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Research article

Noise Emission Assessment of a Utility-Scale Wind Power Plant: Case Study of a 90 MW Wind Power Plant in Mukdaharn Province, Northeastern Thailand

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Abstract: The noise impact of wind power plants is one of the major reasons for social opposition to wind energy development. The complex noise model (ISO 9613) was employed to model the noise generated by 15 GW165-6.0 MW wind turbine generator units based on the manufacturer-defined acoustic profile. The wind resource at a hub height of the wind turbine generators (144 m agl) was first predicted based on computational fluid dynamics flow modeling. The model noise levels were mapped using ArcGIS and twenty-two receptors comprising houses, temples, and other places at varying distances within the project boundary. Likewise, to compare the noise levels of the wind turbine generators with different noise levels, the ambient noise was measured at selected four receptors. The results showed that the predicted noise was less than 70 dB(A) in the vicinity of the wind turbine generators, decreased down to 40-45 dB(A) within the project boundary, and was in the range of 35-40 dB(A) in the community area. The compared results showed that the ambient noise exceeds the noise levels from the wind turbine generators at all four receptor sites. Hence, wind power plants would not cause any additional noise pollution. Such studies are vital to providing awareness to the public based on proven scientific evidence to gain the public's trust and mitigate social opposition to wind power plants.

Keywords: Onshore Wind Power Plant; Noise Disturbance; Noise Profile; Octave Band; Public Opposition.

1. Introduction

Onshore wind energy is one of the primary renewable energy sources for the transition to a net zero energy system of the future. At the COP28 climate conference, world leaders recently reiterated their commitment to global emission control, pledging to triple the installed renewable energy to 11,000 GW by 2030 [1]. Wind energy is at the forefront of this renewable energy development, with the installation of 75 GW in 2022 alone [2]. However, the net-zero energy targets of 2050 require an unprecedented level of wind energy development, which will achieve a 35% share of electricity generation [3]. To accomplish this mammoth goal, global wind installation needs to increase significantly, with the global cumulative installed capacity of onshore wind needing to reach 1,787 GW by 2030 and 5,044 GW by 2050, a nine-fold increase from 542 GW in 2018 [3]. Achieving these targets will be a global task, with countries developing their onshore wind resources on a priority basis.

Thailand is an emerging Southeast Asian economy with relatively good onshore wind resources that can be developed to relieve its heavy reliance on fossil fuels for energy needs. Several studies have been carried out for the resource assessment of the country's onshore wind potential. Employing the wind atlas analysis and application model (WAsP), Kamdar and Taweekun [4] showed that a wind power plant in the Hat Yai region of southern Thailand could generate 2,731 MWh annually [4]. Atmospheric and computational fluid dynamics (CFD) wind flow modeling are other widely used wind resource assessment tools, with the capability to simulate wind speeds at multiple elevations above ground level (agl) [5]. The power production of a 300 MW wind power plant in southern Thailand was estimated using CFD-based wind resource assessments [5]. Similarly, another 13 to 18 GWh/year of wind power potential was estimated along the Amadan coast using CFD-based assessment at 100 and 120 m agl.

Wind energy potential was assessed for the Mekong area in the upper northeastern part of Thailand. High-resolution wind maps were developed at 100, 120, and 200 m agl [6]. This work showed that wind speeds in the 1.29 to 3.79 m/s range were presented near Laos, while the mountainous area in Mukdahan has wind speeds between 1.63 to 3.85 m/s [7].

The MC2 and Ms-Micro models were applied in the same region using mesoscale and microscale atmospheric models and 10 years of NCEP/FNL climatic database. The simulated wind resource showed that the high potential areas mainly occurred in mountainous areas. It can be concluded that the Kalasin Province would produce the largest energy output from wind power plants [8].

Given the proper regulatory and policy attention, Thailand has an onshore wind potential of 13 to 17 GW [9]. However, Thailand has installed only 1,545 MW of onshore wind energy as of 2022 [2], leaving a huge potential yet to be developed. However, in recent years, onshore wind energy development has faced another challenge in the form of public opposition due to its environmental, notably because of its acoustic footprint.

The noise produced by wind turbine generators (WTG) is a major concern for the residents living near wind power plants and has been a major cause of public opposition. Wind turbine noise and the annoyance induced can be a major cause of opposition from the communities near wind power plants [7]. Wind power plant noise has been associated with sleep disturbances in the local population, affecting their daily routines and health [10-12]. In addition to sleep deprivation, people living around wind power plants also complain of anxiety, sleepiness, fatigue, and irritability [13,14]. The low-frequency noise produced by wind turbine generators is often blamed for sleep disorders, hearing loss, and vestibular system anomalies [15].

To assess if specific public policies should be implemented to regulate wind energy development, the Government of Canada recently mandated an international panel of experts to assess the scientific literature on the impact of wind turbine noise on human health [16]. The conclusions of this exhaustive work identified that the evidence is sufficient to establish a causal relationship between exposure to wind turbine noise and annoyance. At the same time, there is limited evidence to establish a causal relationship between exposure to wind turbine noise and sleep disturbances. Further, the evidence suggested a lack of causality between exposure to wind turbine noise and hearing loss. In contrast, the evidence was inadequate to come to any conclusion about the presence or absence of a causal relationship between commonly claimed health impacts and exposure to wind turbine noise.

Nonetheless, wind turbine noise is becoming one of the major causes of public opposition to onshore wind power plants, and addressing this issue is paramount. Unfortunately, misinformation leads to public opposition due to insufficient scientific evidence. Wind power plants generate noise, but it is important to access and compare them with other sources of noise in their vicinity to know if the noise generated from the wind turbines exceeds the ambient noise.

Recently, noise emissions by a utility-scale wind power plant in Thailand were modeled based on a simple noise emission modeling (Simple - ISO9613), which requires the wind speed and the noise profile of a wind turbine generator in normal power mode at arbitrary wind speeds [17]. On the other hand, complex noise modeling requires more information on the 1/3 octave sound power spectrum at the hub height of a wind turbine generator.

This study is aimed at assessing noise emissions of a proposed 90 MW utility-scale wind power plant and its impact on the surrounding communities in the Mukdaharn province of northeastern Thailand. The study employed complex noise modeling to map the noise levels at different locations around the proposed wind power plant, compared to the measured ambient noise within the project's boundary, to determine their impacts. The study is among a handful of studies carried out in the region to study the acoustic effect of wind power plants, which can be very important for developing wind energy and mitigating public opposition to onshore wind power plants.

2. Materials and Methods

2.1 Study Area

The study area is in Mukdaharn province, northeastern Thailand, as shown in Figure 1. This study area is the object of a proposed 90 MW utility-scale wind power plant. The 90 MW wind power plant would consist of 15 units of a 6.0 MW wind turbine generator that will be derated during the operation phase. Figure 2 shows the project boundary of the 90 MW wind power plant, the locations of each wind turbine generator, the locations of sensitive areas, and the locations of the communities around the wind power plant.

