such as two-blade turbines, three-blade turbines, multi-blade turbines with a diffuser, or Magnus turbines, Vertical Axis Wind Turbines (VAWT) for example, Darrieus, Giromill, Savonius, or helical wind turbines.
rate parameters	<ul style="list-style-type: none"> rated power – the maximum value of electrical power that a wind turbine can produce, measured in kW or MW,

	<ul style="list-style-type: none"> • rotor diameter – D, • hub height above ground – H.
rotation speed	<ul style="list-style-type: none"> • constant or variable rotation speed, • low-speed wind turbines, medium-speed wind turbines, or high-speed wind turbines.
tip speed ratio TSR	<ul style="list-style-type: none"> • low-speed turbines - $TSR \leq 3$ (multi-blade 12÷40), • medium-speed turbines – $3 < TSR \leq 6$ (multi-blade 4÷7), • high-speed turbines – $TSR > 6$ (one to three-blade 1÷3).
number of blades	<ul style="list-style-type: none"> • two-blade turbines, three-blade turbines, etc., • multi-blade turbines.
electricity generation	<ul style="list-style-type: none"> • micro wind turbine – rated power below 1 kW, • small wind turbine – rated power between 1-100 kW, • medium-power – rated power between 100 kW-1 MW, • high-power wind turbines – rated power above 1 MW.
electricity generator types	<ul style="list-style-type: none"> • AC synchronous generator, • AC asynchronous generator, • DC direct drive generator.
nature of rotor mounting	<ul style="list-style-type: none"> • downwind – the rotor is on the back side of the turbine (upcoming wind first achieves wind turbine hub), • upwind – the rotor is in the front of the unit and facing upcoming wind.
wind speed at nacelle height	<ul style="list-style-type: none"> • cut-in wind speed typically ~ 2-4 m/s, • rated wind speed typically ~12-15 m/s, • cut-out wind speed typically ~ 20-25 m/s, • survival wind speed typically ~50-65 m/s.
direction control methods	<ul style="list-style-type: none"> • pitch adjustment – maintain the optimum blade angle to achieve certain rotor speeds or power output, • yaw adjustment – refers to the rotation of the entire wind turbine around the vertical axis.
localization	<ul style="list-style-type: none"> • offshore, • onshore.

This paper defines a “high-power” turbine as an onshore horizontal-axis wind turbine (HAWT) with a tower height greater than 120 meters and a rated power exceeding 3 MW.

2.2. Wind turbines noise

Experts typically define airborne sounds audible to humans as being in the range of 20 Hz – 20 kHz. Frequencies below 20 Hz are referred to as infrasound. From a physical perspective, the infrasound range is between 0.1 and 20 Hz [11]. However, ISO 7196:1995 clearly defines these sounds as ranging from 1 to 20 Hz [12]. The combination of infrasound and audible low-frequency sounds (up to 250 Hz) is often referred to as low-frequency noise (ILFN) [13]. The PN-B-02151-2:2018-2 standard [14] states that noise has low-frequency components if the difference between the equivalent or maximum values of the sound pressure level (SPL), weighted by the C and A weighting curves, is greater than 20 dB or if the 1/3 octave band spectrum between 12.5 and 250 Hz contains at least one component exceeding the reference A10 curve by 5 dB.

Due to their long wavelengths, low-frequency noise can propagate over significant distances, making it challenging to attenuate and reduce its intensity. Both natural and artificial sources can generate infrasound and low-frequency noise. Natural sources include rapid air movement (e.g., wind and storms), water flow and sudden changes in atmospheric pressure. Artificial sources of infrasound noise include various types of industrial machinery and equipment, as well as land and water transport (cars, trucks, helicopters, and airplanes) [15].

Wind turbines generate noise across a broadband spectrum, encompassing both dominant low-frequency components and higher-frequency ranges [16]. The nature of the spectrum is a direct result of the mechanism by which wind turbine components generate noise. There are two primary sources of noise:

- *mechanical noise* – generated by the operation of various types of mechanical devices within the nacelle. These devices include the generator, gearbox, cooling fans, and hydraulic units for adjusting the blade pitch,
- *aerodynamic noise* – generated primarily by airflow over the blades or the passage of the blades through the turbine support tower. It is primarily composed of low-frequency and infrasonic components.

Research has shown that infrasound noise measured at wind farm sites, particularly those close to homes, is approximately 15–20 dB below the human hearing threshold for infrasound. The average hearing threshold for infrasound corresponds to tones each having a G-weighted SPL of approximately $L_G = 96$ dB. In turn, infrasound at the G-weighted SPL below 85–90 dB is usually inaudible [17, 18]. Nevertheless, infrasound noise generated by wind turbines, primarily the passage of wind turbine blades through towers, remains the most controversial. This controversy stems from the lack of conclusive research confirming its negative impact on people living near wind farms [19].

3. Wind turbines in Poland

In 2016, Poland enacted the Distance Act and the so-called “10H rule”, which allows the construction of wind turbines at a distance no closer than ten times the height of the wind turbine (including the tower and rotor dimensions) [20]. This law significantly limited the development of innovative technologies and the construction of large wind turbines in Poland. Investors had difficulties obtaining building permits in areas near residential developments. The Polish government amended the Wind Investment Act in 2023, setting a minimum required distance of 700 meters between wind farms and residential buildings [21]. Current legislation does not address the potential impact of the increasing size of wind turbines on residents in terms of infrasound and low-frequency noise in areas near residential developments. Further research into the acoustic implications of larger turbines should be a critical component of future legislative revisions.

