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How do Residents Experience Wind Turbine Noise? The Results of a Two-Year Study

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Summary

Noise from wind turbines is often a significant concern for nearby residents. To better understand the actual impact of wind turbine noise, an interactive app was utilized across several wind projects, allowing residents to easily report their real-time experiences with turbine noise.

One such project involves 26 wind turbines in the Netherlands, grouped into three geographically separated clusters, spread over a 26-kilometre stretch along a busy motorway. For two years, starting from the turbines' initial operation, residents could report noise-related annoyance on a 7-point scale at any time, day or night. For this project, high annoyance - defined as the top two levels on a 7-point annoyance scale - was most frequently reported during wind speeds of 8 to 13 m/s at hub height, at distances of less than 1,000 metres from the turbines, and when the wind blew towards the motorway, reducing background noise and making the turbines more noticeable. Also, high annoyance was most frequently reported during the late evening and at the start and end of the night, highlighting the influence of quieter periods on perceived annoyance.

The annoyance patterns observed for the 26-turbine project were compared with data from other wind farms where the app was implemented, offering a broader perspective. This comparison revealed significant variability in annoyance patterns across different wind farms. Although no clear seasonal trend was identified, over two years, four out of six wind farms using the interactive app showed above-average high annoyance levels in April, August, and September. The lack of a seasonal trend underscores the complexity of annoyance, which is shaped by factors such as weather, environmental conditions, and turbine operations rather than predictable seasonal patterns. These factors vary per location, emphasizing the importance of site-specific analysis.

Daily annoyance patterns were more consistent across wind farms than monthly patterns. Most wind farms showed peaks in high annoyance levels between 9 p.m. and 1 a.m., as well as between 7 a.m. and 8 a.m., corresponding to the end of the evening and the start and end of the night. While some reports submitted at the end of the night may reflect delayed responses to earlier annoyance, the findings suggest that annoyance intensifies during quieter periods when background noise is reduced.

Overall, the results highlight the importance of accounting for time-dependent factors and local environmental conditions when developing noise mitigation strategies for wind farms. Understanding the interaction between turbine noise, background noise, and specific conditions is crucial to minimize annoyance for nearby residents.

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1. Introduction

Noise from wind turbines is often a significant concern for nearby residents. Residents feel uncertain about what to expect and worry about the potential impact on their living environment. Involving residents in the siting process and maintaining clear communication from developers and authorities can help provide clarity and alleviate some of these concerns [1] [2]. However, the day-to-day effects of wind turbine noise remain uncertain, as they are heavily influenced by changing weather conditions. Adding to the concerns is that noise issues of operating wind farms are not always adequately addressed. The variability in both the level and character of wind turbine noise, driven by atmospheric conditions, can make it difficult for operators to fully recognize and address these concerns.

An interactive app has been developed to address both acoustic and non-acoustic factors influencing how people experience wind turbine noise [3]. This app provides residents near wind turbines a hyper-local 48-hour forecast of wind turbine noise and shadow flicker. It also estimates the perceptibility of wind turbine noise, factoring in masking effects from ambient noise like traffic or rustling leaves. Next to these forecasts, the app provides a local weather forecast, wind force and wind direction at hub height, energy production estimates, historical production data, avoided CO₂ emissions, and news updates about the wind farm and related developments. By providing transparency into wind turbine operations, the app builds trust, enhances social acceptance and strengthens the relation between residents and developers.

The app also enables residents to anonymously report, 24/7, how they experience the sound (on a 7-point scale) and shadow flicker (on a 5-point scale) of the wind turbines. This feature provides a sense of control and helps reduce irritation. With user consent, the feedback is linked to location, date and time, forecast data, weather conditions, and turbine conditions, enabling detailed analysis. Resident feedback is essential for monitoring the actual impact of the wind turbines and provides valuable insights into how weather, environmental factors, and turbine conditions affect that impact. This deeper understanding supports the development of more effective noise management strategies and communication efforts. In addition to addressing non-acoustic factors such as transparency and providing a sense of control, the app also addresses acoustic factors by continuously monitoring and optimizing the effectiveness of mitigation measures.

The noise forecast app has been applied in a variety of projects. For several projects already for over two years. For some projects detailed results may not be shared in this stage. This paper focuses on one specific project, Energie A16, where the results have already been made public. This project involves 26 wind turbines grouped into three geographically separated clusters, spanning a 26-kilometre stretch along a busy motorway. Over a two-year period, starting from the turbines' initial operation, residents were given the opportunity to report annoyance by noise on a 7-point scale at any time, day or night. They could also report annoyance by shadow flicker on a 5-point scale. Additionally, this paper briefly revisits another case study for which interim results were previously presented by Koppen et al. [3], providing a summary of findings over an extended period. The patterns in annoyance levels for the Energie A16 project are also compared with findings from other wind farms where the app has been applied, providing a broader context for understanding these trends.

2. Energie A16 wind project - A two-year study

2.1 The Project

The Energie A16 project is a collaborative initiative aimed at generating clean energy along the A16 motorway in West-Brabant, in the Netherlands. The project involves 26 wind turbines situated between the Moerdijk Bridge and the Belgian border, organized into three geographically separated clusters. A total of eight developers have contributed to the initiative [4]. The turbines include seven Nordex N149-4.5 MW, eleven Nordex N149-5.7 MW, and eight Vestas V150-4.3 MW models, all with a hub height of 135 metres. An overview of the turbine locations and the surrounding environment is shown in Figure 1.

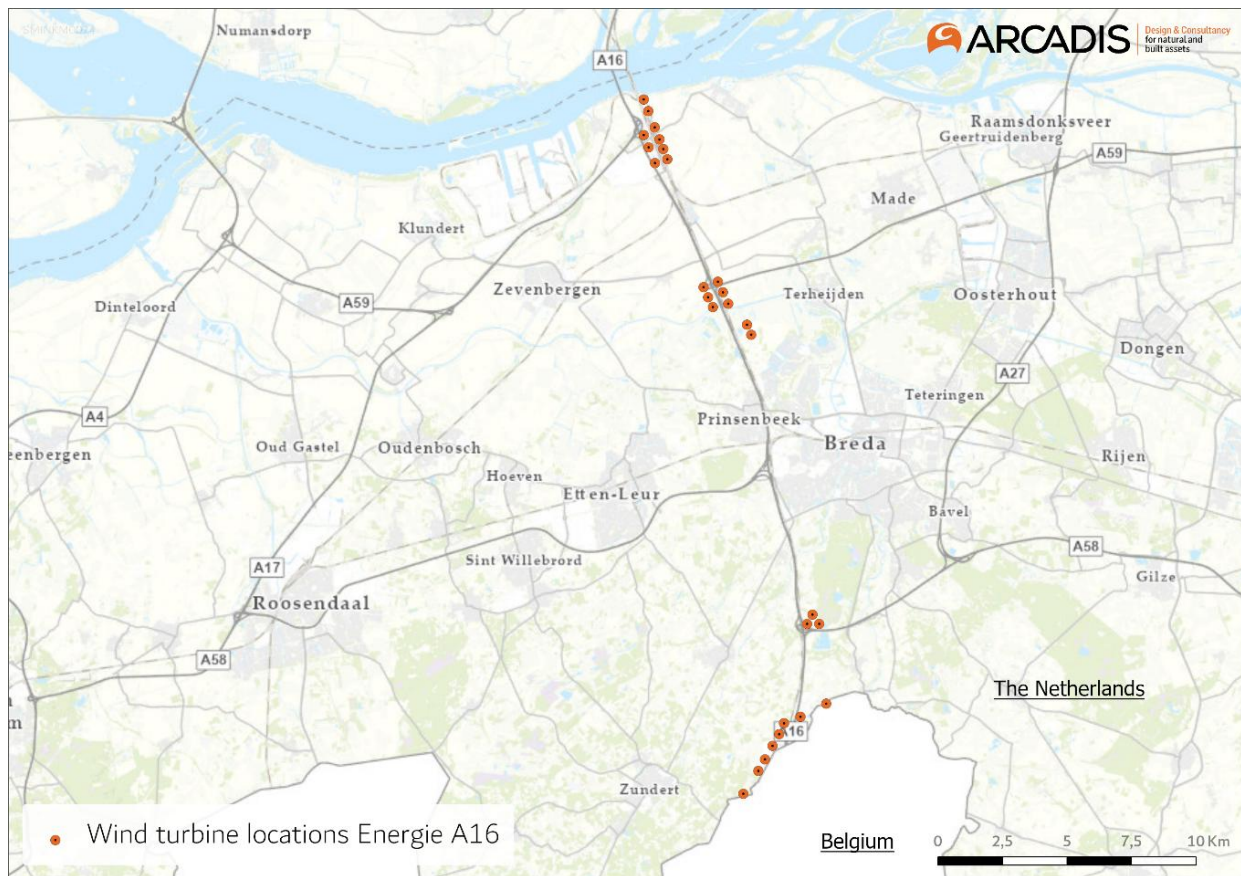


Figure 1 Overview of turbines and surrounding environment Energie A16 project.