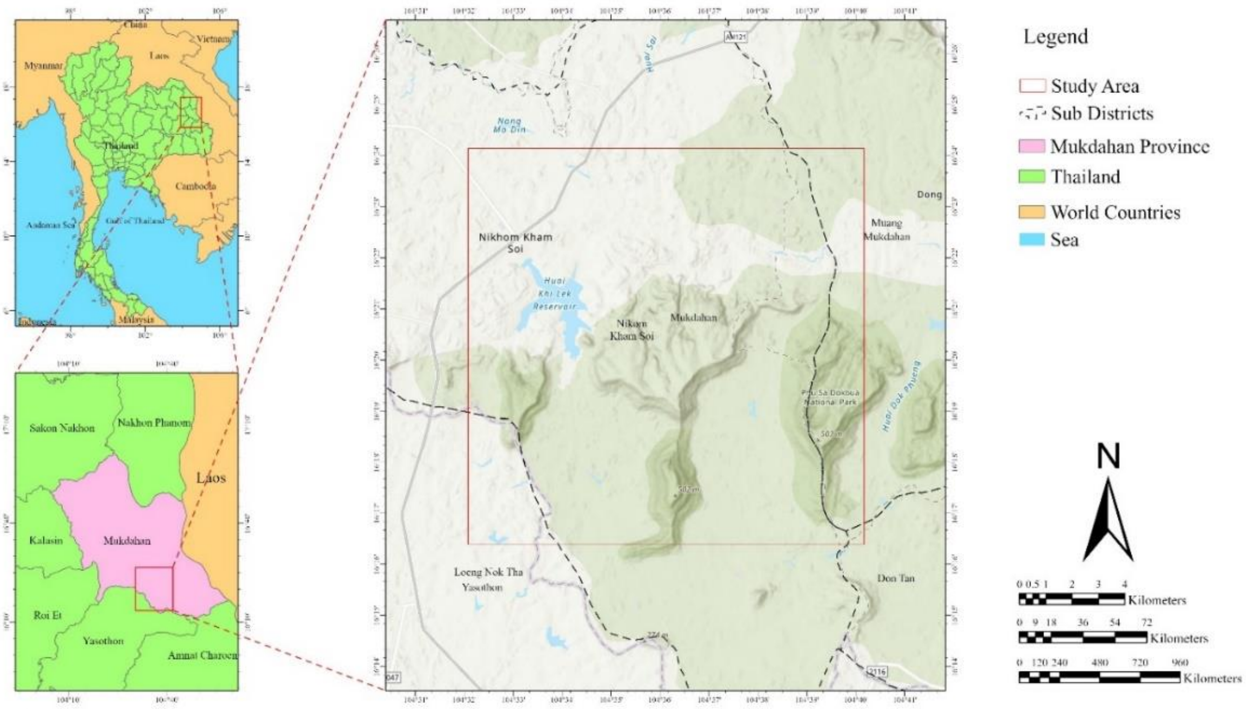

Figure 1. The study area.

2.2 Methodology

The methodology used for the study is illustrated in Figure 3. Initially, a 3 km project boundary is defined around each wind turbine generator, along with a 0.5 km buffer to comply with the Code of Practice (CoP) issued by Thailand's Office of Energy Regulatory Commission (OERC). The connection of these individual boundaries contains the locations of the 15 proposed wind turbine generators, the residences, and the receptors where the noise levels are calculated. The noise generated by the wind turbine generators in the study area is based on the wind speeds obtained from a wind resource map covering a 10 x 10 km^2 area at a resolution of 50 m.

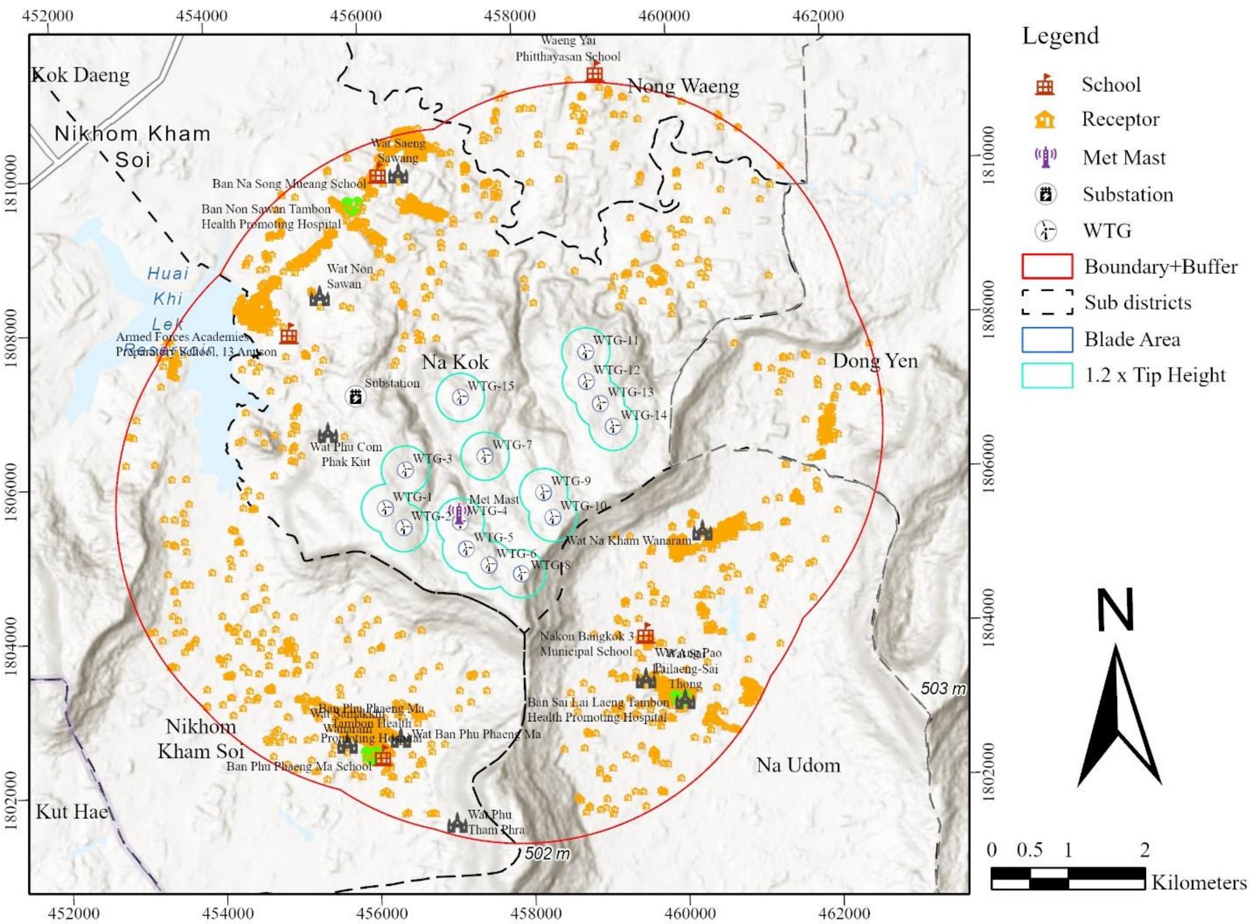

Figure 2. Project boundary of a proposed 90 MW wind power plant in the Mukdaharn province of northeastern Thailand.

The microscale wind resource map was generated from a computational fluid dynamics (CFD) wind flow modeling with the project's observed wind data, along with the input of 30 m resolution topographic data (GDEM), and the Land Cover Land Use (LCLU) from the Land Development Department data of 2021.

The noise impact assessment is simulated using complex noise modeling that complies with the ISO 9631 standards in WindFarmer modeling software. The manufacturer of the wind turbine generator provides the noise characteristics. The noise level simulation generates 24-hour average, daytime and nighttime, and maximum noise levels. Finally, the disturbance was analyzed using the Pollution Control Department (PCD) guidelines [18].

2.3 Microscale Computational Fluid Dynamics Wind Flow Modeling

Computational fluid dynamics (CFD) wind flow modeling is widely used to simulate wind flow caused by the local terrain characteristics and the topography, notably in complex terrains [19–21]. In this study, the CFD modeling was applied for the wind speed prediction over a 10 x 10 km^2 grid, with the measured wind speeds and directions from a 144 m met mast being used as the numerical modeling input. The position of the met mast is shown in Figures 2 and 5.