Wind turbines generate noise that differs significantly from typical industrial noise in terms of its characteristics. However, it is assessed in Poland based on the Regulation of the Minister of the Environment of 7th September 2021 on requirements for emission measurements [22], which is specified for industrial noise. The limit values are specified in the Regulation of the Minister of the Environment of 14th June 2007 on permissible noise levels in the environment [23]. This regulation classifies wind turbines under the category of general noise-emitting facilities.

In Poland in standard PN-86/N-01338 permissible values for acoustic pressure levels at workstations and general requirements for measurements of infrasound noise were established. Between 2002 and 2009 years, the rules for the assessment of infrasound noise were changed to an assessment using the G-frequency weighting filter. As permissible value, an equivalent sound level G related to an 8-hour working day of 102 dB was adopted [24]. In 2009 a special commission considered that the previously applicable limits for infrasound noise represent the threshold for the auditory perception of infrasound and the criteria of annoyance, and not harmfulness. Currently standard PN-86/N-01338 is withdrawn and replaced by PN-Z-01338:2010 “Acoustics - Measurement and assessment of infrasound noise at workplaces”. For the general public workplace the limit value is $L_G = 102$ dB, but at the conceptual work station the limit value is $L_G = 86$ dB.

In order to mitigate the noise exposure from wind turbines affecting residents, numerous governments and medical bodies have developed guidelines on the required distance between wind farms and inhabited areas. Additionally, authorities assess the permissible sound pressure level limits in residential areas. Some countries have established specific regulations for wind turbine noise, while others, such as Poland, use general environmental standards. Table 2 summarizes the recommended distances for wind farms and the permissible environmental noise levels in various countries [25-32].

Table 2 illustrates that the proposed setback distances for wind farm locations from residential buildings vary significantly and also depend on the specific region within each country. Noise limits for wind turbines also differ considerably across jurisdictions. In some countries, legislation regarding wind turbine noise is still absent. However, nations such as Sweden, Denmark, and Australia are among the few that have enacted dedicated regulations for wind turbines. Denmark remains the only country with regulations regarding low-frequency noise levels in buildings caused by wind turbines; the limit is 20 dB(A) in the 1/3 octave frequency range from 10 to 160 Hz, with wind speeds of both 6 and 8 m/s at a height of 10 m [30].

Table 2. Recommended distance between wind farm and residential areas and noise limits.

Region	Distance [m]	Noise Limit [dB(A)]	Reference
Poland	700	$L_{Aeq,Day} = 50/55,$ $L_{Aeq,Night} = 40/45^{1)}$	Dz.U.2014, poz. 112 [23], general environmental limits
England/Scotland/Wales (UK)	350/2000/500	$L_{A90,Day(10min)} = 35-40$ or $BGND+5dB(A),$ $L_{A90,Night(10min)} = 43$ or $BKGND+5dB(A)^{2)}$	ETSU-R-97 [27], specific for wind turbines
Germany	300-1500 (depend on region)	$L_{Aeq,Day} = 50/55,$ $L_{Aeq,Night} = 40/35$	TA Lärm [28], general environmental limits
Sweden	500 (in practice)	$L_{Aeq} = 35/40^{3)}$	Naturvårdsverket [29], specific for wind turbines
Denmark	4 x the total height (typically ≥ 500)	39-44/37-42 ⁴⁾ or 20 dB(A) for low-frequency noise between 10-160 Hz	Bekendtgørelse om støj fra vindmøller [30], specific for wind turbines
Netherlands	4 x the height of the tower	$L_{Aden} = 47,$ $L_{Aeq,Night} = 41$	[26], general environmental limits
Western Australia	1000	$L_{Aeq(10min)} = 35$ or $BKGND + 5dB$	WA Guidelines 2004 [31], specific for wind turbines
China	200 for single wind turbine, 500 for larger wind farm	$L_{Aeq,Day} = 55,$ $L_{Aeq,Night} = 45^{5)}$	GB 3096-2008 [32], general environmental limits

1) Specified for single-family residential areas / multi-family housing.

2) If residents are beneficiaries of the project (e.g., they lease land), the limit may be raised to 45 dB(A).

3) For wind speed of 8m/s @10m and quiet /standard areas.

4) For wind speed of 8m/s @10m or of 6m/s @10m – standard and sensitive noise receptors.

5) Specific for class I – residence, medical treatment/hygiene, cultural, education, scientific research design and the administration office

The Polish wind energy market has been developing at an increasingly dynamic pace in recent years, as demonstrated by large-scale offshore projects in the Baltic Sea. In July 2025, the first Polish offshore wind turbine - built by Orlen in partnership with Northland Power - was installed on the Słupsk Bank (Ławica Słupska in Polish) in the Polish part of the Baltic Sea. This turbine is part of the Baltic Power offshore wind farm [33] and represents the largest offshore model manufactured by Vestas, specifically the V236-15.0 MW. Developers are also implementing innovative installation solutions in onshore wind projects. At the end of 2024, Poland commissioned several high-power wind turbines from leading manufacturers, including the Nordex N149-5.5-5.7 MW and the Vestas V150-4.0 MW. These turbines offer significantly higher rated power compared to typical models previously used in the country. An example of an investment using Nordex wind turbines is the Wysoka wind farm [34], which comprises eleven Nordex turbines with a total installed capacity of 62.5 MW. Its estimated annual energy output is 180 GWh, sufficient to supply electricity to approximately 90000 households in the region.