The project aims to accelerate the energy transition by leveraging wind energy and fostering community engagement. Key aspects of the project include:

- Community involvement: Residents, organizations, developers, and governments work together to produce sustainable energy.
- Investment in local projects: A quarter of the revenue from the wind turbines is reinvested in local energy projects focused on energy saving and clean energy production.
- Support for residents: Special arrangements are made for residents living near the wind turbines, including access to tools like the interactive noise forecast app.

When, in 2016, initial discussions about the project began, many residents were already experiencing noise pollution from the nearby high-speed rail and the A16 motorway. This led to concerns about additional noise from wind turbines. The project team decided to assess the cumulative noise impact, combining expected wind turbine noise with existing noise sources, to provide a clearer picture of overall noise levels. As the wind farm plans became more detailed, noise concerns dominated discussions during public meetings and consultations with residents. Noise was a decisive factor in finalizing the plan. Residents insisted on noise monitoring once the turbines were operational, rather than relying solely on theoretical models. This commitment was made by the project team. The Environmental Service of Central and West Brabant conducted baseline measurements at 10 locations and conducted new noise measurements after the turbines started operations [5]. The post-construction measurements have not been published yet.

Besides noise measurements the province Noord-Brabant decided to apply the noise forecast app to enhance transparency and to monitor the actual impact of the turbines on the residents. The app enables residents to easily share how they experience the sound and shadow flicker of the turbines. The feedback from the residents, combined with the measurement data, provides a comprehensive understanding of the noise situation. The province committed to taking residents' concerns seriously and addressing possible issues.

2.2 Deployment area app and communication efforts

The app was made available to all residents within a radius of 2.1 km of the wind farm, which is ten times the tip height of the wind turbines. This encompassed approximately 6,900 residential addresses: 900 in the northern cluster, 5,000 in the middle cluster, and 1,000 in the southern cluster. Figure 2 illustrates the locations of the turbines and residential addresses.

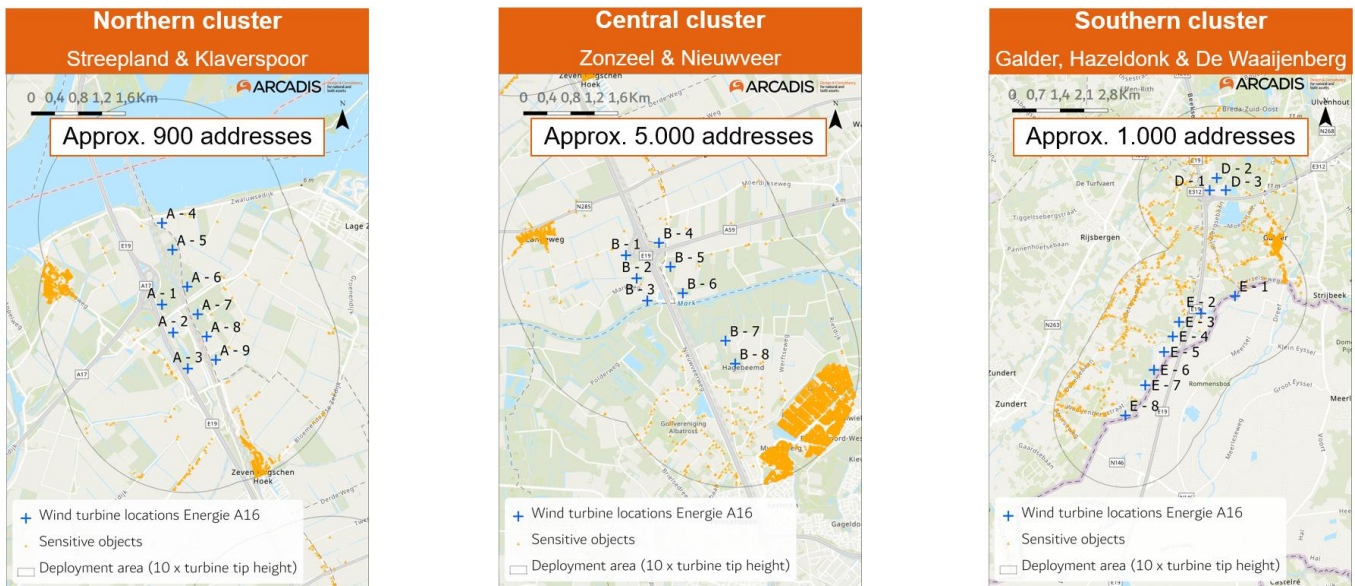


Figure 2 Deployment area noise forecast app Energie A16 project.

All residents received a letter informing them about the app and inviting them to a webinar. Additionally, information was disseminated through the Energie A16 website and a regional newspaper article. Resident feedback was regularly analysed. In 2023, results were shared through monthly reports with infographics. A sample excerpt, in Dutch, is shown in Figure 3. In 2024, an annual report for 2023 was initially published, followed by quarterly reports with infographics [6]. In 2025, a comprehensive report for 2024 was released. These reports were made available through news items in the app and on the Energie A16 website [7].

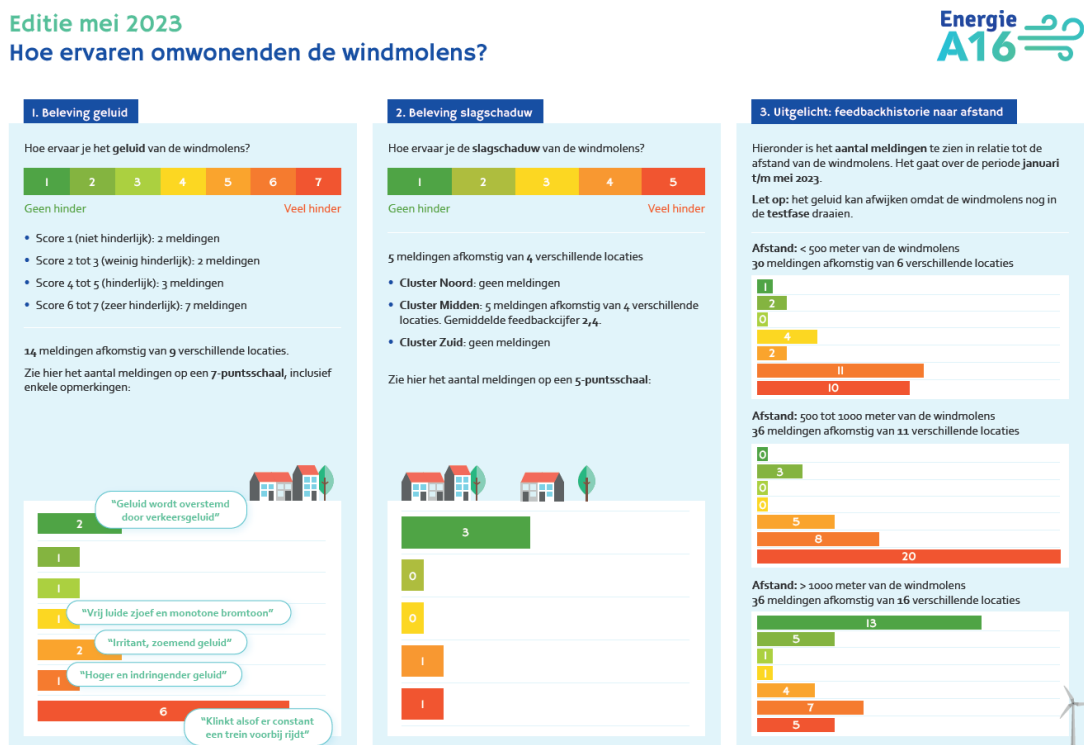


Figure 3 Sample excerpt from a monthly infographic report for residents in the Netherlands (written in Dutch). This excerpt describes the reported annoyance levels for noise and shadow flicker for May 2023, and shows how these annoyance levels vary with distance.

2.3 Users of the app and overview feedback locations

The app was launched in May 2022 to provide residents with updates on the construction activities of the wind turbines. Between May and December 2022, a total of 736 unique users accessed the app. The wind turbines became operational around January 2023. In 2023, the app had 723 unique users. In 2024, this number decreased to 305. Over the entire deployment period, the app was used by a total of 1,359 unique users. This represents 20% of the total residential addresses within a 2.1 km radius of the wind turbines². In 2023, when the turbines were operational, this percentage was 10%, and in 2024, it decreased to 4%. For comparison, in other wind farms where the app was deployed, this percentage ranges from approximately 10% to 30%. In general, when residents feel more annoyed, they use the app more frequently and the number of users increases.

The monthly number of unique users is illustrated in Figure 4, which highlights a peak of 385 users in March 2023 when a webinar on the app was held. Following this peak, user numbers gradually declined, eventually stabilizing at around 50 users per month during the second half of 2024.