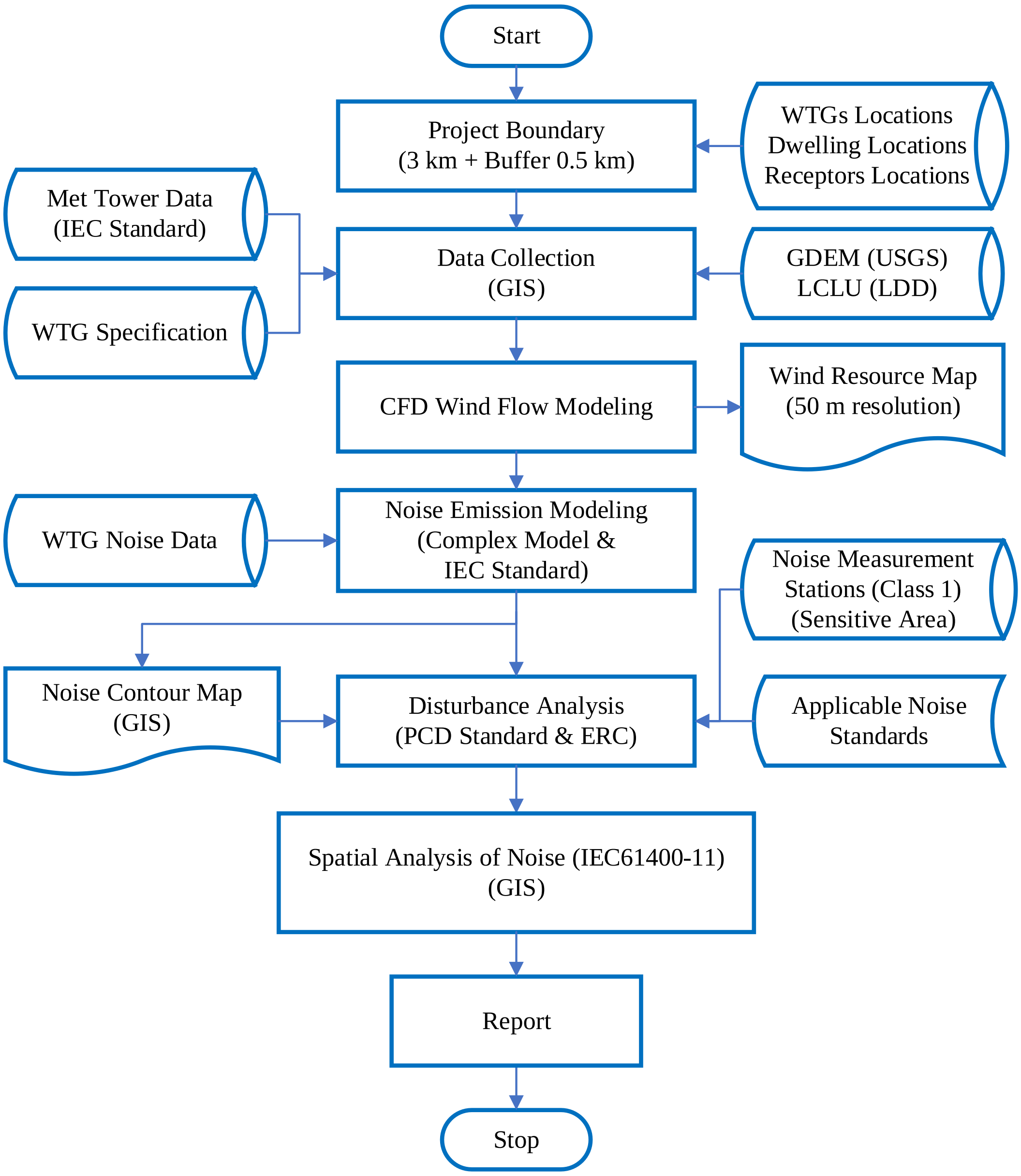

Figure 3. Methodology adopted for the study.

The main inputs required by the CFD wind flow modeling consist of the boundary conditions, i.e., the terrain features (Digital Elevation Model (DEM)), the roughness, as well as the initial conditions, i.e., the wind climatology in the form of wind speeds and directions at typical points of measurement in the study area.

The distribution of the climatic wind speeds, measured from the met mast at 144 m agl and used in the CFD simulations, is shown in Figure 4. At an elevation of 144 m agl, the wind data was collected from the met mast in the project's study area from 00:00 on October 25, 2021, to 00:00 on January 30, 2023. Using a Weibull distribution analysis, the shape parameter was determined to be 2.526 (dimensionless), the scale parameter to be 8.182 m/s, and the annual mean wind speed to be 8.79 m/s, shown in Figure 4 (left), which confirms that the study area is suitable for the development of a wind power plant. To determine the wind direction, the wind rose was partitioned into 16 sections, as shown in Figure 4 (right), indicating a clear dominant wind from the northeast direction.

In this analysis, the ASTER Global Digital Elevation Model (GDEM) V2 [22] provided by the USGS, with 30 m resolution, was used to represent the terrain features of the study area. The roughness was interpreted using the Land Cover Land Use (LCLU) data from the Land Development Department of Thailand [23]. The DEM, the roughness, and the LCLU maps of the study area are presented in Figure 5.

The standard k-epsilon turbulent model was applied to execute the CFD wind flow modeling under neutral air stability conditions and air density of 1.225 kg/m^3 using the GCV solver in the WindSim simulation tool. The details of the conditions used for the CFD wind flow modeling are presented in Table 1.

Table 1. Wind flow simulation conditions using computational fluid dynamics.

Parameter	Condition
Model setup	3-D wind field and 16-sector run
Grid spacing (m)	50
No. of cells	1,722,840
Height of boundary layer (m)	500
Speed above boundary layer (m/s)	10.0
Boundary condition at the top	Fixed pressure
Potential temperature	No
Turbulence model	Standard k-epsilon
Solver	GCV
Air stability	Neutral
Air density (kg/m^3)	1.225

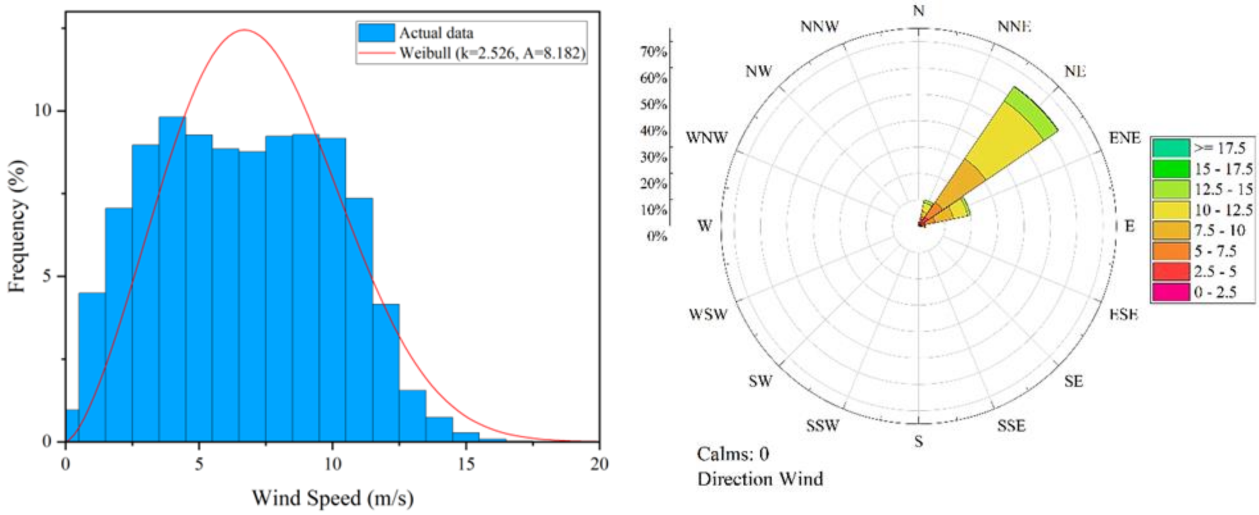

Figure 4. Weibull distribution (left) and wind rose (right) of the wind resource over the study area.

