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Assessing The Impacts Of Wind Turbine Noise And Shadow Flicker: A Systematic Approach For Evaluation Of Shadow Flicker And Noise Of Onshore Wind Turbines

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Abstract
The wind energy industry is growing at a fast pace globally to overcome the gap between demand and supply. There are effects of the industrial revolution on the communities and biodiversity. The wind industry in Pakistan is also evolving rapidly. Wind turbines have positive and negative impacts on nearby communities, including the annoyance effect of wind turbine noise and shadow flicker. This study was conducted to check the status of noise and shadow flicker monitoring by wind farms in Pakistan. The study also developed a convenient methodology to follow and implement noise and shadow flickering at the wind farms. The study shows that only 17 (47%) wind farms in Pakistan are monitoring shadow flicker and noise effects on communities. In contrast, the remaining 19 (52.8%) wind farms are either monitoring shadow or noise effects on the receptors. Out of 36 wind farms, no wind farm has reported an annoyance case in their record. The systematic approach presented in this study can be a useful tool for noise and shadow flicker monitoring in wind farms worldwide.

Keywords: Shadow flicker monitoring, noise monitoring, wind turbine, wind energy, sustainability, health and safety.

Highlights

- Only 47% of wind farms monitor the impact of noise and shadow flicker in Pakistan.
- No significant health effects were reported by the communities at the wind farm.
- Procedures developed for noise and shadow monitoring can be used worldwide.

1. Introduction

Energy has a significant function in lives [1] and social and economic development [2] and also acts as a pushing power in the development of modern civilization[3]. The provision of reliable, affordable, and sustainable energy to everyone by the end of 2030 is the target of the United Nations' Sustainable Development Goal 07[4]. Global electricity demand decreased to approximately 1%. However, due to the COVID-19 pandemic, global electricity demand increased in 2021 and 2022 by about 5% and 4%, respectively (International Energy Agency, 2021). Renewable industries reduce greenhouse gas (GHG) emissions. In contrast, industries generating energy from fossil fuels are the major contributors to GHG emissions [6]. Coal and gas power plants are the reason for water and air pollution and cause many problems like breathing problems, neurological damage, cancer, heart attacks, and many more [7]; that's why economies are avoiding fossil fuels and transitioning to greener alternatives for power production [8], [9]. The demand for alternative energy resources increased in the 21st century due to economic growth, environmental concerns, and limited resources of fossil fuels [10], [11]. Renewable energy is the energy obtained from non-depletable resources [12] that are replenished naturally [13]; such sources are solar, wind, geothermal technologies, hydropower, biomass, and landfill gas [14]. Kinetic energy from wind is the cheapest and most crucial source of energy [15] that globally reduces greenhouse gas emissions and resists climate shifts [16], [17]. Pakistan is committed to increasing its renewable energy share from 4% to 20% through wind and solar by the end of 2025, so new technologies, processes, and materials that lead workers to significant occupational risks are introduced[18]. Incident statistics show that maintenance workers are more vulnerable to risk than construction

workers [19], and organizations develop QEHS management systems for the safety of their workers, environment, and equipment [20]. Wind farms don't evaluate the effect of noise and shadow flicker on the societies located near the wind turbines. Despite the numerous positive aspects of wind turbines, there are also environmental concerns[21].
Due to the operation of wind turbines, the moving shadow is produced (Fig.1) and known as shadow flicker (SF) [22], [23], which creates annoyance in a subset of the exposed population[24]. Sleep disorder risk increases due to light blinking, shadow flicker, and direct visibility (Freiberg et al., 2019a). Wind turbines' annoyance and stress effects on the residents were also studied in the U.S. and Europe [26].

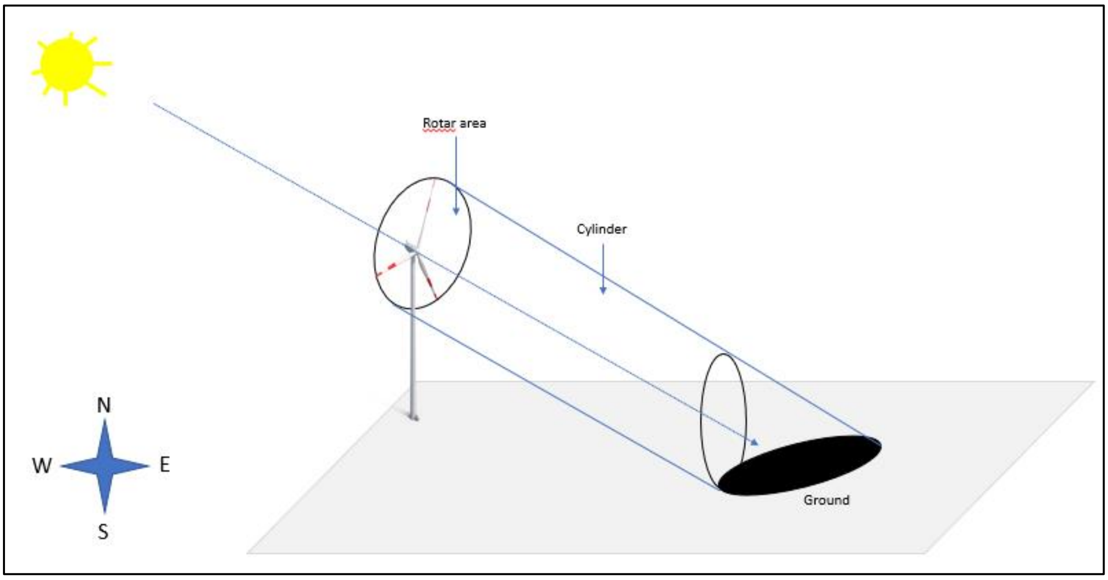


Fig.1: Shadow flicker effect produced by a wind turbine.

Globally, national guidelines were defined by many countries for evaluating and assessing the potential impacts of shadow flicker. Concerning wind turbine noise, two mechanical components, the gearbox and generator, and aerodynamic noise from the blade (Fig.2) are the main sources. At a significant distance, the wind turbine's noise depends on the wind turbine type, the design of the wind farm, and geological and metrological specifications.

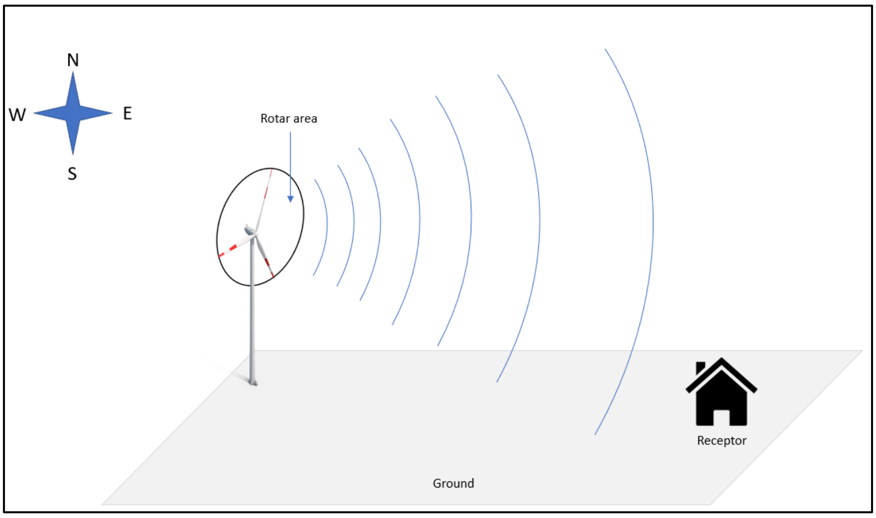


Fig.2: Graphical representation of noise from the wind farm and nearby receptor

The main purpose of this study is to develop a user-friendly and environmentally friendly system for noise and shadow flicker monitoring in wind farms and test the developed system on wind farms in Pakistan for its effectiveness and performance. A protocol for identifying sensitive receptors was also developed. This is the first study on the systematic noise and shadow flicker monitoring technique and current noise and shadow flicker monitoring compliance status of wind farms in Pakistan.