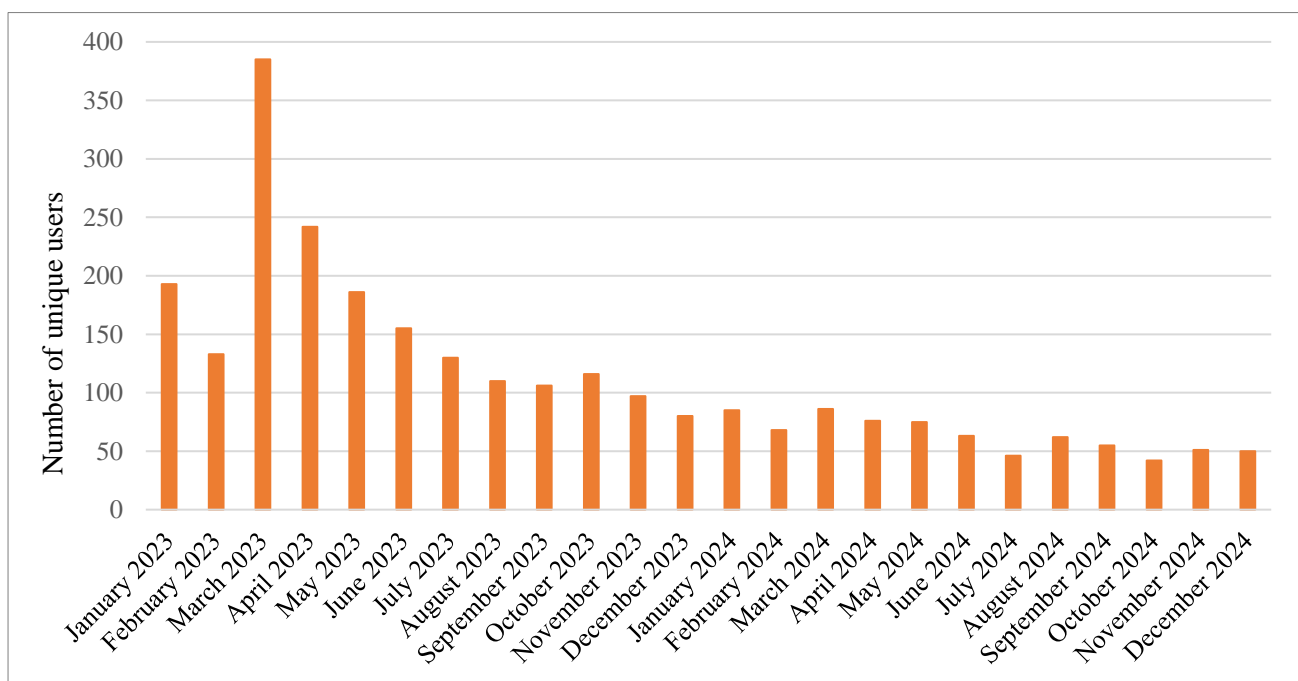


Figure 4 Monthly number of unique users Energie A16 project.

The users are quite evenly distributed across the settlements near the Energie A16 turbines, as shown in Figure 5. A significant portion of the users, 43%, reside in Breda. This is not surprising, as several residential neighbourhoods in northwest Breda fall within the influence area of the turbines located in the central cluster.

² The 2.1 km radius of the wind turbines is equivalent to ten times the turbine tip height and is considered the influential area of the wind turbines

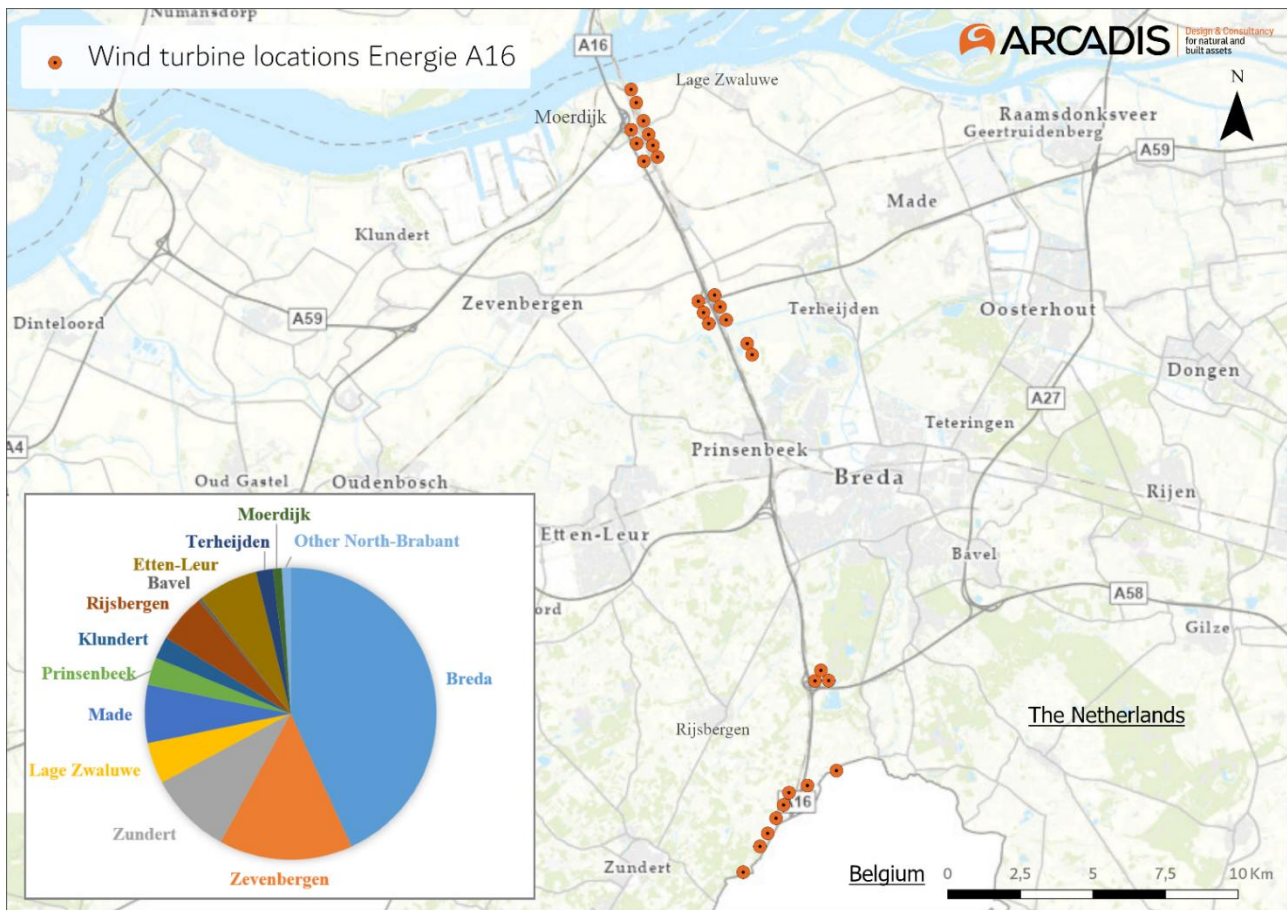


Figure 5 User distribution across various settlements near the Energie A16 turbines.

Figure 6 illustrates the distribution of residents who shared feedback on their experience with turbine noise, grouped by postal code. The visualization indicates that the residents providing feedback were evenly distributed across the area near the Energie A16 turbines.

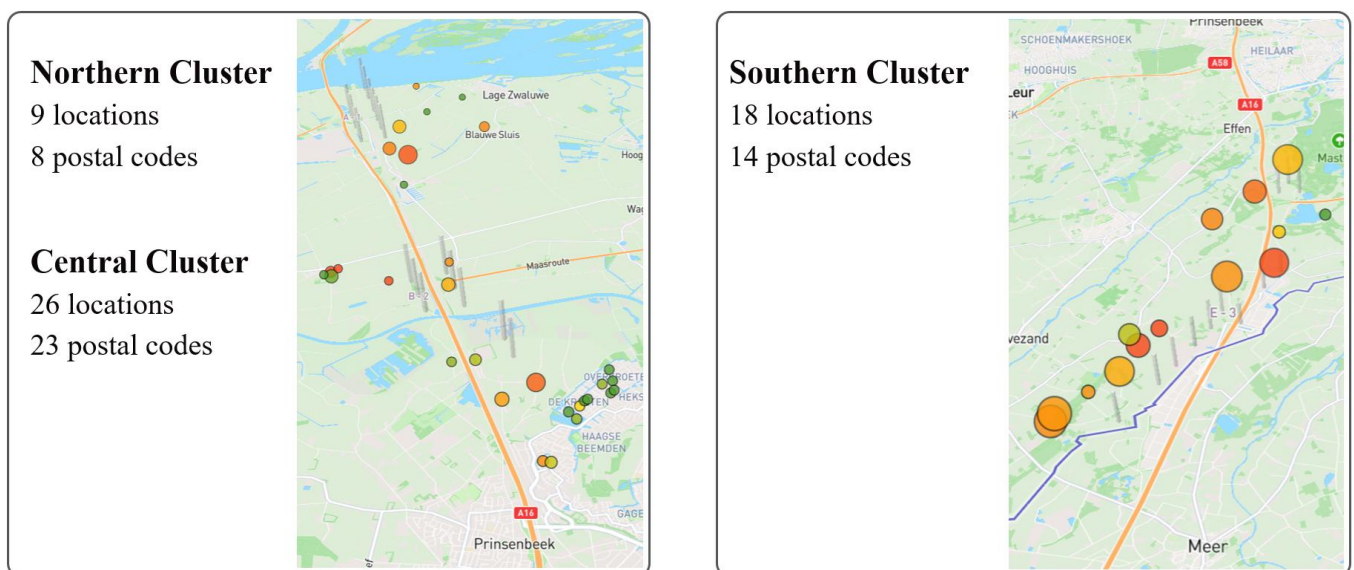


Figure 6 Distribution of residents near the Energie A16 turbines who provided feedback on their experience with turbine noise, grouped by postal code. Larger circles represent a higher number of responses, while darker shades of red indicate more negative feedback.