4. Results of wind turbines noise measurement

4.1. Measurement description and method

The authors conducted noise emission measurements at three wind farms located in Poland. With the collaboration and support of the Department of Mechanics and Vibroacoustics at the AGH University of Krakow (Poland), the analysis incorporated archival measurement data collected in September 2024, as well as original field measurements conducted in June 2025.

All measurements were carried out in accordance with PN-EN 61400-11 “Wind turbine generator systems – Part 11: Acoustic Noise Measurement Techniques” using SVAN 958A sound level meter, GRAS 40AZ free-field measurement microphones, a Davis Vantage VUE weather station, and SONOPAN ZTW-1 windscreen sets specifically designed for wind turbine noise measurements. Table 3 presents detailed information about the wind farms that host the turbines examined in this study.

Table 3. Information about the wind farm under measurement.

Wind farm location	Kalina-Rędziny	Drzeńsko	Tłukomy, Młotkowo, Kijaszwice
Local administrative unit	Miechów	Rzepin	Wysoka
Province	Lesser Poland	Lubusz	Greater Poland
Number of turbines	3	4	11
Holding group	Energa Vita	Farma Wiatrowa Drzeńsko	II Renewable Energy
Launch date	2016-08-10	2024-02-09	2024-10-02
Turbine type	Nordex N54-1.0 MW	Vestas V150-4.0 MW	Nordex N149-5.0-5.7 MW

The distance for the measurement point locations was determined experimentally, based on the forecasted changes in the permissible distances for locating wind farms from residential buildings in Poland. Investigators conducted acoustic measurements of the high-power wind turbines (Vestas V150 and Nordex N149) at a distance of approximately 500 meters downwind from the turbines, at heights of 0 and 1.5 meters above the ground. For the smaller wind turbine (Nordex N54) in Kalina-Rędziny, measurements were also taken at heights of 0 and 1.5 meters, at a distance of approximately 140 meters from the wind turbine. This distance was due to the presence of crops, which prevented measurements at a greater distance. The results for this wind turbine were estimated at a distance of 500 meters, based on the relationship between sound pressure decline with distance, also taking into account air attenuation as a function of frequency.

4.2. Parameters of measured wind turbines

The measurements were conducted on three types of wind turbines, two of which are among the largest and newest installed in Poland in 2024 and are classified as high-power onshore wind turbines.

Table 4 contains the rated parameters of the measured wind turbines, accompanied by illustrative photograph from the measurement locations.

Table 4. Operational parameters of tested wind turbines.

Turbine type	Nordex N54-1.0 MW	Vestas V150-4.0 MW	Nordex N149-5.5-5.7 MW
Rotor diameter [m]	54.0	150.0	149.1
Hub height [m]	60.0/70.0	145.0	125.0
Rotor speed range [RPM (Hz)]	14-21.5 (0.233 - 0.358)	4.9-10.4 (0.082 - 0.173)	6.24-12.24 (0.104 - 0.204)
Gearbox ratio (Hz)	1:70 (16.31 - 25.06)	1:143 (11.73 - 24.74)	1:117 (12.17 - 23.87)
Generator speed [RPM (Hz)]	1513 (25.22)	1485 (24.75)	1836 (30.6)
Maximum SPL [dB(A)]	99.7	104.9	104.8-105.6

Preview



Figure 2 presents the power curves for the tested wind turbines, together with the power coefficient C_P , consistent with Betz's law, as a function of wind speed at the nacelle height. The curves were generated based on the WindPRO 4.0 wind turbine library and catalog data [35].

The power coefficient C_P quantifies the proportion of wind energy that can be converted into mechanical energy by a wind turbine. Theoretically, the maximum power coefficient for a wind turbine is approximately 59%. In practice, aerodynamic losses reduce this efficiency to approximately 30–40% [8]. Due to the absence of C_P data in the Nordex N149 turbine catalog, estimated C_P values were derived from the rotor thrust coefficient C_T . It is important to note that both coefficients are interrelated, under the assumption of a uniform aerodynamic loading across the rotor plane, thereby excluding aerodynamic losses [36].