2. Materials and methods

WindPro 3 software is commonly used for modeling to generate predictive shadow flicker, but most organizations record shadow and noise observations at sensitive receptors manually, which is a more accurate method and first-hand data. This data can be used in modeling as well.

2.1. Field Visits

Eight (08) wind farms, i.e., Foundation Wind Energy-I & II, Tenaga Generasi Ltd., Gul Ahmed, Metro Power, Yunus Energy, Hawa Energy, and Jhimpir Power, were visited and met with the responsible concern of respective wind farms for the evaluation of sensitive receptors and their monitoring practices.

2.2. Tools and Software

Stopwatch, Noise meter (UT353, UNI-T), Google Maps (mobile application), and Google Earth (Version 9.189.0.0) were used for the collection of data.

2.3. Noise and Shadow Flicker Procedures Development

Shadow flicker (SF) and noise monitoring (NM) standard operating procedures (SOPs) were developed covering sensitive receptors, nearest wind turbine generator (WTG), observation range, location coordinates recording methodology, and respective forms for recording noise and shadow flicker readings.

2.4. Survey for Shadow Flicker and Noise Monitoring Data of the Wind Energy Industry of Pakistan

A survey on Microsoft forms was developed with the consultation of field experts, covering personal information having 1 close-ended and 4 open-ended questions, noise monitoring section having 4 close-ended questions, and shadow flicker monitoring consisting of 6 close-ended items. The survey form was circulated via email to concerned personnel in 36 wind farms in Pakistan for the collection of reliable data and also visited where necessary. Survey questions are presented in Table 1 and can be accessed by using the link: https://forms.office.com/r/PLK0mccUyk.

The participation was completely voluntary, and the confidentiality of the information provided by the participants was ensured. The participants were informed about the aims and objectives of the study. Eight wind farms were visited, and meetings were conducted with concerned personnel regarding their response to the survey form and practices they made to ensure the collection of reliable, valid, and recent data from the wind farms.

Table 1: Shadow flicker and noise monitoring in nearby areas of wind turbines through a survey questionnaire.

S. No.	Question	Section
1	Do you monitor the shadow flicker effect/s of the wind turbine at sensitive receptors (communities having effects of wind turbine)?	Shadow Flicker Monitoring
2	The total number of sensitive receptor/s (affected communities) in your wind farm?	Shadow Flicker and Noise Monitoring
3	Minimum distance of receptor from nearest WTG.	Shadow Flicker Monitoring
4	Minimum shadow flicker reading among all receptors in hrs./yr.	Shadow Flicker Monitoring
5	Maximum shadow flicker reading among all receptors in hrs./yr.	Shadow Flicker Monitoring
6	Please select suitable answers to the questions below. a. Annoying effect/s reported by receptor/s. b. Health effect complaint/s received by receptors. c. Corrective &preventive measures taken by your wind farm against shadow flicker.	Shadow Flicker Monitoring
7	Do you monitor the noise effect/s of the wind turbine at sensitive receptor/s?	Noise Monitoring
8	Minimum noise level (in dB) among all receptors.	Noise Monitoring
9	Maximum noise level(in dB) among all receptors.	Noise Monitoring
10	Please select a suitable answer/s to the below questions. a. Annoying effect reported by receptor/s. b. Health effect complaints received by receptor/s. c. Corrective &preventive measures taken by your wind farm against noise.	Noise Monitoring

2.5. Identifying Sensitive Receptors

Sensitive receptors in the context of noise were typically residential premises. However, they can also include schools, places of worship, recreational areas, and noise-sensitive commercial premises[27]. For identifying sensitive receptors for wind turbine noise (WTN) and SF, multiple visits to the whole wind farm were conducted, marking all villages/communities, the nearest wind turbine/s and wind turbine having direct SF and WTN effects on communities, and the distances between wind turbine and receptor/s. Recording coordinates of wind turbine and receptor/s and plotting coordinates of wind turbine and sensitive receptor/s on Google Earth with cardinal directions so that the tentative time of SF observation can be estimated, i.e., morning or evening, were also determined.

Protocols for identifying sensitive receptors were developed on Hawa Energy Pvt. Ltd, Pakistan. Visits of the whole plant area and nearby areas were conducted to identify local communities that can be affected by WTN and SF. These local communities were documented as sensitive receptors. Coordinates of these sensitive receptors were recorded using Google Maps and GPS locator. Distance of sensitive receptor/s from the nearby WTG was also recorded.

2.6. Evaluation of Shadow Flicker at Sensitive Receptor

An observation sheet was developed for recording shadow flicker effects at sensitive receptors, having details of sensitive receptors, location coordinates, date, time, and distance between WTG and receptor at different locations of 50m, 100m, 200m, and 400m, rotation per minute/round per minute (RPM of the rotor, wind direction, weather condition, status of WTG). For observing shadow flicker stand calmly in the direction of the shadow by WTG towards the sensitive receptor, a stopwatch was held and started when the shadow of a blade passed and stopped when the shadow of another blade passed again. Time was noted (reading) in seconds. The method was repeated 5 times, and observations were recorded. Minimum and maximum values were marked, and an average value was calculated. Similarly, observations were obtained at different distances of 50m, 100m, 200m, and 400m, and the RPM of the rotor was obtained from the Supervisory Control and Data Acquisition (SCADA) system. The sun's direction was noted from the direction compass, and weather conditions were observed and recorded. **Error! Reference source not found.** was used to calculate the shadow flicker at the location or receptor.

Shadow flicker in one min (in seconds) = Average flicker readings x RPM of rotor x no. of blades……………………………………………………………………………………... Equation 1

The average time of the shadow at the receptor in a day was recorded, and the shadow flicker effect as minutes or hours in a day and then in a year was calculated. If the reading at the sensitive receptor was less than 30 min/day or 30 hrs./year, it was within the permissible limit.

2.7. Evaluation of noise monitoring at sensitive receptor

For monitoring of noise at sensitive receptors, a calibrated noise meter (UT353, UNI-T) was used. The noise was monitored at specific distances (i.e., 50m, 100m, 200m, 400m) between WTG and sensitive receptors by holding a noise meter, and sound levels were recorded in decibels (dB). The method was repeated 5 times, and observations were recorded similarly to those used for shadow flicker. The minimum and maximum readings were marked, and an average value was calculated. Similarly, observations were obtained at different distances, i.e., 50m, 100m, 200m, and 400m, and wind speed was obtained from the SCADA system. The sun's direction was noted from the direction compass, and weather conditions were observed and recorded.

An observation sheet was developed for recording noise effect at sensitive receptors, having details of sensitive receptors, location coordinates, date, time, and distance between WTG and receptor at different locations (e.g., 50m, 100m, 200m, and 400m), wind speed, weather condition, status of WTG. The average noise level was checked at that receptor. If the reading at the sensitive receptor was less than 80 dB, it was within the permissible limit.

3. Results and Discussion

3.1. Shadow flicker and noise monitoring procedures development

This study proposes a convenient and systematic approach for evaluating shadow flicker and noise and the current status of noise and shadow flicker monitoring by wind farms in Pakistan. Shadow flicker and noise monitoring procedures were developed as samples for wind farms, covering the purpose, scope, responsibility, procedure, sensitive receptors, and related documents. Any wind farm can use these procedures and prepare procedures for its organization. Relevant forms of shadow flicker and noise monitoring were also developed to record observations (Tables 6 and 7). These forms have details of the receptor, location coordinates, nearest WTG, observations detail, wind speed, weather condition, WTG status, and compliance status.

3.2. Evaluation of shadow flicker and noise monitoring sample: a case study

3.2.1. Selection of sensitive receptors

Field visits were conducted in all the areas of wind farms, and communities were identified in the vicinity. The communities near the wind turbine having the probability of wind turbine effects were shortlisted. **Error! Reference source not found.** provides details of villages/communities and receptors which were identified as sensitive receptors having noise and shadow flicker effects of nearby wind turbines in the wind farm.