2.4 How do the residents experience wind turbine noise?

2.4.1 Number of feedback responses and annoyance ratings

Figure 7 presents the number of feedback responses and annoyance ratings on a 7-point scale. Over a two-year period, residents from 53 distinct locations submitted a total of 460 feedback responses. This means that 0.8% of residences located within a 2.1 km radius³ have submitted feedback at least once. For the northern cluster, it was 1% (9 locations); for the central cluster, 0.5% (26 locations); and for the southern cluster, 1.8% (18 locations). For reference, for other wind projects where the app was used, this percentage ranged from approximately 2% to 20%. This suggests that, for the Energie A16 project, both the number of residents using the app and the number of residents providing feedback are relatively low compared to other wind projects, despite the extensive and frequent communication efforts regarding the wind project and the app.

Other wind projects have demonstrated a strong correlation between the frequency of app usage, the number of submissions, and the level of annoyance reported by residents. Typically, the more annoyed residents feel, the more actively they engage with the app. This trend is also observed in the Energie A16 project when analysing the number of residences that have submitted feedback at least once, categorized by their distance from the wind farm. Within the project area, 16.4% of the 55 residences located less than 500 metres from the wind farm provided feedback at least once. For the 196 residences situated between 500 and 1000 metres, this figure was 10.2%, while only 0.4% of the 6,694 residences located between 1 and 2.1 kilometres from the turbines submitted feedback. The feedback percentages for residences within 1000 metres of the wind turbines align more closely with results from other projects where the app was used. The relatively low rate of feedback submission overall can largely be attributed to the fact that 96.4% of all residences within a 2.1-kilometre radius are located at least 1000 metres away from the wind turbines.

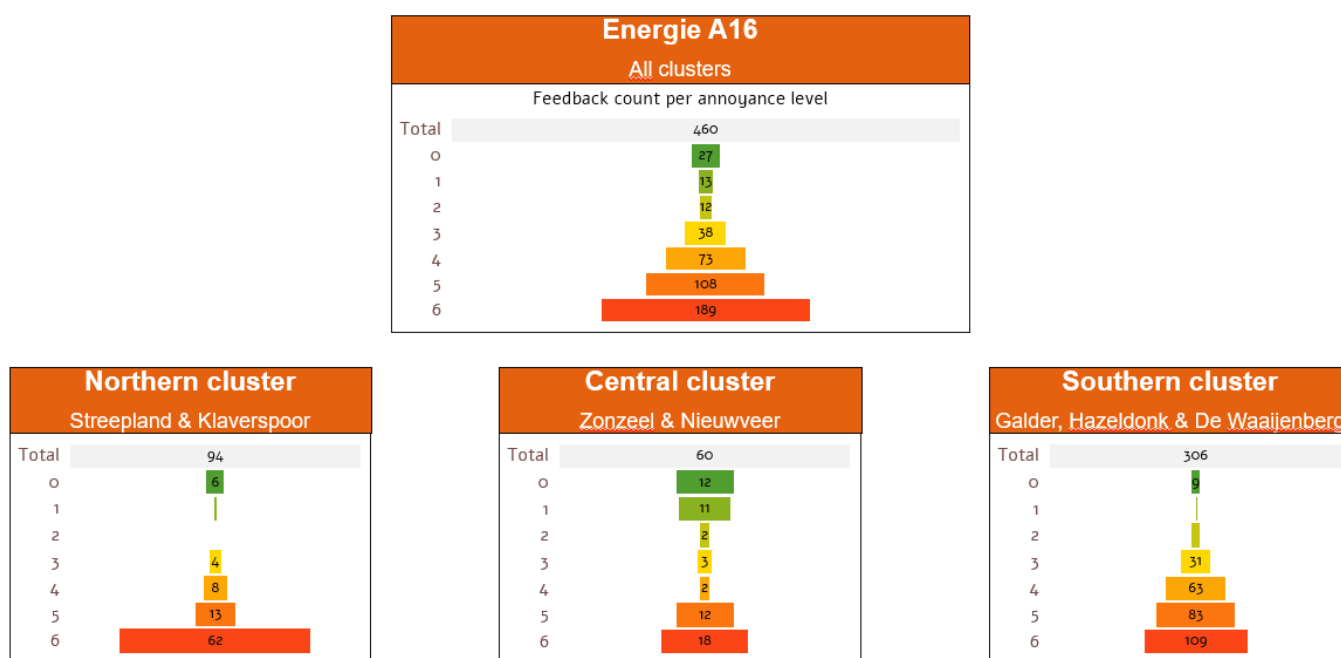


Figure 7 Number of feedback responses and annoyance ratings on a 7-point scale.

Among the feedback responses, high annoyance ratings - defined as the top two levels on a 7-point annoyance scale - were reported by residents from 31 distinct locations, while residents from 22 locations who did provide feedback never reported high annoyance. It is important to note that annoyed residents are generally more likely to provide feedback compared to those who are not annoyed, which is a typical

³ This radius, based on ten times the turbine tip height, reflects Dutch case law, which assumes that beyond this distance, no significant effects are anticipated.

human behaviour. Consequently, the 58.4% of app users reporting high annoyance cannot be considered representative of the percentage of residents within the turbines' influence area who experience high annoyance.

A more accurate estimate of the percentage of the population experiencing high annoyance can be derived from the proportion of residents who submitted high annoyance feedback at least once, compared to the total number of residential addresses within 2.1 km of the turbines. Overall, this percentage is 0.4% (31 out of 6,945 addresses). For specific turbine clusters, the percentages are as follows: 0.7% for the northern cluster, 0.2% for the central cluster, and 1.6% for the southern cluster. This indicates that the southern cluster had the highest number of annoyance reports, both in absolute terms and relative to the number of residents.

2.4.2 Monthly feedback responses and annoyance ratings

Figure 8 displays the monthly number of feedback responses and annoyance ratings on a 7-point scale for the Energie A16 project, with the blue line representing the number of distinct locations providing feedback. The figure demonstrates that the trend in the number of feedback submissions closely corresponds to the trend in the number of feedback locations. However, the figure highlights notable differences between the clusters.

For the northern cluster, the highest levels of annoyance were reported in April and June 2023, followed by a significant decrease, with a slight increase again in September and October 2024. In the central cluster, most annoyance was reported in April 2023, after which it declined steadily, with feedback ceasing entirely from September 2024 onward. In contrast, the southern cluster saw the highest levels of annoyance between July 2023 and January 2024, which later decreased, followed by an increase in April 2024 and again between August and October 2024.



Figure 8 Monthly number of feedback responses and annoyance ratings for the total Energie A16 project, the northern, central and southern clusters. The blue line indicates the number of distinct locations providing feedback.

2.4.3 Feedback responses and annoyance ratings by hour of the day

Figure 9 displays the number of feedback responses and annoyance ratings for the Energie A16 project by hour of the day, with the blue line representing the number of distinct locations providing feedback. This

figure shows that most annoyance was reported during the late evening and at the start and end of the night. The figure demonstrates that again the trend in the number of feedback submissions closely aligns with the trend in the number of feedback locations. As presented by Koppen et al. [3] in 2023, an analysis of feedback - taking into account factors such as time, location, distance from turbines, forecasted sound levels, turbine Scada data, and field sound measurements - suggests that residents generally provide honest responses. There is no evidence of intentional negative manipulation significantly affecting the overall results. Feedback generally appears logical, showing a clear correlation with input from other residents, identifiable trends, and comparisons with measured sound levels and the sound spectrum.

Figure 9 highlights notable differences between the clusters. In the northern cluster, the highest levels of annoyance were reported during the late evening and at the start of the night, with less prominent levels in the early morning. In the central cluster, most annoyance occurred during the evening and at the end of the night. Overall, annoyance was most frequently reported around the times when residents go to sleep or wake up. It must be noted that the annoyance reported at the end of the night might, in part, be attributed to delayed responses from residents who experienced annoyance during the night. In contrast, the southern cluster experienced the highest levels of annoyance between 7 a.m. and 12 p.m., with surprisingly lower levels of annoyance reported between midnight and 7 a.m.



Figure 9 Number of feedback responses and annoyance ratings for the total Energie A16 project, northern, central and southern clusters by hour of the day. Each time label represents the hour starting at the specified time.

2.4.4 Feedback responses and annoyance ratings by wind direction sector

The feedback from residents has also been categorized by wind direction sector. The left graph of Figure 10 displays the wind rose for the period between January 2023 and December 2024. The wind rose illustrates the percentage of time specific wind directions and wind speeds occurred. The graph shows that the prevailing wind direction is southwest. The right graph presents the feedback rose, which indicates the wind direction at the time feedback was submitted along with the corresponding annoyance rating. A comparison of these graphs shows that annoyance occurs relatively more frequently during northeastern to eastern wind directions.