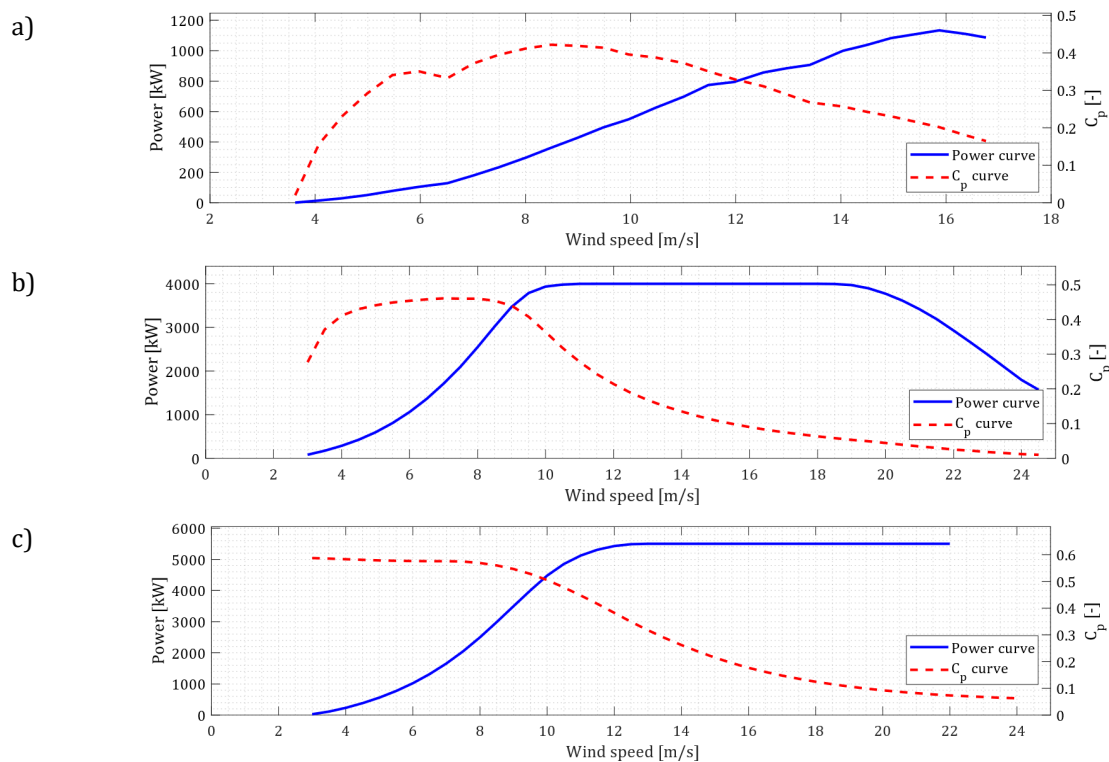


Figure 2. Power and C_p curves for wind turbine: a) Nordex N54 1.0 MW, b) Vestas V150-4.0 MW, c) Nordex N149 5.5 MW, air density 1.225 kg/m^3 .

The Nordex N54 turbine attains rated power at a wind speed of approximately 16 m/s at nacelle height. Its highest efficiency, approximately 42%, is observed at a wind speed of around 9 m/s. In contrast, high-power turbines achieve rated power at lower wind speeds at nacelle height – specifically, 11.5 m/s for the Vestas V150 and 13 m/s for the Nordex N149. The power coefficient C_p for these turbines is higher than for the Nordex N54. Once the V150 and N149 turbines reach rated power, they maintain it at a constant level despite increasing wind speeds. This is due to the operation of turbine performance control systems, which protect mechanical and electrical components from overloads.

An important parameter for proper wind turbine operation is the cut-in wind speed, defined as the minimum speed at which the turbine produces electricity. It is important to note that wind turbines can rotate below the cut-in speed without producing electrical power. The cut-in speeds for turbines under measurement range from 3 to 3.5 m/s.

It is possible to estimate the wind speed at any other elevation, given the wind speed at a specific height. This estimation can be performed using the wind profile power law, as demonstrated in formula (1):

$$u = u_r \left(\frac{z}{z_r} \right)^\alpha, \quad (1)$$

where u is the wind speed (m/s) at height z , u_r is a wind speed (m/s) at z_r , and α is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. Under neutral conditions over open terrain, α is typically around 0.14.

Using this relationship (1), the approximate minimum wind speed at a height of 4 meters required for the examined turbine to generate electrical power should be around 2.39, 1.81, and 1.85 m/s for the N54, V150, and N149 models, respectively.

4.3 Measurement condition and localization

Table 5 presents average weather conditions recorded during the measurement period. The most stable wind conditions were observed during the measurements of the Nordex N149 wind turbine. For this turbine, the average wind speed at a height of 4 meters was the highest and significantly exceeded the turbine's cut-in wind speed. In contrast, the Vestas V150 turbine experienced substantially lower average wind speeds. It was within the turbine's start-up range, which may have influenced the obtained results. The most unstable wind conditions were observed during measurements of the Nordex N54 turbine. The

direction of the wind shifted multiple times throughout the measurement session, causing rapid rotor reorientation in response to the approaching airflow.

Table 5. Average weather conditions during measurements.

Wind turbine	Nordex N54, P1	Vestas V150, P2	Nordex N149, P3
Atmospheric pressure [hPa]	1027	1062	1060
Temperature [°C]	24	10	13
Humidity [%]	61	78	62
Wind speed at 4m [m/s]	2.3	2.0	5.0
Wind direction	NW, NNW	SE, SSE	E

4.4. Results

The results were analyzed in ten-minute segments of the equivalent continuous sound pressure level (L_{eq}), recorded without frequency weighting (LIN). Data were sampled at 100 ms intervals and collected using a high-pass (HP) filter operating within the frequency range of 0.8–20000 Hz. For consistency, only data blocks with uniform wind speed and direction, measured at a height of 4 meters above ground level, were selected for analysis, allowing for reliable comparisons across the ten-minute intervals. Following the acquisition of LIN values, frequency weighting corrections (A, C, and G) were applied to obtain the corresponding adjusted results. Based on the averaged data obtained in 1/3-octave bands, total sound pressure level values were calculated for each wind speed and applied frequency weighting curve.

Tables 6 and 7 present the results of the total average sound pressure level values corresponding to the different frequency weight curves (Z, A, C, G), for two types of high-power wind turbines. Additionally, the total value within the ILFN frequency range was analyzed.