Table 2. List of villages/communities near sensitive receptors

S. No.	Villages/ Communities	Receptors
1	Muhammad Urs Burfat	at a distance of 746m from HEPL - WTG # 01
2	Ghulam Hussain Burfat	at a distance of 499m from HEPL - WTG # 01
3	Aijaz Ali Khaskheli	at a distance of 500m from HEPL - WTG # 16
4	Ameer Bux Khaskheli	at a distance of 261m from HEPL - WTG # 17
5	Ghulam Hussain Brohi	at a distance of 365m from HEPL - WTG # 20
6	Khan Babbar	at a distance of 373m from HEPL - WTG # 26

3.2.2. Recording coordinates of receptor and nearest WTG

Google Maps application was used to record the exact location of receptors and nearest wind turbines. For this purpose, the current location was recorded and pinned to get the location coordinates, and the detailed step was shown in Fig. 6. However, after recording the coordinates, Google Earth Pro (Version 9.189.0.0) was used for the geospatial representation of the location of a wind turbine, the sensitive receptor, and the approximate distance between them as shown in **Error! Reference source not found.**3.

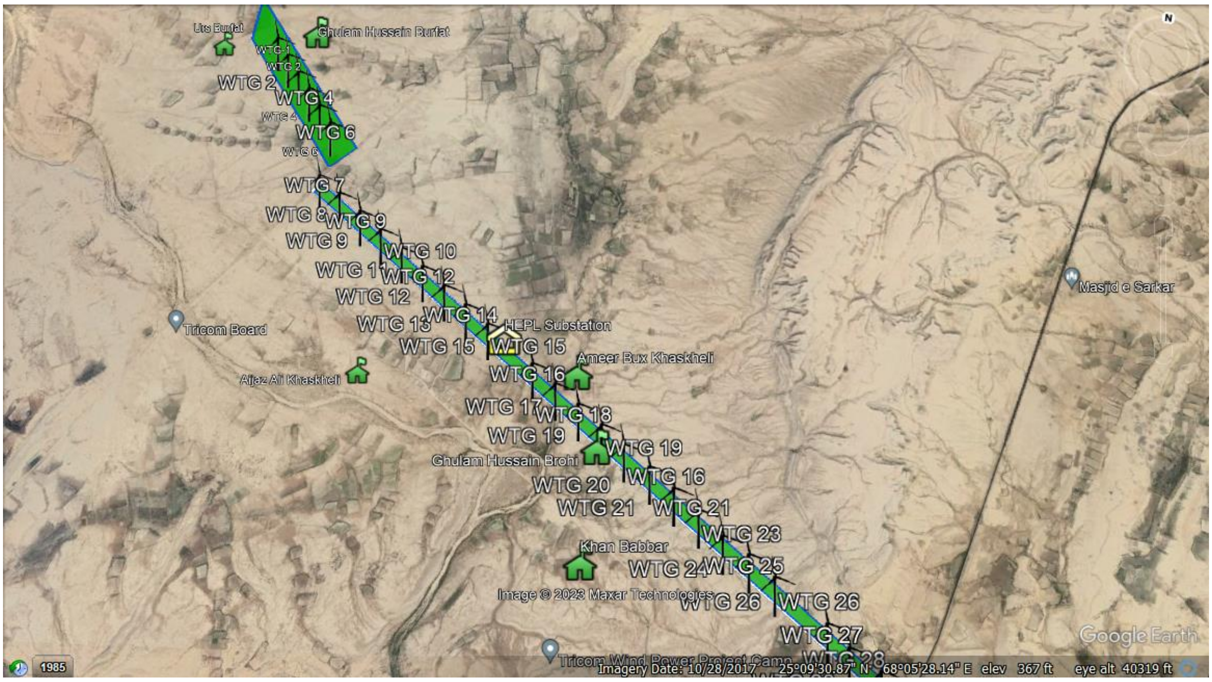


Fig.3: Coordinates plotting on Google Earth Pro for the geographical location of wind turbines.

3.2.3. Recording noise and shadow flicker

A noise meter was used to record noise levels at different distances towards sensitive receptors from the base of WTG, and readings were recorded at the specified template (Table 7). The protocols developed were used to monitor the shadow flicker and noise at the Hawa Energy wind farm. The detailed chart has been provided in the Table 6 and Fig. 6 shows the computed value for the shadow flicker based on **Error! Reference source not found.**. The results showed that at WTG-16, shadow flicking was observed only at a distance of 200m.

In comparison, no shadow flicking was observed at any WTG at a distance of 50m except at WTG-01, which receives the minimal effect, as shown in Fig. 4a. Similarly, the graphs were plotted for average noise monitoring (Fig. 4b). Through the monitoring, it was observed that the values are within permissible limits i.e., Daytime (6:00 AM to 10:00 PM): 80 decibels (dB), Nighttime (10:00 PM to 6:00 AM): 70 dB and hence no heath problems are observed in nearby sensitive receptors.