Figure 11 presents the feedback rose for the northern, central, and southern clusters separately. The feedback rose for the northern cluster shows that most nuisance was reported for northeastern to eastern wind directions, while - for the same period - the prevailing wind direction was southwest. Figure 6 indicates that all feedback for this cluster was submitted by residents located east of the A16 motorway and south to west of the wind turbines. This indicates that most nuisance was experienced when the wind was blowing towards the A16 motorway and, to some extent, towards the wind turbines. This suggests that background noise plays an important role in how residents perceive the sound of the wind turbines. When the wind blows towards the A16 motorway, background noise levels are relatively low, and most annoyance is reported. Conversely, when the wind blows from the motorway towards the residents, background noise levels are relatively high, and fewer instances of nuisance are reported.

The feedback rose for the central cluster presents a more mixed picture. While most nuisance was reported for a south-southeastern wind direction, a relatively high level of nuisance was also reported for eastern to northeastern wind directions, though less prominently than in the northern cluster. Figure 6 shows that feedback was submitted by residents located both east and west of the A16 motorway, as well as from multiple sides of the wind turbines.

The feedback rose for the southern cluster shows that most nuisance was reported for southwestern wind directions and, to a much lesser extent, for northeastern wind directions, while the prevailing wind direction was southwest. Figure 6 indicates that most feedback was submitted by residents living west of the A16 motorway, though a substantial number of annoyance reports were also received from residents living east of the motorway. Most residents submitting feedback live west of the wind turbines, but also some live north of the turbines. Similar to the northern cluster, this suggests that most annoyance was experienced when the wind was blowing towards the A16 motorway and less when the wind was blowing from the motorway towards the residents. Once again, this highlights the role of background noise caused by the motorway in how residents perceive the sound of the wind turbines.

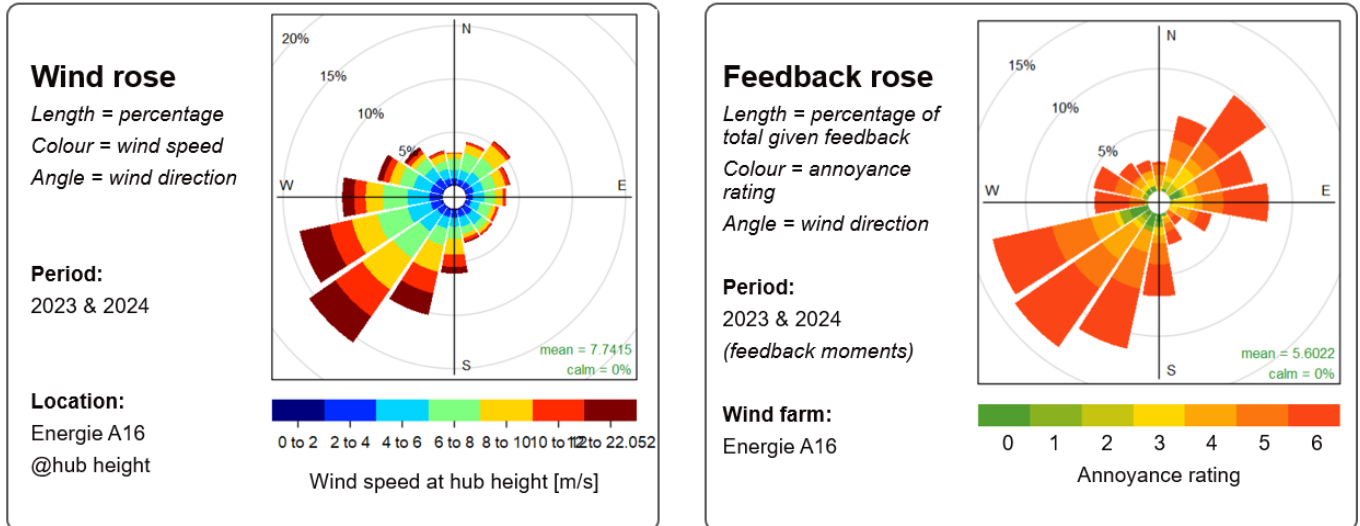


Figure 10 Wind rose for the 2023–2024 period (left graph) and the number of feedback responses and annoyance ratings for the Energie A16 project categorized by wind direction sector (right graph).

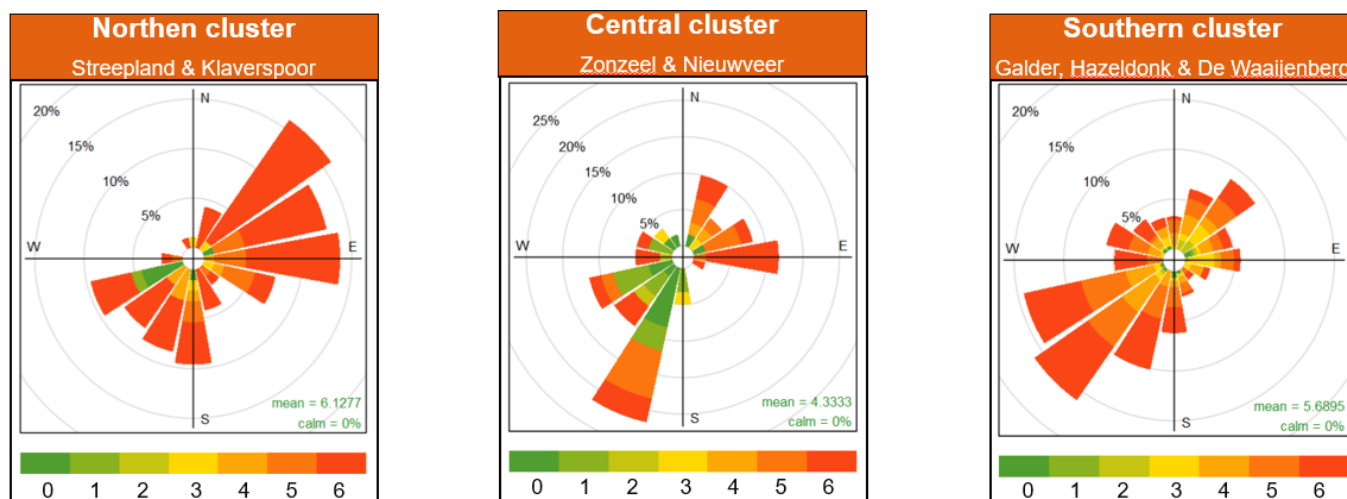


Figure 11 Number of feedback responses and annoyance ratings for the northern, central, and southern clusters categorized by wind direction sector.

2.4.5 Feedback responses and annoyance ratings by distance to the turbines

The feedback from residents has been grouped into three distance categories based on their proximity to the wind turbines. Figure 12 illustrates that for the northern cluster, residents living within 500 to 1000 meters of the wind farm most frequently reported high annoyance by the sound of the wind turbines. This feedback originated from two locations. For distances less than 500 metres or greater than 1000 metres, feedback was received from three and four locations respectively, but it was significantly less frequent compared to the 500 to 1000 metre distance category. In relation to the total number of residential addresses within the northern cluster, 11.5% of the 26 addresses located less than 500 metres from the wind farm reported high annoyance, 8.0% of the 25 addresses at a distance of 500 to 1000 metres, and 0.1% of the 864 addresses at a distance of 1 to 2.1 kilometres.

Similarly, Figure 12 shows that for the central cluster, the highest number of nuisance reports came from residents living 500 to 1000 metres away from the wind turbines, followed by those residing within 500 metres. Feedback for these distances was submitted from five and four locations respectively. When considering the proportion of residences at these distances from the wind farm, the percentage of residents reporting nuisance was highest among those living less than 500 metres away. Residents living more than 1000 metres from the wind farm submitted the most feedback overall. However, most of these reports indicated no or only slight levels of annoyance. In relation to the total number of residential addresses within the central cluster, 20.0% of the 20 addresses located less than 500 metres from the wind farm reported high annoyance, 4.2% of the 48 addresses at a distance of 500 to 1000 metres, and 0.1% of the 4,937 addresses at a distance of 1 to 2.1 kilometres.

For the southern cluster, most nuisance reports were submitted by residents living 500 to 1000 metres from the wind farms, originating from 13 different locations. Residents at a distance of less than 500 metres also reported nuisance frequently, with feedback coming from two locations. At distances greater than 1000 metres, nuisance reports were submitted by residents from three locations, but these reports were less frequent compared to those from residents living within 1000 metres of the wind farm. In relation to the total number of residential addresses within the southern cluster, 22.2% of the 9 addresses located less than 500 metres from the wind farm reported high annoyance, 9.8% of the 123 addresses at a distance of 500 to 1000 metres, and 0.2% of the 893 addresses at a distance of 1 to 2.1 kilometres.

Overall, the highest number of nuisance reports came from residents living 500 to 1000 metres away from the wind turbines. In relation to the total number of residential addresses within the Energie A16 project area, 16.4% of addresses situated less than 500 metres from the wind farm reported high levels of annoyance. This figure was 8.2% for addresses located 500 to 1000 metres away and 0.1% for those at a distance of 1 to 2.1 kilometres from the turbines.