The spatial distribution of the wind speed obtained from the CFD modeling across the study area at 144 m agl is shown in Figure 6. Most of the study area has wind speeds above 8 m/s, with pockets of the area having less than 6.5 m/s and above 10 m/s, thus confirming that the study area is highly suitable for utility-scale wind power plants [24].

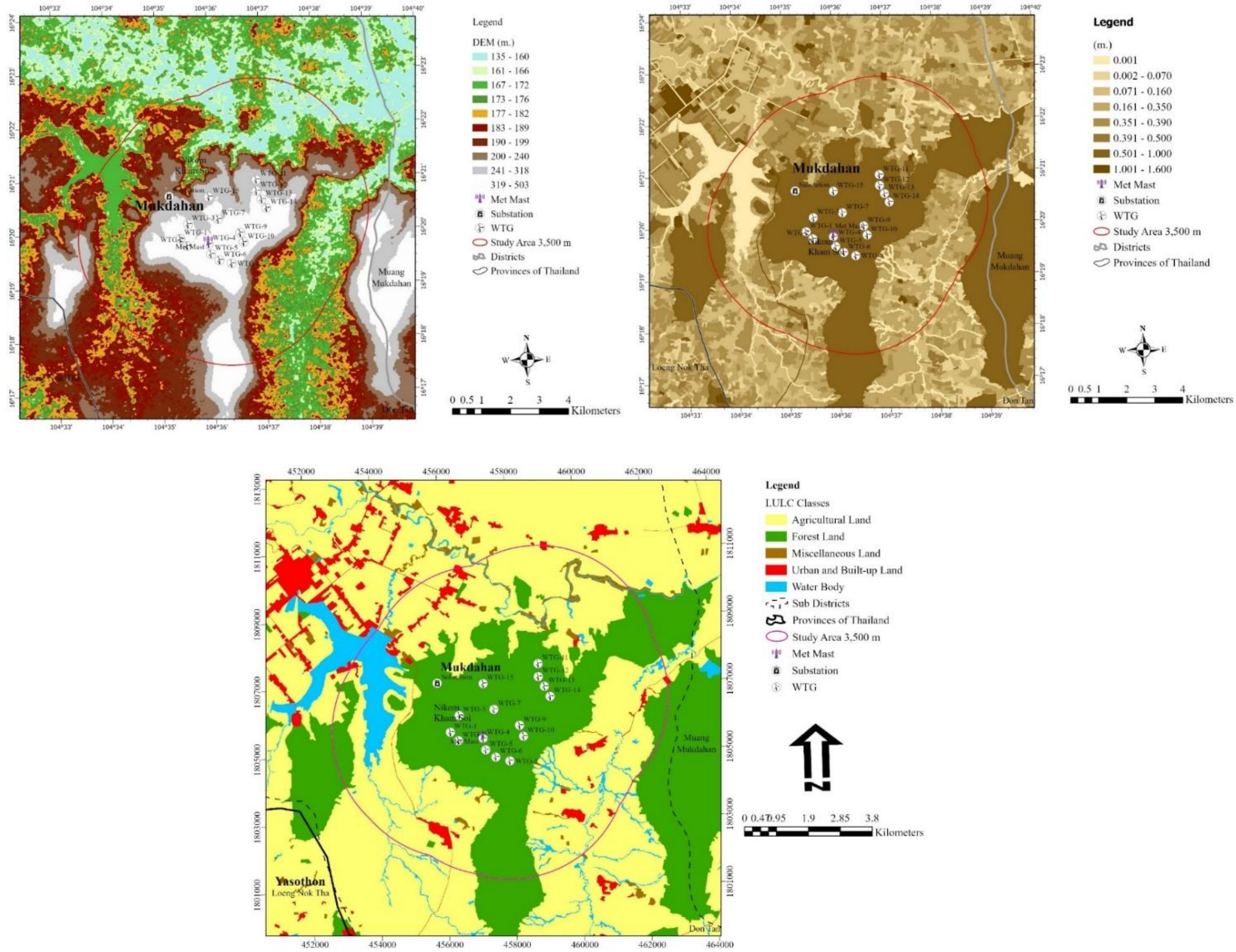

Figure 5. The topography (DEM, upper left), the roughness (upper right), and the Land Cover Land Use (LCLU, bottom) maps of the study area.

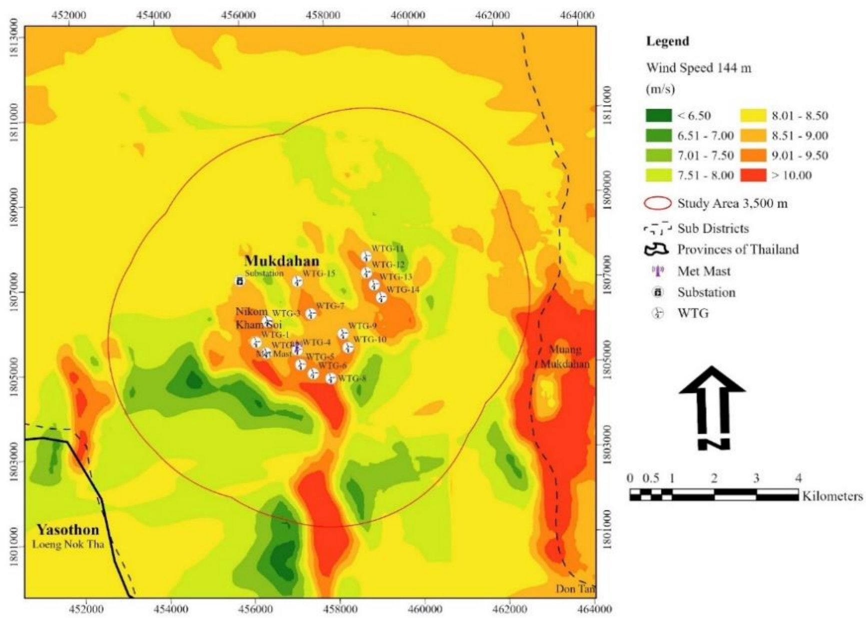

Figure 6. The spatial distribution of the wind speeds in the study area at the hub height of the wind turbine generators (144 m above ground level).

2.4 Noise Level Measurement

2.4.1 Noise Level calculation of the wind turbine generators

The noise impact assessment of the wind turbine generators installed in the wind power plant was calculated using the complex noise modeling of WindFarmer [25]. This noise model calculates the noise impact of a wind turbine generator following the ISO 9613 standard, together with the noise database of the wind turbine manufacturers. Table 2 shows the characteristics and the acoustic details of the GW165-6.0 wind turbine generator used in this study. With a hub height of 155 m agl, the acoustic footprint of the wind turbine generator at an 11.5 m/s wind speed is 110.5 dB(A). The acoustic performance of this model of wind turbine generator is in line with the IEC61400-11 edition 3.0 2012-11 standard.