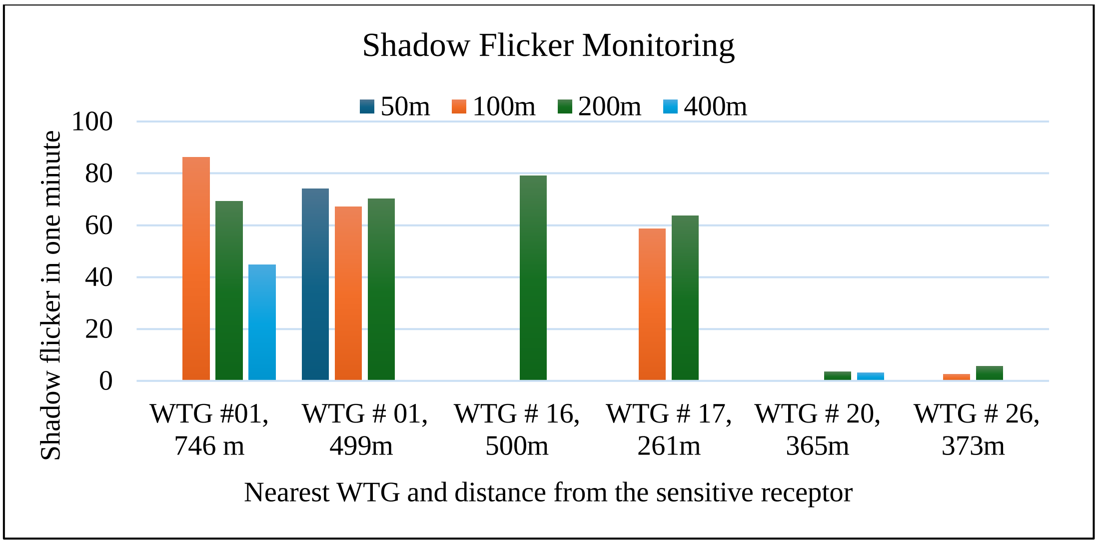


Fig. 4a: Shadow flicker monitoring status of Hawa Energy wind farm

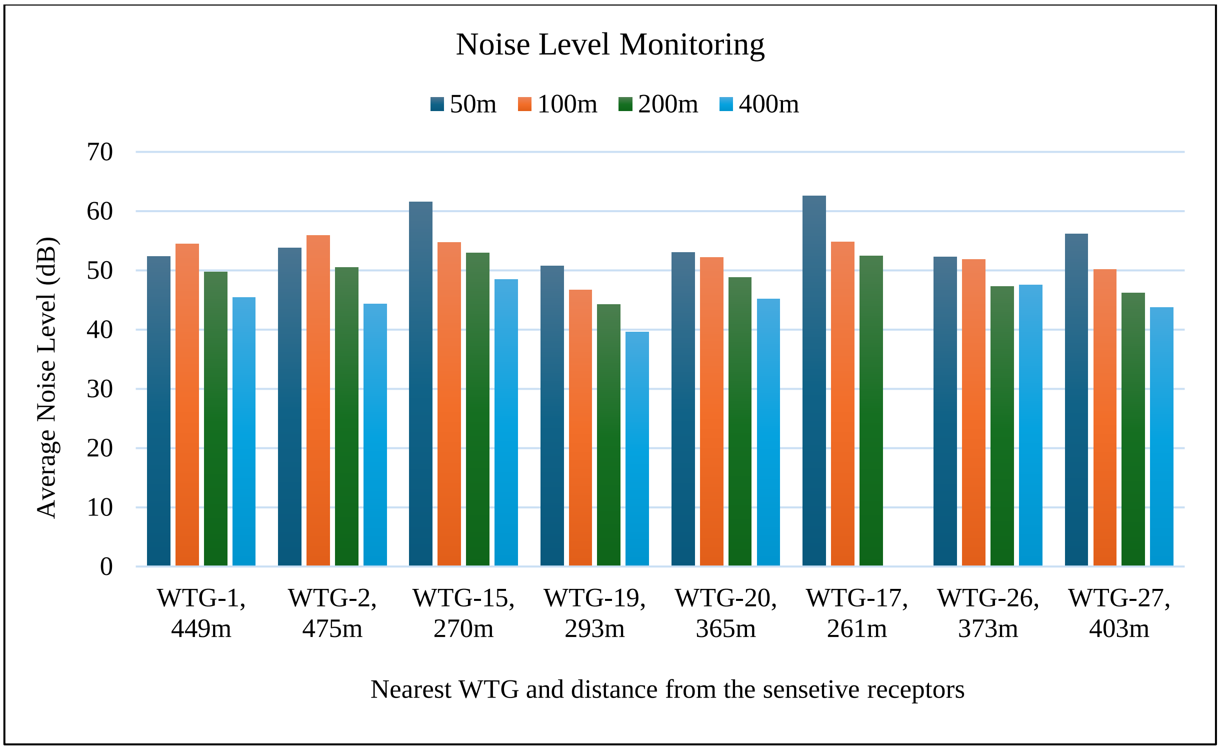


Fig.4b: Noise monitoring status of Hawa Energy wind farm.

Evaluation of shadow flicker and noise monitoring status of wind farms

Currently, 36 wind farms are operational in Pakistan. A survey form was developed and sent to the responsible concerns of wind farms for data collection. The response was received from all 36 wind farms in Pakistan (100% sample size covered). Shadow flicker and noise monitoring status of wind farms is presented in Table 3. The results from the survey (Table 3 and Table 4) show that 17 (47%) wind farms are monitoring shadow flicker and noise effects on communities, whereas the remaining 19 (52.8%) wind farms are either monitoring shadow or noise effects on the receptors.

Table 3: List of operational wind farms and their monitoring status

Wind Farm	Shadow Flicker	Noise
FFC Energy Ltd.	No	Yes
Zorlu Enerji Pakistan (Pvt.) Ltd.	Not Applicable	Yes
Three Gorges First Wind Farm Pakistan (Pvt.) Ltd.	Yes	Yes
Three Gorges Second Wind Farm Pvt. Ltd.	Yes	Yes

Three Gorges Third Wind Farm Pvt. Ltd.	Yes	Yes
Foundation Wind Energy – II Ltd.	Not Applicable	Yes
Foundation Wind Energy – I Ltd.	Not Applicable	Yes
Sapphire Wind Power Company Ltd.	Yes	Yes
Yunus Energy Ltd.	No	Yes
Metro Power Company Ltd.	Yes	Yes
Tapal Wind Energy Pvt. Ltd.	No	Yes
Tenaga Generasi Ltd.	Yes	Yes
Master Wind Energy Pvt. Ltd.	Yes	Yes
Gul Wind Energy Ltd.	Yes	Yes
Hydro China Dawood Power Pvt. Ltd.	No	Yes
Sachal Energy Development Pvt. Ltd.	Yes	Not Applicable
United Energy Pakistan Pvt. Ltd.	No	No
Hawa Energy Pvt. Ltd.	Yes	Yes
Jhampir Wind Power Ltd.	Yes	Yes
Artistic Energy Pvt. Ltd. (formerly Hartford Energy Pvt. Limited)	No	Yes
Tricon Boston Consulting Corporation Pvt. Ltd. (A)	Yes	Yes
Tricon Boston Consulting Corporation Pvt. Ltd. (B)	Yes	Yes
Tricon Boston Consulting Corporation Pvt. Ltd. (C)	Yes	Yes
Zephyr Power (Pvt.) Ltd.	Not Applicable	Yes
Master Green Energy Ltd.	Yes	Yes
Tricom Wind Power (Pvt.) Ltd.	Yes	Yes
Lakeside Energy (Pvt.) Ltd.	Yes	Yes
Artistic Wind Power (Pvt.) Ltd.	No	Yes
Liberty Wind Power 1 (Pvt.) Ltd.	No	Yes
Indus Wind Energy Ltd.	No	Yes
Act2 Wind (Pvt.) Ltd.	No	Yes
Metro Power Company Ltd. 2	Not Applicable	Yes
Liberty Wind Power 2 (Pvt.) Ltd.	No	Yes
Gul Ahmed Electric Ltd.	Not Applicable	Yes
Din Energy Ltd.	Yes	Yes
Nasda Green Energy (Pvt.) Ltd.	No	No

Results show that among the wind farms where shadow flicker was applicable and monitored, 11 out of 17 had receptors within 300m of the nearest WTG, and the shadow flicker limit of 06 wind farms was greater than 30 hours/ year (exceeding the permissible limit). As per the provided data, 5 wind farms had not taken appropriate corrective and preventive measures. The data shows that no annoyance effect has been reported by any of the receptors yet (refer to Table 4). 33 out of 36 wind farms are monitoring noise, 2 are not and not applicable on 1 wind farm. 11 wind farms had receptors within 300m from the nearest wind turbine.

The noise limit was either less than 45dB or between 46 – 80dB (within the permissible limit of NEQS). Out of 11, 6 wind farms took minimal (less than 20%) corrective and preventive actions, and there was no ill health effect reported by the receptor (Table 5).

Survey results depict (Fig.***5***5) that out of 36 wind farms, 18 (50%) wind farms were monitoring shadow flicker, 12 (33.33%) were not monitoring. It was not applicable to 06 (16.7%) wind farms. Among 36 wind farms, 33 (91.7%) wind farms were monitoring noise at the sensitive receptors, and 02 (5.6%) were not watching it. At the same time, it was not applicable to 01 (2.8%) wind farms. A few wind farms had receptors within 300m of the nearest wind turbine, while other wind farms were concerned about keeping an eye on the wind farm's area so that they could check if there was any nomadic type of community.

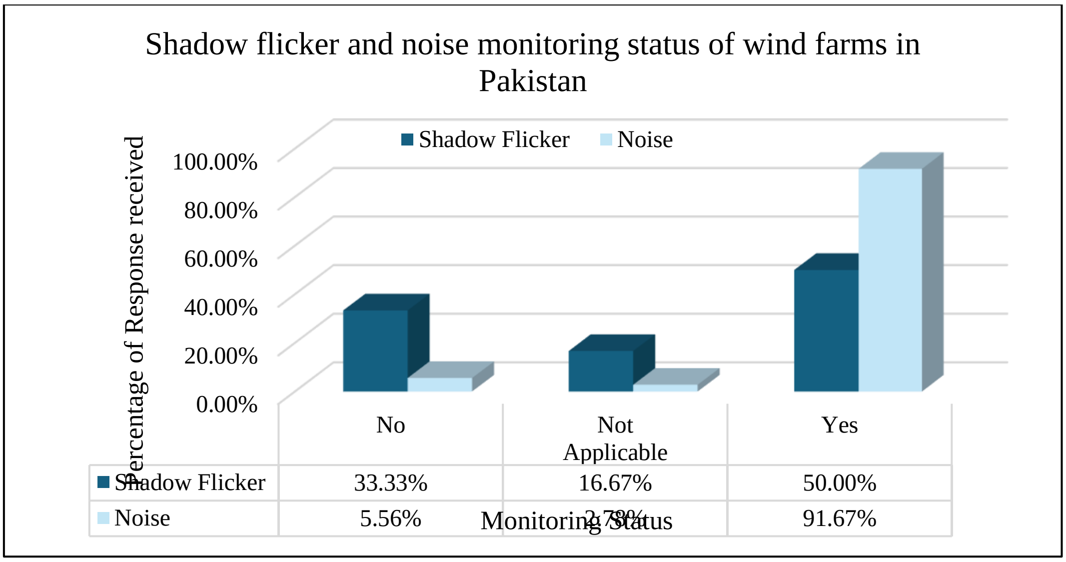


Fig.5: Shadow flicker and noise monitoring status (%) of 36 wind farms in Pakistan.