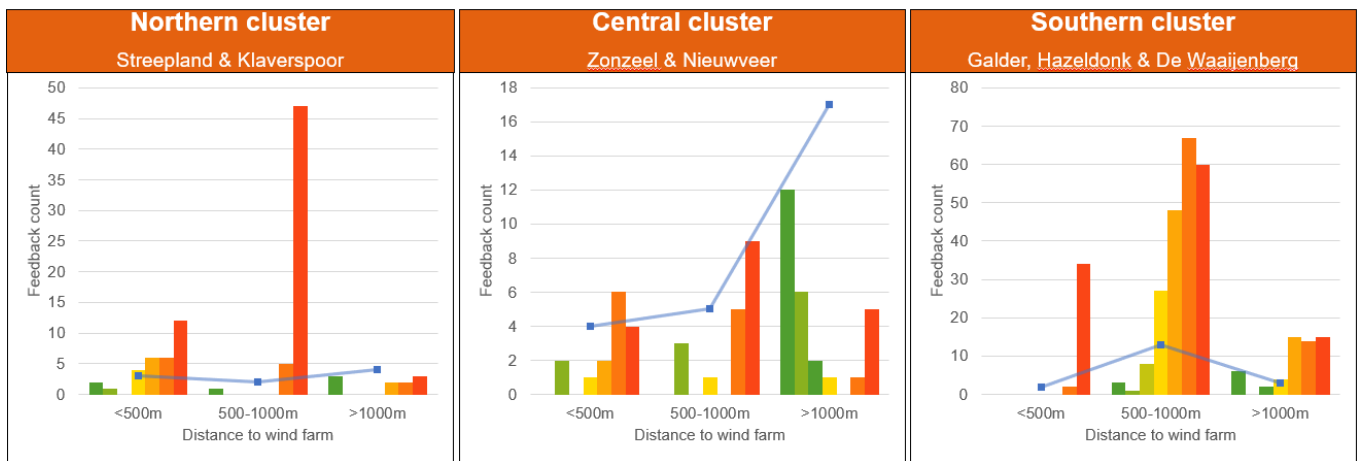


Figure 12 Number of feedback responses and annoyance ratings for the northern, central, and southern clusters as a function of the distance to the wind farm. The blue line indicates the number of distinct locations providing feedback.

2.4.6 Feedback responses and annoyance ratings by wind speed bins

Figure 13 presents the number of feedback responses and annoyance ratings categorized by wind speed bins. The dots represent the percentage of feedback received within specific wind speed bins, while the color of the dots reflects the average annoyance rating. Darker shades of red indicate more negative average annoyance ratings. The grey line in the graph represents the average wind speed distribution at hub height.

The data shows that relatively more nuisance is reported at higher wind speeds (greater than 8 m/s at hub height), while relatively less nuisance is reported at lower wind speeds (less than 8 m/s). This observation is consistent with expectations since the Vestas turbines of the Energie A16 project reach their maximum noise production at a wind speed of 9 m/s at hub height. The Nordex turbines reach their maximum noise production at 11 m/s, though at 9 m/s their noise output is only 1.1 to 1.6 dB(A) below maximum. From a wind speed of 13 m/s, the feedback distribution aligns more closely with the wind distribution. At these wind speeds, wind turbine noise will be partially masked by wind-induced background noise. A notable exception is observed in the results at a wind speed of 16.5 m/s.

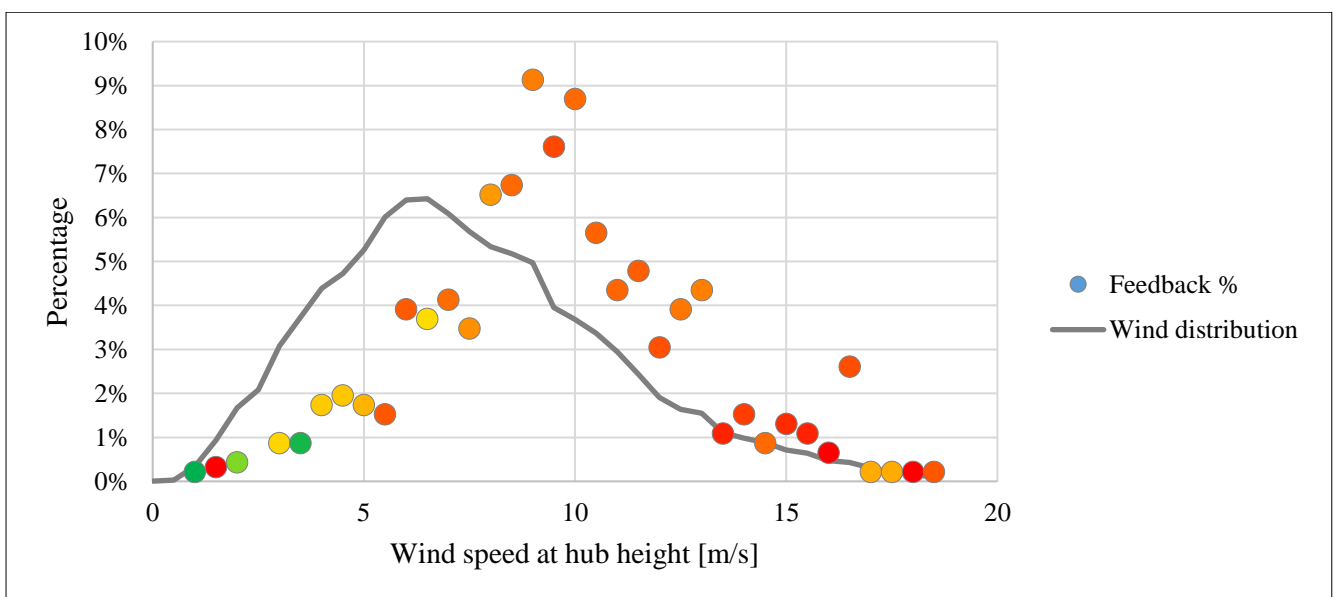


Figure 13 Number of feedback responses and annoyance ratings for the Energie A16 project categorized by wind speed class at hub height. The dots represent the percentage of feedback received within specific wind speed bins, while the colour of the dots reflects the average annoyance rating. The grey line represents the average wind speed distribution at hub height.

2.5 Characterizations of the wind turbine sound by residents

When submitting feedback about their experience with the sound of wind turbines, residents could also include comments describing their observations. A number of these comments refer to the aerodynamic noise emissions of the turbines and amplitude modulation.

Residents have described the sound of wind turbines using terms such as “loud whooshing sound,” “pulsating whooshing sound,” “rotating sound,” “thumping sound,” “scooping sound,” and “whoosh sound.” Other comments refer to sounds emitted by the drive train of the wind turbines, including descriptions like “low humming”, “buzzing sound”, “airplanes that seem to hover in the air”, and “intermittent humming sound.” These observations often point to low-frequency sounds, possibly with a tonal character.

Additional feedback compares the sound of wind turbines to background noise from the nearby motorway, with comments such as “almost no traffic and a rhythmic intermittent humming tone”, “distinct scooping sound because the motorway makes less noise”, and “a lot of noise during evening hours when there is less traffic on the A16”

Some residents also noted how wind turbine sound varies depending on wind direction and background noise, providing comments such as “audible indoors with an eastern wind, even though the house is east of the turbines”, “normally completely silent with eastern wind, but now sounds like a large fan”, and “more noise due to strong northeastern wind”.

These comments align with the findings described in Chapter 2.4.4. They demonstrate that background noise plays a significant role in how residents experience the sound of wind turbines. The comments related to wind direction are all from residents living east of the A16 motorway. It is unlikely that the reported annoyance is caused by higher wind turbine sound levels. Instead, it is more likely that residents are able to hear the wind turbines more clearly because the noise levels from the motorway are significantly reduced when the wind blows toward the motorway. The presence of the nearby motorway means that background noise near the residences is highly dependent on wind direction.

2.6 Conclusions Energie A16 wind project

This study provides valuable insights into the impact of wind turbine noise on nearby residents. Despite extensive and frequent communication efforts, the proportion of residents actively providing feedback about the wind turbines remains relatively low compared to other wind farm projects, with only 0.8% of addresses within a 2.1-kilometre radius submitting feedback. However, the results show that residents using the app for information and feedback are evenly distributed across settlements near the Energie A16 turbines. The relatively low rate of feedback submission is largely explained by the fact that 96.4% of all residences within a 2.1-kilometre radius are located at least 1000 metres from the wind turbines. When feedback is categorized by proximity to the turbines, clear patterns emerge. Within the project area, 16.4% of the 55 residences less than 500 metres from the wind farm submitted feedback at least once. Among 196 residences located 500 to 1000 metres away, the figure was 10.2%, while only 0.4% of the 6,694 residences between 1 and 2.1 kilometres submitted feedback. Feedback rates for residences within 1000 metres of the turbines are consistent with findings from other projects using the app.

High annoyance was reported by 0.4% of all residential addresses within 2.1 kilometres of the Energie A16 wind turbines. In general, residents are more inclined to provide feedback when they experience high levels of annoyance. While the overall number of affected residents is limited, certain conditions lead to severe annoyance for some, particularly those living close to the turbines or near the southern cluster of turbines. Within the Energie A16 project area, 16.4% of 55 residential addresses situated less than 500 metres from the wind farm reported high levels of annoyance at least once. This drops to 8.2% among 196 addresses located 500 to 1,000 metres away, and to 0.1% among 6,694 addresses situated 1 to 2.1 kilometres from the turbines. For addresses within 500 metres of the turbines, the percentage reporting high annoyance levels is nearly twice as high in the central and southern clusters compared to the northern cluster. The results suggest that background noise, primarily caused by the A16 motorway and heavily impacted by wind direction, plays a key role. The findings indicate that when the wind blows from the motorway toward nearby residences, the background noise often masks the sound of the wind turbines.