Table 2. Characteristics of the GW165-6.0 MW wind turbine generator.

Parameter	Specification
Rated power (MW)	6
Hub height agl (m)	155
Rotor diameter (m)	165
Wind class	IEC IIIB
Sound level (dB(A)) at hub height and 11.5 m/s	110.5
Generator	Permanent Magnet Direct Drive (PMDD)
Tower	Steel/Hybrid
Voltage; Frequency	950 V; 50/60 Hz
Grid code	Comply
Certification	IEC IIIB
Rotational speed in operation (rpm)	5.5 – 9.5

The noise level of a wind turbine generator is directly proportional to the operational wind speed. The noise level of the wind turbine generator proportionally increases with the increased operating wind speeds. Table 3 presents the sound levels of the GW165-6.0 wind turbine generator at different operating wind speeds.

Table 3. The acoustic performance in normal power mode of the GW165-6.0 MW wind turbine generator.

Wind Speed (m/s)	Sound Level (dB(A))	Wind Speed (m/s)	Sound Level (dB(A))
6.0	102.2	9.5	110.1
6.5	104.0	10.0	110.3
7.0	105.6	10.5	110.3
7.5	106.9	11.0	110.3
8.0	108.0	11.5	110.5
8.5	108.0	12.0	110.5
9.0	109.5	-	

Humans sense sound within the frequency range of 20 to 20,000 Hz, which is notably broad. However, calculating sound levels across this broad spectrum is a significant challenge. An analysis based on octave frequency bands has been devised to address this. This method divides the frequency range from 20 to 20,000 Hz into octave bands and determines the center frequency value of each band. The approach simplifies the assessment process by quantifying the sound level exclusively at these center frequencies. The sound levels measured at individual frequencies represent their respective octave bands.

Various components of wind turbines produce sound at distinct frequencies. Usually, the manufacturers of wind turbines provide the required data for determining the center frequency of each octave band. Table 4 shows the sound level and its corresponding octave band.

Different frequencies are characteristic of various noise sources, with many employing either the 1/1 octave band or the 1/3 octave band. These bands divide frequency levels according to Equations 1 and 2, respectively:

$$1/1 \text{ octave band} = F \; x \; 2 \quad (1)$$

$$1/3 \text{ octave band} = F \; x \; 2^{1/3} \quad (2)$$

where F is the frequency.

Therefore, regarding the octave frequency values, emphasis is placed on the representative center frequency value. This value, situated between the upper and lower cutoff frequencies, is a pivotal point in the analysis. As depicted in Table 4, wind turbines, while generating electricity, emit sound waves with varying frequencies. These frequencies align with different bands, each characterized by median and corresponding sound frequencies. Following the ANSI (1966) standards, sound level measurement equipment divides the sound range into ten bands for research purposes. The specified center values for each band are 31.5, 63, 125, 250, 500, 1000, 2000, 3000, 4000, 8000, and 10000 Hz. Typically, in sound level analyses, eight wave bands are employed (Octave-Band Analysis). However, the third-octave band analysis offers more comprehensive data by recording measurements with up to three sound level values. Wind turbine manufacturers utilize the acoustic spectrum band analysis to quantify the sound level produced by the turbine operating across various frequency bands, per the IEC 61400-11 standards. This approach accounts for differences in sound levels relative to the wind speed.

Table 4. The 1/3-octave sound power spectrum value at hub height for the GW165-6.0 MW wind turbine model under normal power mode [26].

Octave Band (Hz)	Sound Level (dB(A))	Octave Band (Hz)	Sound Level (dB(A))
20.0	64.6	500.0	101.0
25.0	68.8	630.0	100.3
31.5	72.7	800.0	99.4
40.0	78.1	1,000	98.8
50.0	83.2	1,250	97.3
63.0	86.2	1,600	94.0
80.0	90.2	2,000	89.6
100.0	92.5	2,500	85.3
125.0	95.1	3,150	80.6
160.0	98.2	4,000	73.9
200.0	99.5	5,000	66.2
250.0	100.6	6,300	63.9
315.0	101.8	8,000	63.3
400.0	101.6	10,000	62.3

2.4.2 Complex Noise Model (ISO 9613)

The WindFarmer noise simulation model [25] follows the ISO 9613-2 standard to model the noise generated by wind turbine generators. The complex model (Complex - ISO 9613) used in this study considers the noise attenuation for each octave band, including the ground attenuation and directional meteorological effects.

Firstly, the continuous octave-band sound pressure level for an arbitrary receiver location (Lft) is modeled using Equation 3:

$$\text{Lft} = \text{LW} + \text{DC} - \text{A} \quad (3)$$

Where LW is the sound power level (dB(A)) that is produced by each turbine (a point source). DC is the directivity correction (dB(A)). A is the attenuation that occurs during the propagation from the point sound source to the receiver (dB(A)). For the case of an assumed omni-directional point sound source (such as a wind turbine generator), DC will be 0 dB(A). While measuring the sound power level, the directivity of the wind turbine noise is considered.

The attenuation A is defined by Equation 4:

$$A = Adiv + Aatm + Agr + Abar + Amisc + Amet \quad (4)$$

Adiv, Aatm, Agr, Abar, Amisc, and Amet are the attenuation due to geometrical divergence, atmospheric absorption, ground effects, barriers, other effects such as foliage or buildings, and meteorological effects, respectively.

The geometric attenuation considers the spherical spreading in the free field from a point sound source over hard ground and is calculated using Equation 5:

$$Adiv = [20\log(d) + 11]\ dB = [20(d) + 11] \quad (5)$$

Where d is the 3-D distance between the source and the receiver, a hemispherical model is called for combining a hard ground plane and the spherical spreading.

The atmospheric absorption causes the sound attenuation, and it is calculated using Equation 6:

$$Aatm = \alpha\ d\ 1000 = 1000 \quad (6)$$

Where α is the atmospheric attenuation coefficient in dB(A)/km for each octave, the complex noise model uses a coefficient for each octave band. The atmospheric attenuation coefficients are the user-defined parameters and are a function of frequency, temperature, and humidity. The default attenuation coefficients are set and are valid for 10°C temperature and 70% humidity.

The sound could be reflected or absorbed by the ground surface. This is considered as an attenuation by ground (Agr). Three regions, the source, the receiver, and the middle regions, were considered in ISO 9613-2. Each region has acoustic properties depending separately on the ground factors (G), as indicated in Table 5.

Table 5. Ground factors (G) for three different ground surfaces.

Type of Ground	Example	Value of G
Hard	Low porosity surface (paving, water, ice, concrete)	0
Porous	Porous surfaces suitable for the growth of vegetation (ground covered with grass, trees, and vegetation)	1
Mixed	Both hard and porous ground	0 - 1

The sum of the individual absorption coefficients for the source region (As), the receiver region (Ar), and the middle region (Am) are calculated for the total ground attenuation for each octave band using Equation 7:

$$Agr = As + Ar + Am \quad (7)$$

As, Ar, and Am are calculated as a function of G, given in Table 5, based on the ISO 9613-2 standards.

Finally, complex noise modeling considers noise attenuation to be a function of the frequency distribution of the noise. The octave band noise emission of the wind turbines was defined. The attenuation of the noise is calculated by using the frequency-specific attenuation coefficients. In the case of wind power plants where multiple wind turbine generators operate simultaneously, the noise propagation is calculated in the complex noise modeling by summing the contributing sound pressures for each octave band of each wind turbine generator using Equation 8:

$$L_{total} = 10\log\left[\sum_{i=1}^{n}\sum_{j=i}^{8} 10^{\frac{Lft(ij)}{10}}\right] \quad (8)$$

Where n is the number of sources i, j indicates the eight standard octave band frequencies [63 Hz to 8 kHz]. Octave band sound pressure level represented by Lft.