Table 6. Total average L_{eq} [dB] for the Vestas V150 at different wind speeds.

Vestas V150	1.8 m/s		2.2 m/s		2.7 m/s	
	0 m	1.5 m	0 m	1.5 m	0 m	1.5 m
TOTAL Z (10-20000 Hz)	69.2	69.5	69.1	69.9	69.2	71.9
TOTAL A (10-20000 Hz)	50.0	50.5	47.4	48.0	48.3	49.7
TOTAL C (10-20000 Hz)	64.2	63.8	63.7	63.4	63.6	64.9
TOTAL G (0.8-315 Hz)	73.3	74.0	73.5	74.8	73.6	76.8
TOTAL Z ILFN (0.8-250 Hz)	78.3	82.0	78.7	83.7	80.3	86.7

Table 7. Total average L_{eq} [dB] for the Nordex N149 at different wind speeds.

Nordex N149	2.7m/s		4.0m/s		6.3 m/s	
	0 m	1.5 m	0 m	1.5 m	0 m	1.5 m
TOTAL Z (10-20000 Hz)	68.6	69.4	68.8	71.5	69.8	76.9
TOTAL A (10-20000 Hz)	44.4	43.9	44.5	44.9	48.6	50.7
TOTAL C (10-20000 Hz)	64.1	64.2	64.1	65.6	65.2	70.6
TOTAL G (0.8-315 Hz)	73.8	74.8	74.3	76.9	74.5	81.9
TOTAL Z ILFN (0.8-250 Hz)	75.6	79.7	78.4	84.2	84.9	90.6

The total average sound pressure level measured at a height of 1.5 meters is higher than at ground level (0 meters), primarily due to the increased influence of wind-related background noise. As wind speed increases, the G-weighted total sound pressure level also rises. For the Nordex N149 turbine operating at a wind speed of 6.3 m/s, the difference between the A- and C-weighted total sound pressure levels is approximately 20 dB. As noted in Chapter 2.2, this may indicate the presence of low-frequency components within the noise spectrum. The total Z-weighted ILFN values are significantly higher than the total Z-weighted totals, indicating a high energy load in the low-frequency range of the noise spectrum generated by the analyzed wind turbines. Figures 3 and 4 illustrate the L_{eq} noise spectra in 1/3-octave bands for individual high-power wind turbines (V150 and N149), along with the corresponding wind speed data.

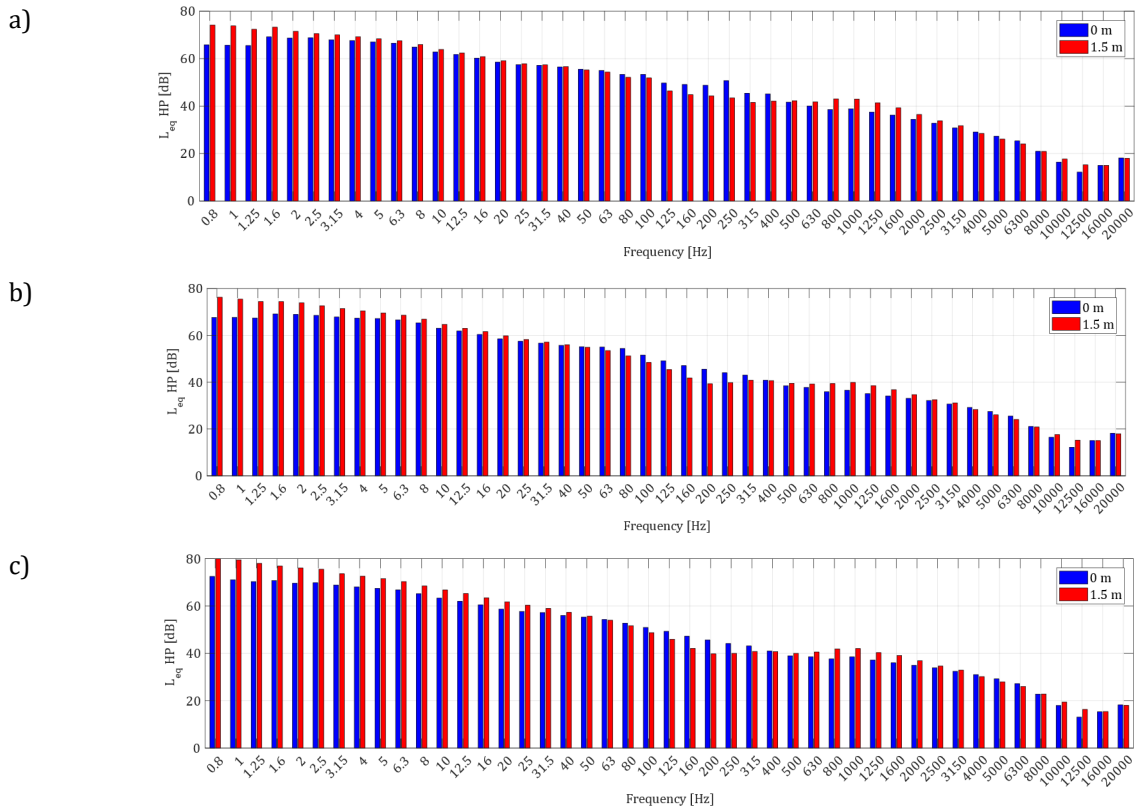


Figure 3. Spectrum of the sound pressure level for Vestas V150 and:
 a) 1.8 m/s, b) 2.2 m/s, c) 2.7 m/s wind speed at 4 m.