Table 4: Shadow flicker survey response of all 36 wind farms in Pakistan.

Wind farm	Q-1	Q-2	Q-3	Q-4	Q-5	Q-6	Q-7	Q-8
FFC Energy Ltd.	No	0	-	-	-	-	-	-
Zorlu Enerji Pakistan (Pvt.) Ltd.	Not Applicable	3	-	-	-	-	-	-
Three Gorges First Wind Farm Pakistan (Pvt.) Ltd.	Yes	8	Between 100 – 200 meters	Less than 30 hr/yr	Greater than 30 hr/yr	Not at all	Not at all	Very little[1]
Three Gorges Second Wind Farm Pvt. Ltd.	Yes	8	Between 100 – 200 meters	Less than 30 hr/yr	Greater than 30 hr/yr	Not at all	Not at all	Very little
Three Gorges Third Wind Farm Pvt. Ltd.	Yes	8	Between 100 – 200 meters	Less than 30 hr/yr	Greater than 30 hr/yr	Not at all	Not at all	Very little
Foundation Wind Energy – II Ltd.	Not Applicable	0	-	-	-	-	-	-
Foundation Wind Energy – I Ltd.	Not Applicable	0	-	-	-	-	-	-
Sapphire Wind Power Company Ltd.	Yes	5	Between 200 – 300 meters	Less than 30 hr/yr	Greater than 30 hr/yr	Not at all	Not at all	Very much

Yunus Energy Ltd.	No	0	-	-	-	-	-	-
Metro Power Company Ltd.	Yes	1	Between 600 – 1000 meters	Not Applicable	Not Applicable	Not at all	Not at all	Not at all
Tapal Wind Energy Pvt. Ltd.	No	0	-	-	-	-	-	-
Tenaga Generasi Ltd.	Yes	3 1	Between 0 – 50 meters	Less than 30 hr/yr	Greater than 30 hr/yr	Not at all	Not at all	Not Applicable
Master Wind Energy Pvt. Ltd.	Yes	0	Not Applicable	Not Applicable	Not Applicable	Not at all	Not at all	Not Applicable
Gul Wind Energy Ltd.	Yes	1	Between 600 – 1000 meters	Not Applicable	Not Applicable	Not at all	Not at all	Not at all
Hydro China Dawood Power Pvt. Ltd.	No	0	-	-	-	-	-	-
Sachal Energy Development Pvt. Ltd.	Yes	0	Between 500 – 600 meters	Not Applicable	Not Applicable	Not at all	Not at all	Not at all
United Energy Pakistan Pvt. Ltd.	No	0	-	-	-	-	-	-
Hawa Energy Pvt. Ltd.	Yes	6	Between 200 – 300 meters	Less than 30 hr/yr	Less than 30 hr/yr	Not at all	Not at all	Very much
Jhampir Wind Power Ltd.	Yes	6	Between 200 – 300 meters	Less than 30 hr/yr	Less than 30 hr/yr	Not at all	Not at all	Very much
Artistic Energy Pvt. Ltd. (formerly Hartford Energy Pvt. Ltd.	No	0	-	-	-	-	-	-
Tricon Boston Consulting Corporation Pvt. Ltd. (A)	Yes	3	Between 100 – 200 meters	Less than 30 hr/yr	Less than 30 hr/yr	Not at all	Not at all	Very much
Tricon Boston Consulting Corporation Pvt. Ltd. (B)	Yes	6	Between 200 – 300 meters	Less than 30 hr/yr	Less than 30 hr/yr	Not at all	Not at all	Very much
Tricon Boston Consulting Corporation Pvt. Ltd.C	Yes	6	Between 200 - 300 meters	Less than 30 hr/yr	Less than 30 hr/yr	Not at all	Not at all	Very much

Zephyr Power (Pvt.) Ltd.	Not Applicable	0	-	-	-	-	-	-
Master Green Energy Ltd.	Yes	0	Not Applicable	Not Applicable	Not Applicable	Not at all	Not at all	Not Applicable
Tricom Wind Power (Pvt.) Ltd.	Yes	0	Between 300 - 400 meters	Not Applicable	Less than 30 hr/yr	Very little	Not at all	Not at all
Lakeside Energy (Pvt.) Ltd.	Yes	0	Between 500 - 600 meters	Not Applicable	Not Applicable	Not at all	Not at all	Not Applicable
Artistic Wind Power (Pvt.) Ltd.	No	0	-	-	-	-	-	-
Liberty Wind Power 1 (Pvt.) Ltd.	No	0	-	-	-	-	-	-
Indus Wind Energy Ltd.	No	0	-	-	-	-	-	-
Act2 Wind (Pvt.) Ltd.	No	0	-	-	-	-	-	-
Metro Power Company Ltd. 2	Not Applicable	0	-	-	-	-	-	-
Liberty Wind Power 2 (Pvt.) Ltd.	No	3	-	-	-	-	-	-
Gul Ahmed Electric Ltd.	Not Applicable	0	-	-	-	-	-	-
Din Energy Ltd.	Yes	2	Between 50 - 100 meters	Greater than 30 hr/yr	Greater than 30 hr/yr	Very little	Very little	Not at all
Nasda Green Energy (Pvt.) Ltd.	No	0	-	-	-	-	-	-

Q-1: Do you monitor the shadow flicker effect of the wind turbine at sensitive receptors (communities having effects of wind turbine)? Q-2: The total number of sensitive receptors (affected communities) in your wind farm? Q-3: Minimum distance of receptor from nearest WTG. Q-4: Minimum shadow flicker reading among all receptors in hr/yr. Q-5: Maximum shadow flicker reading among all receptors in hr/yr. Q-6: Annoying effect reported by receptors Q-7: Health effect complaints received by receptors Q-8: Corrective & Preventive Measures taken by your wind farm against shadow flicker. very much refer to the satisfaction level >80%, very little <20%

Table 5: Noise monitoring survey response of all wind farms in Pakistan.

Wind farm	**Q-1**	**Q -2**	**Q-3**	**Q-4**	**Q-5**	**Q-6**	**Q-7**

FFC Energy Ltd.	Yes	0	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much[2]
Zorlu Enerji Pakistan (Pvt.) Ltd.	Yes	3	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Three Gorges First Wind Farm Pakistan (Pvt.) Ltd.	Yes	8	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Very little
Three Gorges Second Wind Farm Pvt. Ltd.	Yes	8	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Very little
Three Gorges Third Wind Farm Pvt. Ltd.	Yes	8	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Very little
Foundation Wind Energy – II Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Foundation Wind Energy – I Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Sapphire Wind Power Company Ltd.	Yes	5	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Very little
Yunus Energy Ltd.	Yes	0	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much
Metro Power Company Ltd.	Yes	1	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Tapal Wind Energy Pvt. Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not Applicable	Not Applicable	Not at all
Tenaga Generasi Ltd.	Yes	3 1	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Not Applicable
Master Wind Energy Pvt. Ltd.	Yes	0	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much
Gul Wind Energy Ltd.	Yes	1	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Hydro China Dawood Power Pvt. Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not Applicable
Sachal Energy Developm	Not Applicable	0	-	-	-	-	-