This work measured the noise levels over five (5) days, consisting of regular business days and holidays. The collected measured parameters were obtained following the regulations set forth by the Energy Regulatory Commission of Thailand, as follows:

- 24-hour A-weighted Equivalent Continuous Sound Level (Leq24hr), which is a common measurement used in industry to characterize noise levels in loud environments;
- Percentile Level 90 (L90), which describes the level that was exceeded 90% of the time;
- Day-night average sound level (Ldn), where the average sound level is the average noise level over 24 hours; and,
- Maximum Noise Level (Lmax) is the maximum acceptable noise level.

The noise levels calculated were then mapped using ArcGIS Pro V3.0.1 to assess the effects on the residents living inside the boundaries of the study area.

3. Results and Discussion

Using the complex noise modeling in WindFarmer, the noise of each wind turbine generator of the wind power plant was calculated and mapped according to the noise levels, the 24-hour average noise levels, the average noise levels during the day and the night, and the maximum noise levels. A comparison study of these effects was also done using the Pollution Control Board's regulations to measure the basic sound levels and analyze the disturbance. In addition, the international standard, defined by the World Health Organization (WHO) and the World Bank Group, was also considered according to the thresholds defined as follows:

- The maximum permissible noise level resulting from the power plant operations is 10 dB(A).
- The maximum permissible 24-hour average noise level resulting from the power plant operations is 70 dB(A).
- The noise level produced by the power plant operations is limited to a maximum of 115 dB(A).
- The World Health Organization (WHO) suggests the upper noise limit should not exceed 45 dB(A) when the wind speed is 10 m/s and the height is 10 m. However, the World Bank Group suggests that the LA90 be below 35 dB(A) at a wind speed of 10 m/s and 10 m from the receptor during the day and night.

Twenty-two sound receptor types, ranging from temples to houses, were selected at multiple locations and distances from the wind power plant to measure the noise levels; the individual sound receptor ID assigned to identify them and their respective details are shown in Table 6. Figure 7 shows the positions of the sound receptors, along with the positions of the wind turbine generators and their associated noise emissions within the study area.

Table 6 shows the noise at the individual sound receptors in the study area, while Table 7 shows the overall noise levels and their associated area within the study area. With 23.1 km^2, 30-35 dB(A) accounts for the highest coverage areas, while only a 2.3 km^2 area, accounting for 3.2% of the total area within the study boundary, experiences the highest noise level of 55-60 dB(A).

The ambient noise levels were also calculated and recorded in four selected spots within the study area to compare the noise produced by the wind turbine generators with other noise sources. The ambient noise level at a particular location is the overall environmental noise level caused by all noise sources in the area, both near and far. These noises can be traffic, temple rings, noise from insects, birds, and other wildlife, etc.

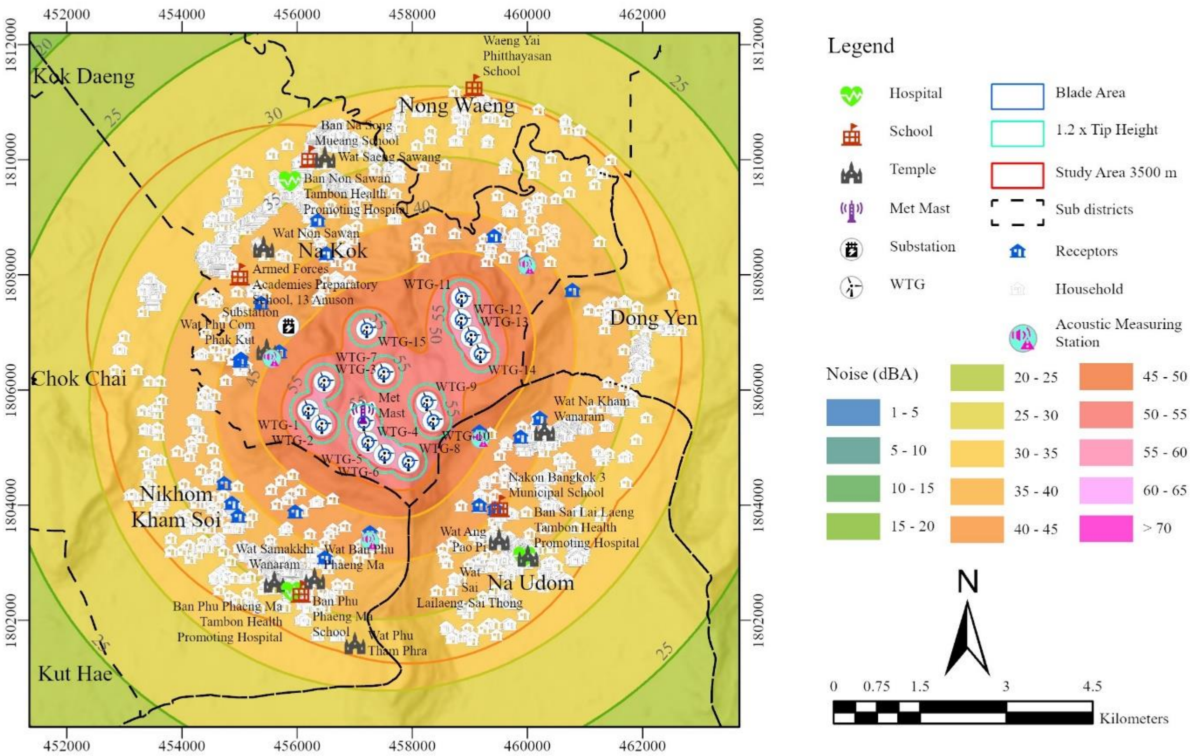

Figure 7. Noise levels and sound receptor location map.

Table 6. Sound receptor locations, detailed characteristics within the study area, and noise level at each sound receptor.

Receptor ID (KMZ)	Receptor Type	Elevation (m)	Distance to Nearest WTG (m)	Predicted Noise (dBA)
2109	House	200.0	1,403.3	33.64
2115	House	200.0	1,398.2	33.62
2517	House	200.0	2,146.9	30.09
2465	House	200.0	2,015.6	30.51
2080	Phu Com Phakkad Temple	280.2	880.6	37.37
1959	Dong Bang-i Forest Park	200.0	1,666.8	32.43
2517	House	200.0	2,146.9	30.09
2553	House	200.0	1,687.1	33.11
2568	House	200.0	2,231.7	29.81
2606	House	200.0	1,487.9	33.87
3008	House	200.0	2,166.2	30.74
2289	Huai Koh Tao Monk Residence	200.0	859.4	37.72
2338	House	200.0	1,568.1	33.80
2529	House	186.7	1,503.1	33.09
2541	Nakon Bangkok 3 Municipal School	180.1	1,761.0	31.93
1435	House	165.0	1,112.3	34.23
1602	Phuratanotham Monastery	196.7	1,242.1	34.19
1602	House	196.7	1,242.1	34.19
1855	Pa Phutthammasilakhun Temple	201.2	1,882.9	31.48
2184	House	200.0	1,606.7	33.11
1528	House	200.0	1,387.1	32.81
1327	House	200.0	1,966.1	30.10

Table 7. Percentage of the study area affected by different noise levels from the wind turbine generators.