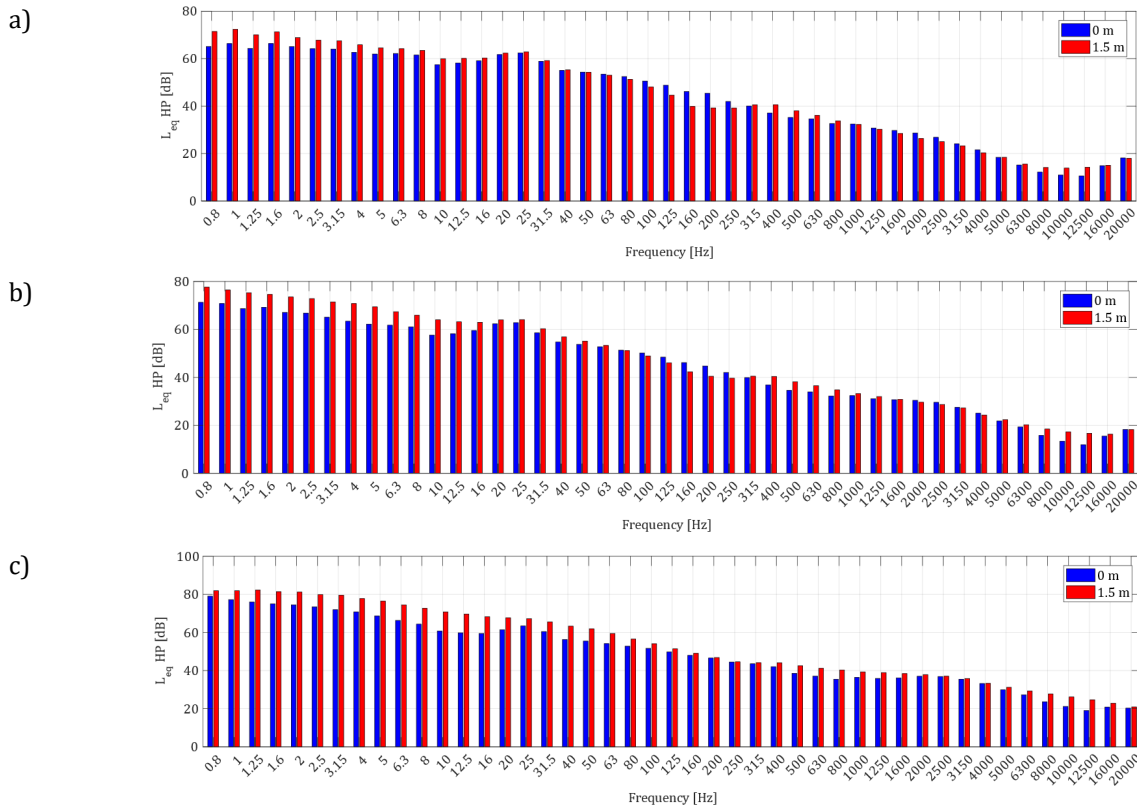


Figure 4. Spectrum of the sound pressure level for Nordex N149 and:
 a) 2.7 m/s, b) 4.0 m/s, c) 6.3 m/s wind speed at 4 m.

Frequency components indicative of wind turbines' operation are evident in the analyzed spectra. Specifically, for the N149 turbine, a distinct peak at 25 Hz corresponds to the second harmonic generated by the gearbox. As wind is a natural source of infrasound, elevated sound pressure levels are observed at low frequencies (0.8–80 Hz) when measured at a height of 1.5 meters. Measurements performed on the plate surface (0 m) effectively attenuate low-frequency components generated by wind.

Due to unstable weather conditions, a representative 10-minute sample was selected for comparative analysis using the low-power Nordex N54 turbine and a moderate wind speed of approximately 2.1 m/s measured at a height of 4 meters. Table 8 presents the total results for this wind speed, while Figure 5 illustrates the 1/3-octave band spectrum for the Nordex N54 wind turbine.

Table 8. Total average L_{eq} [dB] for the Nordex N54 at 2.1 m/s wind speed.

Nordex N54	2.1 m/s	
	0 m	1.5 m
TOTAL Z (10-20000 Hz)	60.1	59.8
TOTAL A (10-20000 Hz)	46.1	46.1
TOTAL C (10-20000 Hz)	59.3	58.0
TOTAL G (0.8-315 Hz)	51.2	59.1
TOTAL Z ILFN (0.8-250 Hz)	65.0	70.8

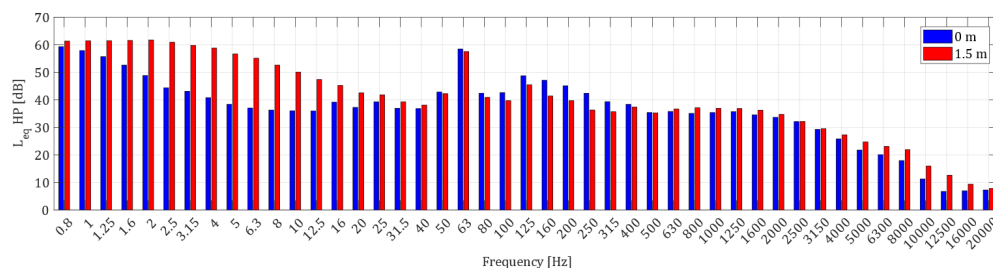


Figure 5. Spectrum of the sound pressure level for Nordex N54 and 2.1 m/s wind speed at 4 m.