Over time, there was a noticeable decline in the number of reported annoyances for the northern and central clusters, but annoyance reports increased for the southern cluster. This suggests that annoyance levels are dynamic and influenced by factors such as weather conditions, environmental circumstances, and turbine operations.

The analysis highlights specific conditions under which severe annoyance is reported. The analysis indicates that the noise impact of the wind turbines is partially dependent on wind direction and the level of background noise. Most annoyance was reported:

- At the end of the evening, and the start and end of the night.
- During wind speeds between approximately 8 and 13 m/s at hub height.
- In the northern cluster during eastern and northeastern winds, and in the southern cluster during southwestern winds. In these instances, the wind blows toward the A16 motorway, reducing background noise and making the turbines more audible.
- At distances of less than 1,000 metres from the wind farm.

These findings underscore the importance of considering wind direction-dependent background noise when assessing the impact of wind turbine noise on nearby residents. While the number of reports remains limited overall, the feedback highlights specific circumstances under which annoyance is most likely to occur. This information provides valuable insights for improving future planning and implementing effective mitigation strategies.

3. Wind farm Oude Maas

In 2023, Koppen et al. [3] presented the results of applying the app to the Oude Maas wind farm in the Netherlands, using data collected until April 2023. Since then, the app has continued to monitor the impact of the wind turbines for nearly two more years. The results from the entire monitoring period are summarized below. Residents living near the Oude Maas wind farm in the Netherlands have been using the noise forecast app since March 2022. The wind farm, situated in an agricultural area along the Oude Maas river, consists of five Nordex N131-3.6 MW wind turbines with a hub height of 120 meters. The turbines became operational on July 12, 2022. Residents raised concerns about the noise impact of the turbines and requested noise measurements. In response, the municipalities of Barendrecht and Hoeksche Waard chose to use the interactive noise forecast app as an alternative method to monitor the turbines' impact.

The closest residences are 550 to 650 metres from the wind farm, with a total of 4,196 residences within a 2-kilometre radius. Residents were invited to use the app, and feedback was regularly analysed and shared. Koppen et al. [3] presented that from July 2022 to April 2023, the app had an average of 416 users per month, with 260 feedback responses regarding noise and 17 regarding shadow flicker. Most feedback indicated no annoyance. Since April 2023 the project continued to monitor and report results. The number of users gradually decreased until stabilizing at around 60 to 80 users from July 2024, two years after the wind turbines began operation. Between April 2023 and March 2025, a total of 142 feedback responses regarding noise were submitted from 28 distinct locations. High annoyance (nuisance levels 5 to 6) was reported 16 times (11%) from 4 distinct locations (14%). No annoyance (nuisance level 0) was reported 112 times (79%) from 16 distinct locations (57%). Between July 12, 2024, and March 2025, more than two and a half years after the turbines began operating, high annoyance was reported only three times by a single location.

Figure 14 illustrates the monthly number of feedback responses per nuisance level. Figure 15 shows the monthly number of unique locations that submitted feedback per nuisance level. In total, 402 feedback responses were submitted by 88 distinct locations. Of these, 290 responses (72%) indicated no annoyance, while 38 responses (9%) from 17 distinct locations (19%) indicated high annoyance (nuisance levels 5-6). Most of the negative feedback was received during the first five months of operation.

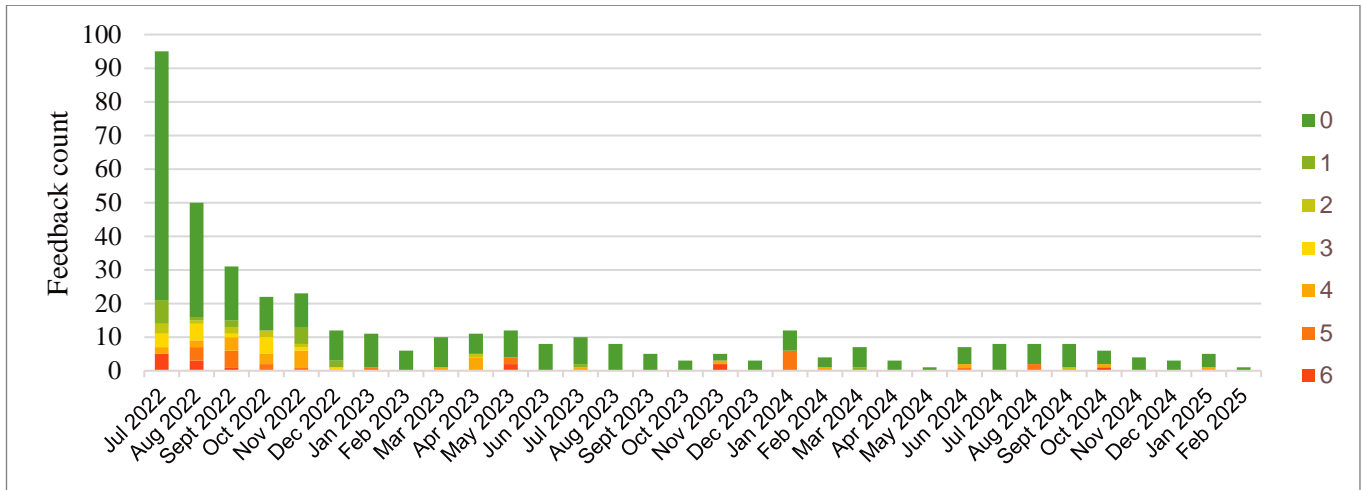


Figure 14 Number of feedback responses per nuisance level, per month.

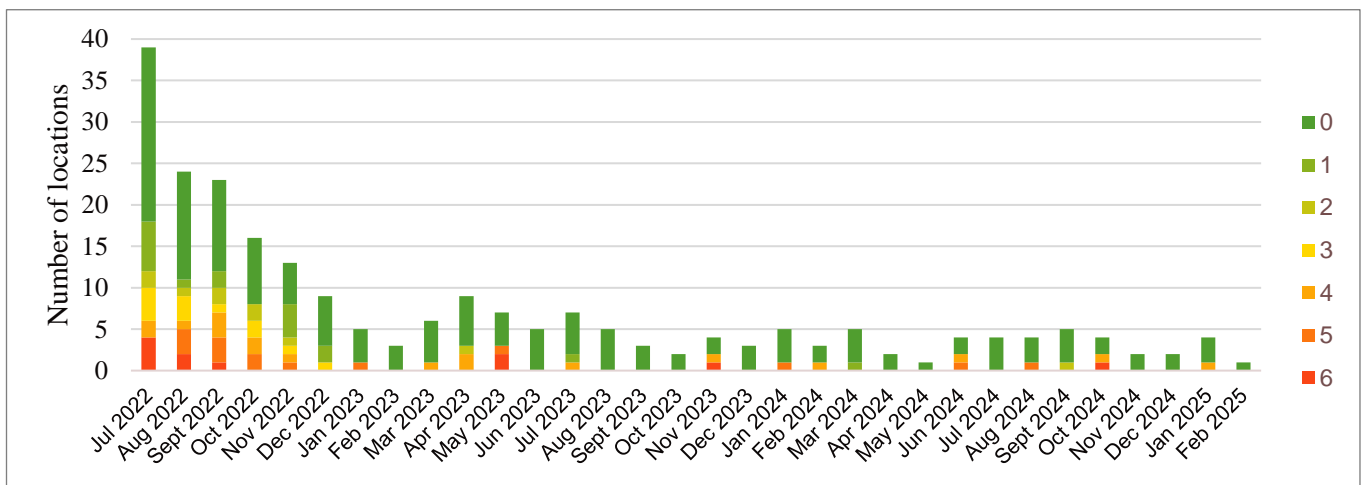


Figure 15 Number of locations submitting feedback per nuisance level, per month.

4. Pattern in annoyance levels compared to other projects

4.1 Monthly variation in high annoyance levels

The monthly number of feedback responses and annoyance ratings on a 7-point scale across the entire Energie A16 project and its three clusters - north (A), central (B), and south (C), - have been presented in chapter 2.4.2. Based on this data, the relative amounts of reported high annoyance levels by month over a two-year period were derived for these clusters. High annoyance levels are defined as the top two ratings on a 7-point annoyance scale. The results are presented in Figure 16. Additionally, a similar analysis was conducted for three other wind projects where the app was used for at least a two-year period. The results for these projects, labelled as D, E, and F, are also shown in Figure 16. While the analysis for these projects also covers exactly two years, the start and end dates of this period differ for two of the projects compared to the Energie A16 project.

Figure 16 shows that the pattern of high annoyance varies between wind farms. The data does not reveal a clear seasonal trend. However, it does show that, for four out of six wind farms, high annoyance levels are above average in April, August, and September. The absence of a seasonal trend is not surprising, as the underlying data reveal that the conditions leading to high annoyance are influenced by factors such as prevailing background noise, wind direction, and wind speed. The specific wind directions and wind speeds that lead to the highest levels of annoyance differ for each wind farm and location.