ent Pvt. Ltd.							
United Energy Pakistan Pvt. Ltd.	No	0	-	-	-	-	-
Hawa Energy Pvt. Ltd.	Yes	6	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much
Jhampir Wind Power Ltd.	Yes	6	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much
Artistic Energy Pvt. Ltd. (formerly Hartford Energy Pvt. Ltd.)	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not Applicable
Tricon Boston Consulting Corporation Pvt. Ltd. (A)	Yes	3	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Somewhat
Tricon Boston Consulting Corporation Pvt. Ltd. (B)	Yes	6	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Very much
Tricon Boston Consulting Corporation Pvt. Ltd.(C)	Yes	6	Less than or equal to 45 dB	Less than or equal to 45 dB	Not at all	Not at all	Very much
Zephyr Power (Pvt.) Ltd	Yes	0	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much
Master Green Energy Ltd.	Yes	0	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Very much
Tricom Wind Power (Pvt.) Ltd.	Yes	0	Less than or equal to 45 dB	Between 46 and 80 dB	Somewhat	Not at all	Not at all
Lakeside Energy (Pvt.) Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not Applicable
Artistic Wind Power (Pvt.) Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not Applicable
Liberty Wind Power 1 (Pvt.) Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Indus Wind Energy Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not Applicable
Act2 Wind (Pvt.) Ltd.	Yes	0	Between 46 and 80 dB	Not Applicable	Not Applicable	Not Applicable	Not at all
Metro Power Company Ltd. 2	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all

Liberty Wind Power 2 (Pvt.) Ltd.	Yes	3	Less than or equal to 45 dB	Between 46 and 80 dB	Not at all	Not at all	Somewhat
Gul Ahmed Electric Ltd.	Yes	0	Between 46 and 80 dB	Between 46 and 80 dB	Not at all	Not at all	Not at all
Din Energy Ltd.	Yes	2	Between 46 and 80 dB	Between 46 and 80 dB	Very little	Very little	Very little
Nasda Green Energy (Pvt.) Ltd.	No	0	-	-	-	-	-

Q-1:Do you monitor the noise effect of the wind turbine at sensitive receptors? Q-2: The total number of sensitive receptors (affected communities) in your wind farm? Q-3: Minimum noise (in dB) level among all receptors. Q-4: Maximum noise level among all receptors in dB. Q-5: Annoying effect reported by receptors. Q-6: Health effect complaints received by receptors. Q-7: Corrective andpreventive Measures taken by your wind farm against noise.very much refer to the satisfaction level >80%, very little <20%. Wind turbines affect the population and cause annoying effects in the susceptible population of strongly annoyed residents (SAR) during the night in their bedrooms, while the general population feels annoyed when they are directly exposed to wind turbines (Muller et al., 2023). Noise pollution from wind turbines is the most significant concern [28]–[30], followed by visibility, bird mortality, land use, and shadow flicker effect (Alphan, 2021; Peri et al., 2020; Waewsak et al., 2017; Knopper et al., 2014). Wind turbine noise not only causes mental health issues and sleep pattern disorders but impacts the quality of life as well (Freiberg et al., 2019b). Noise annoyance is considered the major and the most common problem in the wind turbine (Radun et al., 2022; Ata Teneler and Hassoy, 2021; Hansen and Hansen, 2020; Taylor et al., 2013; Katsaprakakis, 2012) and it is more annoying than other community noise sources [37]. Wind turbines also cause headaches, dizziness, nausea, fatigue, ear pressure sensation, tinnitus, and cardiovascular symptoms in people living nearby [38]. At a long distance from the wind turbine base and an approximate wind speed of 12m/s, the wind turbine noise will be equal to the background noise level [39], but wind turbine noise is considered serious when the background noise is low [40]. For derived and suggested wind turbine noise, it is set for a limit of 43 dB(A), comparable with British and Danish standards [41], and the wind turbine annoyance effect improved when variables of WTN [42] were considered. Wind turbines do not affect diabetic patients at night, and there is no significant relation between the two [43].

The shadow flicker and noise monitoring procedures developed in the study are easily accessible and downloadable by browsing the given links in this study. After making minor amendments or zero amendments, these documents can be implemented in any wind farm in the O&M phase. Out of 36, 17 (47%) wind farms in Pakistan are monitoring shadow flicker and noise effects on communities, whereas 19 (52.8%) wind farms are monitoring shadow or noise effects on the receptors. There is one major reason for insignificant reporting of annoying and ill health: few communities in wind farm areas are nomadic and do leave the area due to seasonal, cultural, and other reasons. Through a case study of Hawa Energy (Pvt.) Ltd. it was demonstrated how to evaluate noise and shadow flicker during the operational phase of a project. Results of a case study are mentioned in Tables6 and 7. One can easily understand and, by following the steps, can easily implement noise and shadow flicker monitoring in the wind farm. During the case study, there has been no annoyance or ill health effect by the wind turbine reported since the commercial date of operation (COD) of Hawa Energy Pvt. Ltd., Pakistan. There are significant gaps in the shadow flicker aspect, such that government policymakers did not develop any policy and procedure on shadow flicker standards and compliance. Though the performance standard of IFC is there, these are best practices but not the mandatory requirements. The standards established on noise by the government are not aligned with the studies available, so there is another area for improvement.

Table 6: Results of shadow flicker monitoring at Hawa Energy Pvt. Ltd.

Logo	**SHADOW FLICKER MONITORING REPORT**	Document No.	
		Revision No.	
		Issue Date	

S.No.	Sensitive Receptor Description	Location Coordinates	Nearest WTG No. and Distance	Coordinates	Distance from Source (m)	Reading Time	Shadow Flicker Readings in seconds (s)								RPM of Rotar	Shadow Flicker in one min (in seconds) (Reading*RPM	Sun Direction	Weather	Status of Turbine	Date of Reading	Permissible Limits (PL)
							1	2	3	4	5	Min	Max	Avg							
1	Muhammad Urs Burfat	25°10'33.7"N 68°00'35.8"E	HEPL - WTG #01, 746 m between receptor and WTG	25.177081N, 68.01681E	50	8:44	0	0	0	0	0	0	0	0	13.16	0.00	South East	Clear Sky	Operational	2023.4.02	Within the PL
				25.176838N, 68.016302E	100	8:49	2.21	2.17	2.21	2.14	2.18	2.14	2.21	2.18	13.16	86.15	South East	Clear Sky	Operational	2023.4.02	Within the PL
				25.176569N, 68.015355E	200	9:54	1.82	1.81	1.85	1.89	1.88	1.81	1.89	1.85	12.48	69.26	South East	Clear Sky	Operational	2023.4.02	Within the PL
				25.176471N, 68.013309E	400	8:59	1.1	1.21	1.23	1.24	1.21	1.1	1.24	1.2	12.48	44.85	South East	Clear Sky	Operational	2023.4.02	Within the PL
2	Ghulam Hussain Burfat	25°10'43.1436"N 68°01'18.9444"E	HEPL - WTG # 01, 499m between receptor and WTG	25.177348N, 68.018000E	50	16:48	1.91	1.93	1.92	1.96	1.96	1.91	1.96	1.94	12.74	73.99	North East	Clear Sky	Operational	2023.4.02	Within the PL
				25.177177N, 68.018378E	100	16:51	1.71	1.76	1.75	1.76	1.79	1.71	1.79	1.75	12.74	67.04	North East	Clear Sky	Operational	2023.4.02	Within the PL
				25.176941N, 68.019434E	200	16:57	1.81	1.84	1.88	1.83	1.82	1.81	1.88	1.84	12.74	70.17	North East	Clear Sky	Operational	2023.4.02	Within the PL