Noise Level (dB(A))	Area within Project Boundary (km^2)	%
25 - 30	-	-
31 – 35	23.1	31.3
36 – 40	22.3	30.2
41 – 45	12.7	17.3
46 – 50	7.1	9.7
51 – 55	6.1	8.3
56 – 60	2.3	3.2
61 – 65	-	-
> 70	-	-
Total Surface Area	73.6	100

The ambient noise levels were measured using the Sound Level Meter Scarlet Tech (Model: ST-11D, Serial Number: 820965) between September 7 and 12, 2023. A magnitude of parameters was used to measure the ambient noise at four locations in the study area as follows:

- Equivalent Sound Level (Leq): average noise level value throughout the measurement period of 8 hours.
- Equivalent Sound Level (Leq24): average noise level value throughout the measurement period of 24 hours.
- Maximum Noise Level (Lmax): maximum noise level value throughout the measurement period of 8 hours; Lmax should not exceed 115 dB(A) according to international standards.
- Maximum Noise Level (Lmax24): maximum noise level value throughout the measurement period of 24 hours; its standard is also 115 dB(A).
- Percentile Level 5 (L5) for the 8-hour measurement period.
- Percentile Level 5 (L5 24) for the 24-hour measurement period.
- Percentile Level 50 (L10) for the 8-hour measurement period.
- Percentile Level 50 (L10 24) for the 24-hour measurement period.
- Percentile Level 90 (L90) for the 8-hour measurement period.
- Percentile Level 90 (L90 24) for the 24-hour measurement period.
- Day-Night Average Sound Level (Ldn): mean day-night sound level (A-weight) for the period between 10:00 p.m. and 7:00 a.m. after 10 dB(A) is added.

The ambient noise levels at four locations were measured and plotted using these parameters. Figure 8 shows the ambient noise measured at the Phu Kham Phakkad Temple in the study area. It is worth noting that the Lmax24 measurement is always above the standard 70 dB(A) threshold the Pollution Control Department set. The noise produced by the wind turbine generators is well below the ambient noise levels and lower than the standard 70 dB(A). Similarly, the Leq and L90 are also consistently higher, with occasional lower values of the wind turbine generator noise level measured at 5-minute intervals for 24 hours, as shown in Figure 8.

Likewise, the measurements at the remaining three receptors show a similar trend, with the ambient noise being higher than the noise from the wind turbine generators, as shown in Figures 9, 10, and 11.

The Leq and L90 based on 5-min measurements for all four receptors are presented in Figures 8-11. It can be observed that the Leq and L90 were occasionally lower than the noise emitted by the wind turbine generators.

The Leq and L90 are comparatively lower at Huai Koh Tao monk residence than the previous receptors, but still, much of the time, they are above the noise levels of the wind turbine generators (Figure 10). At Phuratanotham monastery, the ambient sound is much less than at the other three receptors, with Leq and

L90 going below the noise from the wind turbine generators more often than at other sites. However, it is still higher than the noise level of the wind turbine generators most of the time throughout the day, as shown in Figure 11.

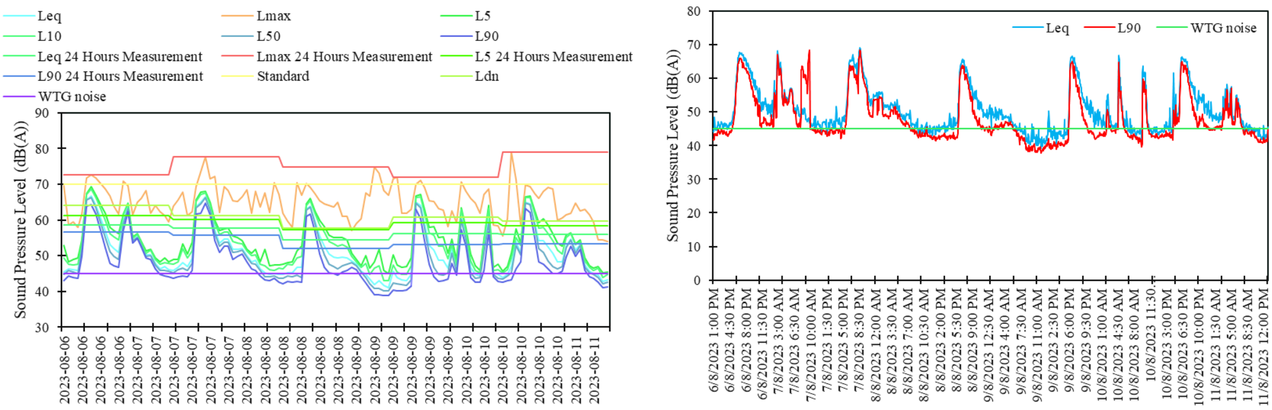

Figure 8. Ambient noise measurements (left) and sound pressure measurements every 5 minutes (right) at the Phu Kham Phakkad Temple.

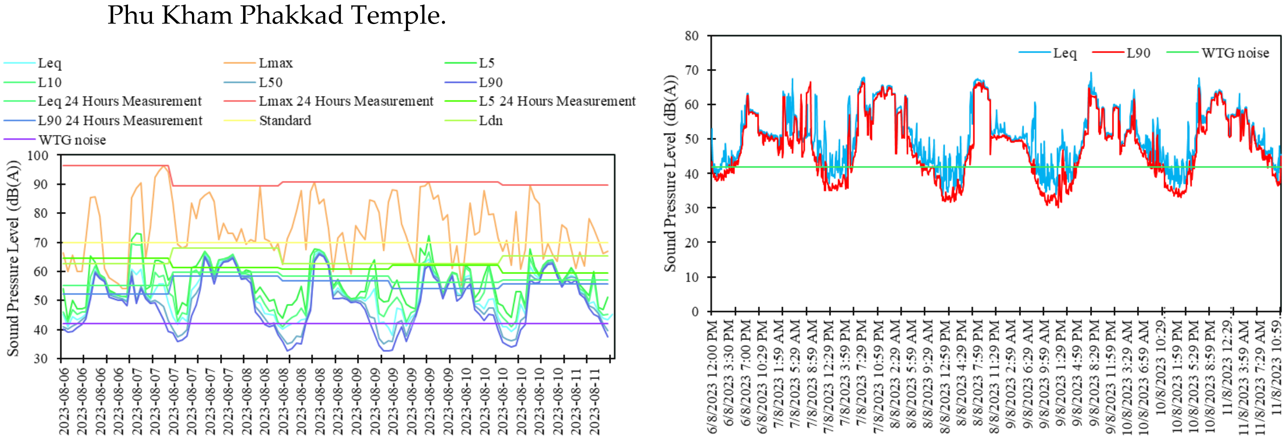

Figure 9. Sound pressures (left) and sound pressure measurements every 5 minutes (right) at the measurement site of the Phu Phaeng Ma Temple.