A comparison of the noise spectra between small and high-power wind turbines shows that the smaller turbine experiences a faster drop in sound pressure level in the low-frequency range. In contrast, high-power turbines have a frequency distribution shifted toward lower frequencies and display a more even profile, which aligns with theoretical expectations.

The presented results represent the initial stage of research. They will be progressively expanded and enhanced through the application of advanced measurement techniques to develop a robust methodology for evaluating infrasound noise emitted by high-power wind turbines under environmental conditions.

5. Conclusion

Despite the passage of time, many countries still lack direct limits and permissible values for noise resulting from the impact of wind farms. Regulatory authorities often categorize this type of noise as industrial, particularly in Poland.

The growing demand for renewable energy and the distinctive nature of noise emitted by wind turbines have created an urgent need to revise and clarify existing legislation concerning noise impact limits, with specific consideration for infrasound and low-frequency components.

Although wind turbines generate relatively low sound pressure levels, they can be significantly disruptive due to the presence of infrasound and low-frequency components in the noise spectrum. The assessment of infrasound and low-frequency noise annoyance in the context of wind turbine impact is uncertain, owing to the limited availability of research in this field and the challenges involved in defining appropriate threshold values and selecting a representative study population.

Only Denmark has regulations regarding low-frequency noise levels in buildings caused by wind turbines; this value is 20 dB(A) in the 1/3 octave frequency range from 10–160 Hz [30]. The HETMAN project [37] also attempted to define environmental noise exposure limits (ILFN) for wind turbines.

The continuous development of the global wind energy sector is driving the creation of increasingly advanced technological solutions for wind turbine design and performance. Increasing the size

of installations enables the generation of more electricity from a single turbine. However, this has led to concerns regarding a shift in the frequency characteristics of emitted noise towards lower ranges. Larger turbines exhibit reduced rotational velocity and generate lower spectral components, which can have adverse effects on the well-being and health of individuals in the vicinity of wind farms. This issue requires serious attention and calls for expanded research into the effects of infrasound generated by high-power wind turbines. Preliminary research indicates a necessity for the further development and enhancement of infrasound noise measurement methods associated with wind turbines. Studying the spectral characteristics of high-power turbines could help researchers assess their impact on human life and health. This issue must become the subject of in-depth research and analysis, with particular consideration for the environmental nuisance of low-frequency noise.

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Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

References

1. International Energy Agency (IEA); <https://www.iea.org/reports/renewables-2024> (accessed on 2025.07.05)
2. Global Wind Energy Council (GWEC); <https://www.gwec.net/reports/globalwindreport> (accessed on 2025.07.05)
3. Wind Europe; <https://windeurope.org/intelligence-platform/product/latest-wind-energy-data-for-europe-autumn-2024/> (accessed on 2025.07.25)
4. Energetyka wiatrowa w Polsce 2024 odpowiedź na unijny zwrot (in Polish); <https://www.teraz-srodowisko.pl/publikacje/energetyka-wiatrowa-w-polsce-2024/> (accessed on 2025.07.05)
5. H. Møller, C.S. Pedersen; Hearing at low and infrasonic frequencies; *Noise & Health*, 2004, 6(23), 37–57
6. M. Pawlaczyk-Łuszczynska, A. Dudarewicz; Review of evaluation criteria for infrasound and low frequency noise in the general environment; In: *New Techniques and Methods for Noise and Vibration Measuring, Assessing and Reducing*, CIOP-PIB, 2022; DOI: 10.54215/Noise_Control_2022_A_Digital_Monograph_Pawlaczyk-Luszczynska_M_Dudarewicz_A
7. R. Ehrlich; *Renewable Energy: A First Course*, 1st ed.; CRC Press, 2013
8. D. Taler, K. Rup; *Podstawy obliczeń turbin wiatrowych* (in Polish); PWN, 2021
9. K. Garbala, A.M. Tokajuk, K. Kałaur, P. Cybulko; Klasyfikacja i charakterystyka turbin wiatrowych (siłowników wiatrowych) (in Polish); *Aparatura Badawcza i Dydaktyczna*, 2020, 25(2), 56–60
10. Wind Turbine Control Methods; <https://www.ni.com/en/solutions/energy/wind-turbine-control-methods.html> (accessed on 2025.07.05)
11. U. Landström; Human exposure to infrasound; In: *EECT, Vol. 7: High Hazard Pollutants*; P.N. Cheremisinoff, Ed.; 1995, 431–453
12. ISO 7196:1995; *Acoustics - Frequency-weighting characteristic for infrasound measurements*, 1995
13. C. Flemmer, R. Flemmer; Wind turbine infrasound: Phenomenology and effect on people; *Sustainable Cities and Society*, 2023, 89, 104308; DOI: 10.1016/j.scs.2022.104308
14. PN-B-02151-2:2018-2; *Building acoustics – Protection against noise in buildings, Part 2: Requirements for permissible sound pressure levels in rooms*, 2018
15. D. Augustyńska; Wartości graniczne ekspozycji na infradźwięki – przegląd piśmiennictwa (in Polish); *Podstawy i Metody Oceny Środowiska Pracy*, 2009, 2(60), 5–15
16. S. Wegner, R. Bareiss, G. Guidati; *Wind Turbine Noise*; Springer, 1996
17. T. Wszolek, D. Mleczko, P. Pawlik, M. Kłaczyński, P. Małecki, B. Stępień; Experimental Verification of the Usefulness of Selected Infrasound and Low-frequency Noise (ILFN) Indicators in Assessing the Noise Annoyance of Wind Turbines; *Vibrations in Physical Systems*, 2022, 33(3), 2022315; DOI: 10.21008/j.0860-6897.2022.3.15
18. M. Pawlaczyk-Łuszczynska, W. Szymczak, A. Dudarewicz, M. Śliwińska-Kowalska; Proposed criteria for assessing low frequency noise annoyance in occupational settings; *Int. J. Occup. Med. Environ. Health*, 2006, 19(3), 185–197; DOI: 10.2478/v10001-006-0022-9