				25.177536N, 68,020058E	400	17:06	0	0	0	0	0	0	0	0	12.74	0.00	North East	Clear Sky	Operational	2023.4.02	Within the PL
3	Aijaz Ali Khaskheli	25°08'14.3"N 68°03'18.6"E	HEPL - WTG # 16, 500m between receptor and WTG	25.139991N 68.058415E	50	9:51	0	0	0	0	0	0	0	0	13.85	0.00	South East	Clear Sky	Operational	2023.4.07	Within the PL
				25.139766N 68.058031E	100	9:56	2.31	2.33	2.34	2.37	2.32	2.11	2.1	2.11	13.85	87.46	South East	Clear Sky	Operational	2023.4.07	Within the PL
				25.139243N 68.057162E	200	9:59	1.71	1.73	1.74	1.71	1.74	1.9	1.91	1.91	13.85	79.15	South East	Clear Sky	Operational	2023.4.07	Within the PL
				25.137787N 68.056080E	400	10:06	0	0	0	0	0	0	0	0	12.57	0.00	South East	Clear Sky	Operational	2023.4.07	Within the PL
4	Ameer Bux Khaskheli	25°08'23.7"N 68°03'50.2"E	HEPL - WTG # 17, 261m between receptor and WTG	25.138736N 68.062333E	50	17:01	0	0	0	0	0	0	0	0	14.57	0.00	North East	scattered clouds	Operational	2023.4.13	Within the PL
				25.139118N 68.062732E	100	17:07	1.31	1.33	1.35	1.32	1.41	1.31	1.41	1.34	14.57	58.75	North East	scattered clouds	Operational	2023.4.13	Within the PL

6	5					
Khan Babbar	Ghulam Hussain Brohi					
25°07'11.1230"N 68°05'36.7756"E	25°07'55.1"N 68°04'03.4"E					
HEPL - WTG # 26, 373m between receptor	HEPL - WTG # 20, 365m between receptor and WTG					
25.1200809N, 68.090504E	25.132706N, 68.067751E	25.132779N, 68.069103E	25.132650N, 68.069909E	25.132577N, 68.070527E	25.140868N 68.065251E	25.1396657N 68.063456E
50	400	200	100	50	400	200
17:34	10:23	10:17	10:13	10:01	17:16	17:11
1.91	1.41	1.53	0	0	0	1.51
1.92	1.42	1.56	0	0	0	1.52
1.93	1.43	1.64	0	0	0	1.53
1.92	1.43	1.55	0	0	0	1.54
1.91	1.42	1.56	0	0	0	1.52
1.91	1.54	1.62	0	0	0	1.51
1.93	1.51	1.61	0	0	0	1.54
1.92	1.53	1.61	0	0	0	1.52
0.03	0.68	0.72	0.72	0.49	13.94	13.94
0.17	3.11	3.48	0.00	0.00	0.00	63.73
South West	South East	South East	South East	South East	North East	North East
Overcast clouds	scattered clouds	scattered clouds	scattered clouds	scattered clouds	scattered clouds	scattered clouds
Operational	Operational	Operational	Operational	Operational	Operational	Operational
2023.4.18	2023.04.13	2023.04.13	2023.04.13	2023.04.13	2023.4.13	2023.4.13
Within the PL	Within the PL	Within the PL	Within the PL	Within the PL	Within the PL	Within the PL

				25.120384N, 68.090969E	100	17:41	1.81	1.82	1.81	1.8	1.88	1.8	1.88	1.82	0.47	2.57	South West	overcast cloud	Operational	2023.4.18	Within the PL
				25.120486N, 68.092626E	200	17:57	1.61	1.63	1.65	1.66	1.65	1.61	1.66	1.64	1.13	5.56	South West	overcast cloud	Operational	2023.4.18	Within the PL
				25.120167N, 68.094165E	400	18:03	0	0	0	0	0	0	0	0	0	0.00	South West	overcast cloud	Operational	2023.4.18	Within the PL

Table 7: Results of noise monitoring at Hawa Energy Pvt. Ltd.

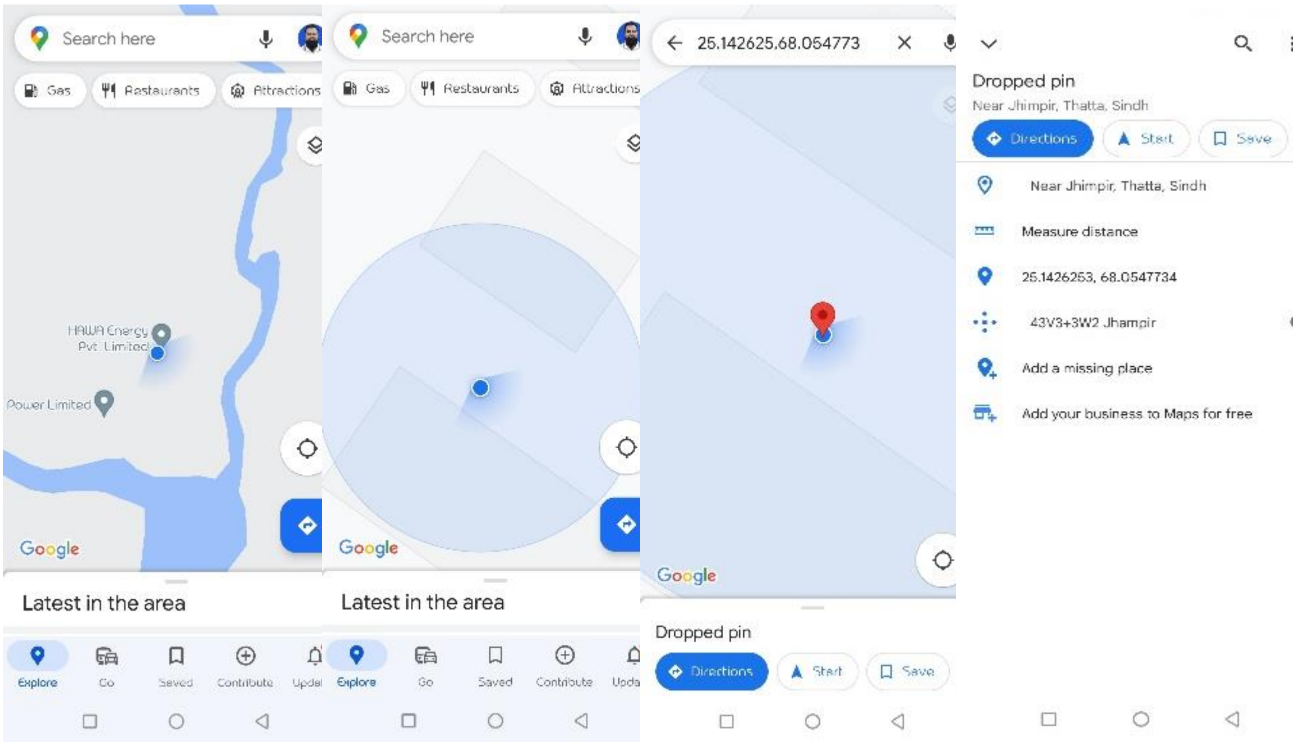
Logo				NOISE MONITORING REPORT														Document No.		
																		Revision No.		
																		Issue Date		
S.No.	**Sensitive Receptor Description**	**Location Coordinates**	**Nearest WTG No. and Di...**	**Distance from Source (in m)**	**Coordinates**	**Reading Time**	**Noise Level Recording in DB**								**Wind Speed**	**Temp in *C**	**Weather**	**Status of Turbine**	**Date of Reading**	**Permissible Limits (PL)**
							1	2	3	4	5	Min	Max	Avg						
1	Ghulam Hussain Burfat - HEPL	25°10'43.1436"N 68°01'18.9444"E	WTG-1, 499m	50	25.177348N,	16:45	52.3	53.1	51.9	52.7	52.6	51.9	52.70	52.4	10.39	30.5	Clear Sky	Operational	02.4.2023	Within the PL
				100	25.177177N,	16:50	54	54.6	54.8	54.3	54.6	54	54.80	54.5	10.39	30.5	Clear Sky	Operational	02.4.2023	Within the PL
				200	25.176941N,	16:54	50.1	49.9	49.6	49.8	49.3	49.3	50.10	49.7	10.55	30.39	Clear Sky	Operational	02.4.2023	Within the PL