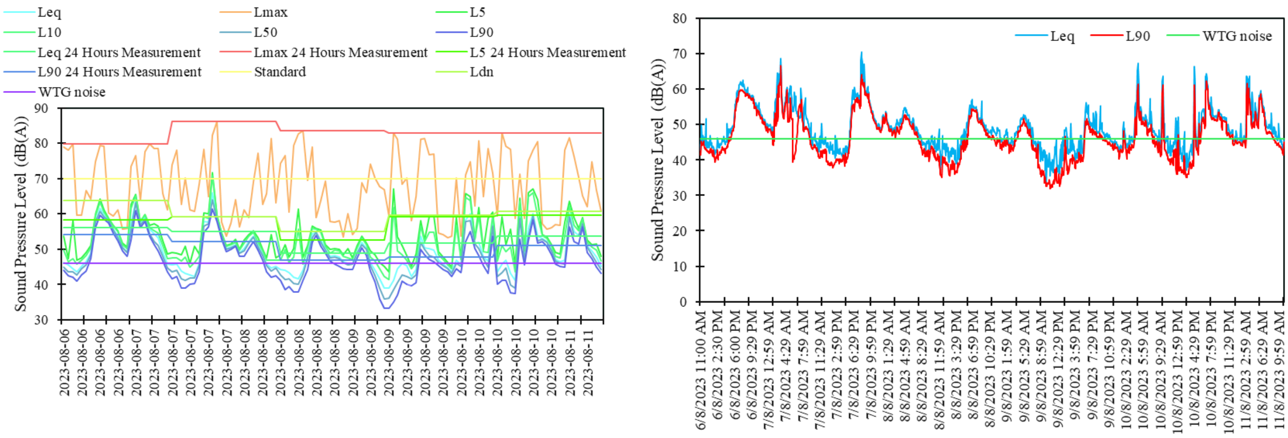

Figure 10. Sound pressures (left) and sound pressure measurements every 5 minutes (right) at the measurement site of the Huai Koh Tao monk residence.

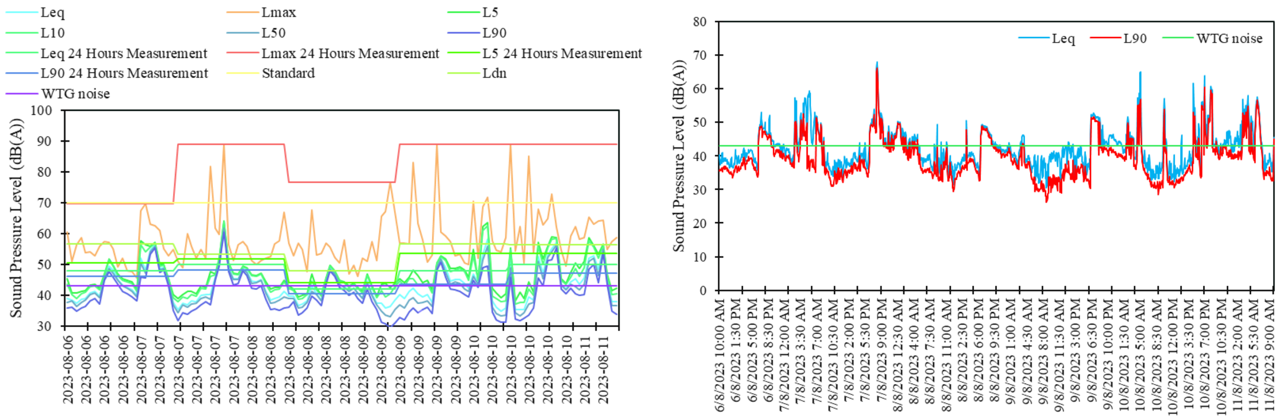

Figure 11. Sound pressures (left) and sound pressure measurements every 5 minutes (right) at the measurement site of the Phuratanotham monastery.

To compare the multiple measurement parameters of the ambient noise with the noise levels of the wind turbine generators, Table 8 shows the hours the ambient noise levels at the four acoustic measurement stations are below the noise level emitted by the wind turbine generators. The percentage of time that the Leq and the L90 are below the noise level of the wind turbine generators corresponds to less than 50%, except at Phuratanotham monastery, where they are higher than 50%. Even though it is situated closer to the wind power plant, as illustrated in Figure 7, the ambient noise at Phuratanotham monastery is quite low due to fewer activities and is far away from the community.

A further comparison of the ambient noise and the wind turbine generator noise is shown in Table 9. The ambient noises at all the receptor sites are higher than the noise from the wind turbine generators, resulting in no disturbance caused by the wind turbine generators throughout the study area. Hence, the 90 MW wind power plant in Mukdaharn province in northeastern Thailand does not cause any noise disturbance in the surrounding area as it is below the ambient noise the residents are used to hearing daily.

The results in this study were compared to a previous investigation using a simple noise emission model for a 50 MW wind power plant [18], and it was found that the predicted noise for a 50 MW wind power plant had a maximum of 50 dB(A) in the vicinity of the wind turbine generators. These results were similar to two wind power plants in Greece, where the maximum noise emission level obtained from a simple noise modeling under wind speed of 8.0 m/s was less than 45 dB(A) [27].

Table 8. Percentage of time that the ambient noise was below the noise from the wind turbine generators.

No.	Acoustic Measurement Station	Ambient Noise < WTG Noise (%)					
		L_{eq}	L_{max}	L_5	L_{10}	L_{50}	L_{90}
1	Phu Kham Phakkad Temple	11	0	0	2	21	31
2	Phu Phaeng Ma Temple	17	0	0	6	27	46
3	Huai Koh Tao Monk Residence	34	0	4	8	42	49
4	Phuratanotham Monastery	54	0	32	39	57	68

Table 9. Mean Leq, WTG noise, and disturbance.

Acoustic Measurement Station	Mean Leq	Std. Leq	WTG Noise	Residual	Disturbance (%)
Phu Com Phak Kut Temple	53.2	8.1	43	-10.2	0
Phu Phaeng Ma Temple	52.1	7.4	45	-7.1	0
Huai Koh Tao Monk Residence	50.6	6.7	46	-4.6	0
Phuratanotham Monastery	44.6	7.4	43	-1.6	0

4. Conclusions

The noise produced by wind turbine generators is often among the major causes of social opposition to wind energy development. In extreme cases, these oppositions can lead to the cancellation of planned projects, causing hurdles to achieving energy transition targets. Dedicated research to study the noise profiles and their impacts on residents near wind power plants can help mitigate social opposition. Often, misinformation can be the primary cause of the opposition to wind power plant developments. To address this important issue, this research assessed the noise emission impacts of a 90 MW utility-scale wind power plant in Mukdaharn province in northeastern Thailand.

The complex noise model (Complex - ISO 9613) of the WindFarmer simulation software was employed to model the noise profile of the GW165-6.0 MW wind turbine generator considered for the wind power plant based on the acoustic profile of the wind turbine generator provided by the manufacturer. The noise produced by the 15 wind turbine generators was mapped using ArcGIS, employing the results of the complex noise modeling to visualize the noise impacts on the surrounding areas. Twenty-two sound receptors, mainly comprised of residential buildings, temples, and other important locations, were selected throughout the study areas at varying distances to model the impacts of noise from the wind turbine generators. The 24-hour average noise levels, the average noise levels during the day and night, and the maximum noise levels were the primary parameters used to determine the noise levels, which were compared to national and international standards defined for acceptable noise levels for a healthy environment.

In addition, to compare the noise levels of the wind turbine generators with the ambient noise levels in the study area, the ambient noise levels at four selected locations within the study area were measured using a Sound Level Meter Scarlet Tech (Model: ST-11D, Serial Number: 820965) measuring tool. The equivalent sound level (Leq), the equivalent sound level (Leq24), the maximum noise level (Lmax), the maximum noise level (Lmax24), and several other parameters were measured and compared with the noise levels from the wind turbine generators. The results clearly showed that the noise levels of wind turbine generators were much lower than the ambient noise levels within the study area. Hence, the wind power plant is not the source of any additional noise for the residents living within the study area.

Studies like these are important to assess the impacts of wind power plants on residents' lives and provide evidence to confront misinformation and gain the trust of local communities to mitigate the social opposition to wind power plants.

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