19. M. Pawlaczyk-Łuszczynska, T. Wszolek, A. Dudarewicz, P. Małeck; Should limit values be set for infrasound caused by wind turbines?; *Int. J. Occup. Med. Environ. Health*, 2025, 38(1), 3–17; DOI: 10.13075/ijomh.1896.02422
20. Ustawa z dnia 20 maja 2016 r. o inwestycjach w zakresie elektrowni wiatrowych (Dz.U.2016 poz. 961); <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20160000961/T/D20160961L.pdf> (accessed on 2025.07.06)
21. Ustawa z dnia 9 marca 2023 r. o zmianie ustawy o inwestycjach w zakresie elektrowni wiatrowych oraz niektórych innych ustaw (Dz.U. 2023 poz. 553); <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20230000553/T/D20230553L.pdf> (accessed on 2025.07.06)
22. Rozporządzenie Ministra Klimatu i Środowiska z dnia 7 września 2021 w sprawie wymagań w zakresie prowadzenia pomiarów wielkości emisji (Dz.U. 2021 poz.1710); <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20210001710/O/D20211710.pdf> (accessed on 2025.07.06)
23. Rozporządzenie Ministra Środowiska z dnia 14 czerwca 2007 r. w sprawie dopuszczalnych poziomów hałasu w środowisku (Dz. U. z 2014 r. poz. 112); <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20140000112/O/D20140112.pdf> (accessed on 2025.07.06)
24. M. Pawlaczyk-Łuszczynska, A. Dudarewicz, M. Waszkowska; Assessment of low frequency noise annoyance in steering premises according to subjective annoyance rating of workers. A pilot study (in Polish); *Medycyna Pracy*, 2001, 52(6), 465–470
25. D. Kaoshan, B. Anthony, L. Chao, X. Wei-Ning, H. Zhenhua; Environmental issues associated with wind energy – A review; *Renewable Energy*, 2015, 75, 911–921; DOI: 10.1016/j.renene.2014.10.074
26. J.L. Davy, K. Burgemeister, D. Hillman; Wind turbine sound limits: Current status and recommendations based on mitigating noise annoyance; *Applied Acoustics*, 2018, 140, 288–295; DOI: 10.1016/j.apacoust.2018.06.009
27. ETSU-R-97: The Assessment and Rating of Noise from Wind Farms, London, 1996; https://assets.publishing.service.gov.uk/media/5a798b42ed915d07d35b655a/ETSU_Full_copy__Searchable_.pdf (accessed on 2025.07.12)
28. Technische Anleitung zum Schutz gegen Lärm - TA Lärm (in German); <https://www.staedtebauliche-laermfibel.de/pdf/TA-Laerm.pdf> (accessed on 2025.07.12)
29. Buller från vindkraft (in Swedish); https://www.boverket.se/sv/samhallsplanering/sa-planeras-sverige/planeringsfragor/information-om-buller-och-goda-ljudmiljoer/buller-i-planeringen/buller-fran-vindkraft/?utm_source=chatgpt.com (accessed on 2025.07.12)
30. Statutory Order on noise from wind turbines; Bekendtgørelse om støj fra vindmøller (in Danish); <https://www.retsinformation.dk/eli/lta/2019/135> (accessed on 2025.07.12)
31. Western Australian Planning Bulletin Number 67, Guidelines for Wind Farm Development; <https://www.wa.gov.au/system/files/2022-04/PB-67-%20Guidelines-for-wind-farm-development-2004.pdf> (accessed on 2025.07.12)
32. GB 3096-2008 Environmental Quality Standard for Noise (in English), China National Standard; <https://www.codeofchina.com/standard/GB3096-2008.html> (accessed on 2025.07.12)
33. Baltic Power; <https://balticpower.pl/> (accessed on 2025.07.06)
34. OX2; <https://www.ox2.com/pl/polska/projekty/wysoka/> (accessed on 2025.07.06)
35. Product preview documentation package - wind turbine class Nordex Delta 4000 N149/5.X; <https://www.scribd.com/document/857310932/1-Product-Preview-Documentation-Package-N149-5-7-MW> (accessed on 2025.07.25)
36. K. Loenbaek, C. Bak, J.I. Madsen, B. Dam; Optimal relationship between power and design-driving loads for wind turbine rotors using 1-D models; *Wind Energy Science*, 2020, 5(1), 155–170; DOI: 10.5194/wes-5-155-2020
37. HETMAN - Healthy Society towards optimal management of wind turbine noise; <https://hetman-wind.ios.edu.pl/> (accessed on 2025.07.09)