				400	25.177536N,	16:59	46.1	44.8	45.7	45.7	44.9	44.8	46.10	45.4	10.55	30.39	Clear Sky	Operational	02.4.2023	Within the PL
2	Ghulam Hussain Burfat - HEPL	25°10'43.1436"N 68°01'18.9444"E	WTG-2, 475m	50	25.1755981N,	9:43	54.3	54.7	53.6	54.8	51.6	51.6	54.80	53.8	7.45	27.09	Clear Sky	Operational	02.4.2023	Within the PL
				100	25.176090N,	10:46	55.6	56.4	55.6	55.8	55.9	55.6	56.40	55.9	7.45	27.09	Clear Sky	Operational	02.4.2023	Within the PL
				200	25.176941N,	10:52	50.1	49.8	50.7	50.7	51.3	49.8	51.30	50.5	7.98	27.54	Clear Sky	Operational	02.4.2023	Within the PL
				400	25.177536N,	10:58	44.1	44.5	44.6	44.8	444	44.1	443.50	124	7.98	27.54	Clear Sky	Operational	02.4.2023	Within the PL
3	HEPL Accommodation	25°08'33.2"N 68°03'16.3"E	WTG-15, 270m	50	25.144590N,	10:35	62.4	61.3	62.6	61.5	60	60	62.60	61.6	2.69	31.06	Clear Sky	Operational	04.4.2023	Within the PL
				100	25.144267N,	10:39	55.1	54.5	55	54.3	54.6	54.3	55.10	54.7	2.69	31.06	Clear Sky	Operational	04.4.2023	Within the PL
				200	25.143938N,	10:44	53	53	52	53.5	53.1	52	53.50	52.9	3.31	31.02	Clear Sky	Operational	04.4.2023	Within the PL
				400	25.142614N,	10:49	49.3	48.4	47.6	48.8	48.3	47.6	49.30	48.5	3.31	31.02	Clear Sky	Operational	04.4.2023	Within the PL

4	Ghulam Hussain Brohi-HEPL	25°07'55.1"N 68°04'03.4"E	WTG-19, 293m	50	25.134124N,	10:10	51	50.1	50.8	50.4	51.4	50.1	51.40	50.7	7.5	30.61	Clear Sky	Operational	07.4.2023	Within the PL
				100	25.133804N,	10:14	45	46.2	46.7	47.5	48.2	45	48.20	46.7	7.5	30.61	Clear Sky	Operational	07.4.2023	Within the PL
				200	25.133108N,	10:19	43.4	43.7	44.8	46.2	43	43	46.20	44.2	7.5	30.61	Clear Sky	Operational	07.4.2023	Within the PL
				400	25.132706N,	10:25	38.6	40.3	39.4	40	39.5	38.6	40.30	39.6	6.32	31.24	Clear Sky	Operational	07.4.2023	Within the PL
5	Ghulam Hussain Brohi-HEPL	25°07'55.1"N 68°04'03.4"E	WTG-20, 365m	50	25.132577N,	9:51	53	53.5	54.1	51.6	52.9	51.6	54.10	53	4.91	27.44	broken clouds	Operational	11.4.2023	Within the PL
				100	25.132650N,	9:55	49	52	54	53.1	52.9	49	54.00	52.2	4.91	27.44	broken clouds	Operational	11.4.2023	Within the PL
				200	25.132779N,	9:59	48	49	48	50	49	48	50.00	48.8	4.91	27.44	broken clouds	Operational	11.4.2023	Within the PL
				400	25.132706N,	10:06	44.1	44.4	44.7	45.9	46.8	44.1	46.80	45.2	4.09	27.94	broken clouds	Operational	11.4.2023	Within the PL
6	Ameer Bux Khaskheli - HEPL	25°08'23.7"N 68°03'50.2"E	WTG-17, 261m	50	25.138789N, 68.062402E	17:48	62	63	62.4	63.8	61.5	61.5	63.80	62.5	10.41	35.63	scattered clouds	Operational	13.4.2023	Within the PL

				100	25.138528N, 68.062670E	17:52	53.7	55.8	55	54.7	54.7	53.7	55.80	54.8	8.09	35.47	scattered clouds	Operational	13.4.2023	Within the PL
				200	25.139019N, 68.063498E	17:56	51.1	53	55	53	50.2	50.2	55.00	52.5	8.09	35.47	scattered clouds	Operational	13.4.2023	Within the PL
				400	25.139888N, 68.063882E	18:01	0	0	0	0	0	0	0.00	0	7.72	35.42	scattered clouds	Operational	13.4.2023	Within the PL
7	Khan Babbar - HEPL	25°07'11.1230"N 68°05'36.7756"E	WTG-26, 373m	50	25.1200809N, 68.090504E	10:30	53.2	54.1	52.1	49.1	53	49.1	54.10	52.3	8.25	35.04	overcast cloud	Operational	18.4.2023	Within the PL
				100	25.120384N, 68.090969E	10:33	50.2	52	53.1	52	52	50.2	53.10	51.9	8.25	35.04	overcast cloud	Operational	18.4.2023	Within the PL
				200	25.120486N, 68.092626E	10:39	48	47	47.1	47.5	46.9	46.9	48.00	47.3	8.25	35.04	overcast cloud	Operational	18.4.2023	Within the PL
				400	25.120167N, 68.09465E	10:44	47.1	50.3	47.4	46	47.1	46	50.30	47.6	8.51	35.08	overcast cloud	Operational	18.4.2023	Within the PL

8	Khan Babbar - HEPL	25°07'11.1230"N 68°05'36.7756"E	WTG-27, 403m	50	25.117891N, 68.096329E	10:51	55.2	56.1	57.8	57.2	54.3	54.3	57.80	56.1	9.61	35.06	overcast cloud	Operational	18.4.2023	Within the PL
				100	25.118389N,	10:55	53.1	56	47.3	46.5	48	46.5	56.00	50.2	9.61	35.06	overcast cloud	Operational	18.4.2023	Within the PL
				200	25.119331N,	10:59	46.4	47.1	46.4	45	45.9	45	47.10	46.2	9.61	35.06	overcast cloud	Operational	18.4.2023	Within the PL
				400	25.120167N, 68.094165E	11:07	43	39	42.1	42.4	52	39	52.00	43.7	9.11	35.13	overcast cloud	Operational	18.4.2023	Within the PL



(a) (b) (c) (d)

Fig. 6: Steps for recording coordinates of receptor and nearest WTG. (a) Google Map user Interface, (b) Check current location location, (c) Pin the current location, and (d) Location Coordinates.

Conclusion

The wind energy industry is growing so rapidly that till 2020, only 24 wind farms were operational, and now in 2023, 36 wind farms are operating in the region (Pakistan). In a very short period of three years, 12 more wind farms were installed and producing about 600MW. The O&M phase is the longest phase among the phases of wind turbines, so it is crucial to consider the safe operational activities and impact of wind turbines on societies. Wind turbines have noise and shadow flicker effects on the receptors. The government of Pakistan has a standard for noise but not for the shadow flicker effect of wind turbines, so this study was conducted to develop procedures for monitoring noise and shadow flicker effects. A survey was also conducted to check the status of noise and shadow flicker evaluation by the wind farms. In Pakistan, out of 36, only 17 wind farms are monitoring wind turbines' noise and shadow flicker effect on societies. The procedures developed in this study can be used in any wind farm in the world to evaluate noise and shadow flicker effects. They can be useful for the wind energy farms which are increasing in the world to overcome the energy crises.

Authors contribution

Waqar Hussain and Sadia Khan conceptualized the idea. Waqar Hussain, Minza Mumtaz, and Alan N. Cochran collected, compiled, and analyzed the data. Waqar Hussain, Minza Mumtaz, and Sadia Khan wrote the paper, Sana Ullah Memon, Muhammad Sharique Ahmed, Rahul Kumar, and Muhammad Shahid supported in the collection and analysis of the data. All authors reviewed the manuscript.

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Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in this article.

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