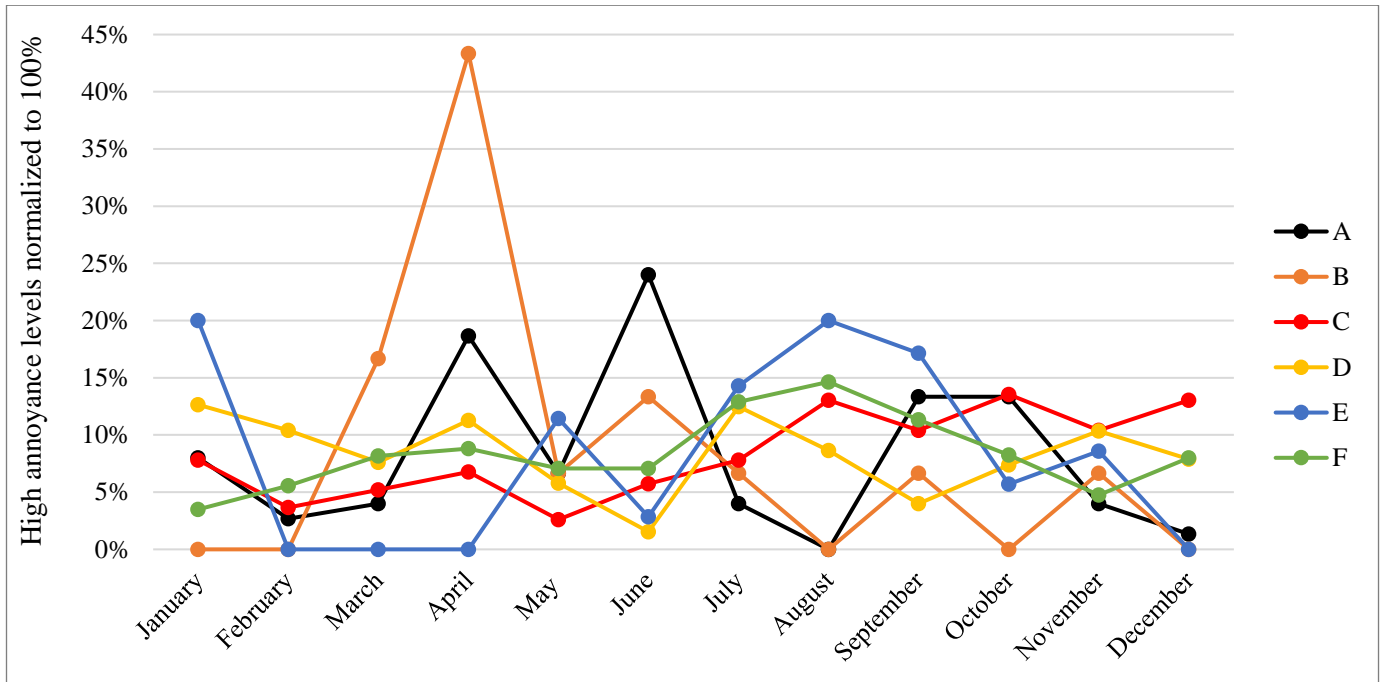


Figure 16 Reported high annoyance levels by month normalized to 100% for six wind projects over a two-year period, including clusters north (A), central (B) and south (C) of the Energie A16 project.

4.2 Variation in annoyance level by hour of the day

The number of feedback responses and annoyance ratings on a 7-point scale, categorized by hour of the day, across the entire Energie A16 project and its three clusters - north (A), central (B), and south (C), - have been presented in chapter 2.4.3. Based on this data, the relative amounts of reported high annoyance levels by hour of the day over a two-year period were derived for these clusters. The results are presented in Figure 17. A similar analysis was carried out for three other wind projects where the app was used for at least two years. The results for these projects, labelled as D, E, and F, are also shown in Figure 17. While the analysis for these projects also spans exactly two years, the start and end dates of this period differ for two of the projects compared to the Energie A16 project.

Figure 17 shows that most wind farms experience a peak in high annoyance levels between 9 p.m. and 1 a.m. and again between 7 a.m. and 8 a.m., corresponding to the end of the evening and around the start and end of the night. It should be noted, however, that some annoyance reports submitted at the end of the night may reflect delayed responses to annoyance experienced earlier during the night.

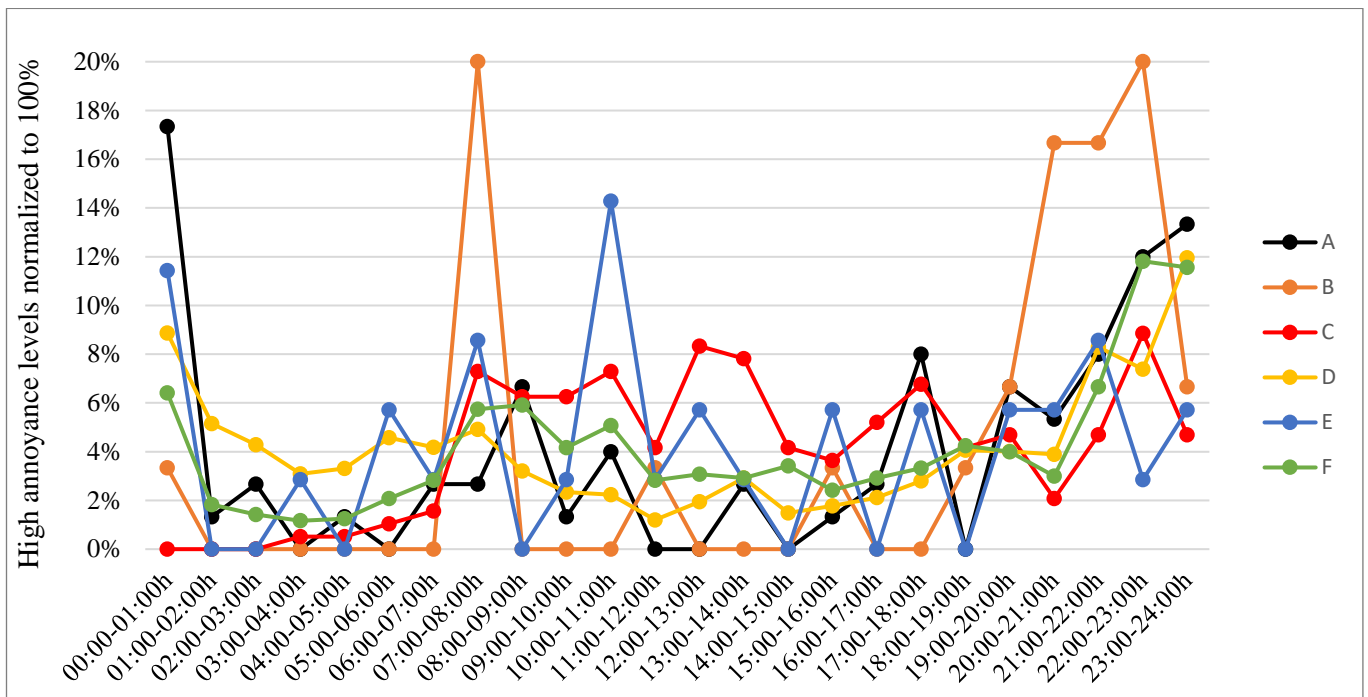


Figure 17 Reported high annoyance levels by hour of the day normalized to 100% for six wind projects over a two-year period, including clusters north (A), central (B) and south (C) of the Energie A16 project.

5. Conclusions

This study provides valuable insights into the impact of wind turbine noise on nearby residents, revealing significant variability in annoyance patterns across wind farms. While no clear seasonal trend is evident, two years of data show that for four out of six wind farms using the interactive app, high annoyance levels were above average in April, August, and September. The absence of a seasonal trend underscores the complexity of annoyance, which is influenced by factors such as weather, environmental conditions, and turbine operations, rather than predictable seasonal patterns. These factors vary across wind farms and locations, making site-specific analyses crucial.

For the Energie A16 project, the analysis highlights specific conditions under which annoyance is most likely to occur. High annoyance was most frequently reported during wind speeds of 8 to 13 m/s at hub height, at distances of less than 1,000 metres from the turbines, and during specific wind directions that reduce background noise (e.g. northeastern winds for the northern cluster and southwestern winds for the southern cluster). These findings emphasize the need to account for wind direction-dependent background noise when assessing the impact of wind turbine noise on nearby residents. Additionally, high annoyance levels were most frequently reported during the late evening and at the start and end of the night, further highlighting the influence of quieter periods on perceived annoyance. In relation to the number of residences near the wind turbines, high annoyance was most frequently reported by residents living within 500 metres of the wind turbines. Within this distance, the proportion of residents reporting high annoyance levels is nearly twice as high in the central and southern clusters compared to the northern cluster. The findings suggest that background noise from the A16 motorway, heavily influenced by wind direction, is a key contributing factor.

Daily annoyance patterns show greater consistency across wind farms than monthly patterns. Most wind farms using the interactive app exhibited peaks in high annoyance levels between 9 p.m. and 1 a.m. and again between 7 and 8 a.m., corresponding to the end of the evening and the start and end of the night. While some reports submitted at the end of the night may reflect delayed responses to annoyance experienced earlier, the findings suggest that annoyance is more pronounced during quieter periods when background noise is reduced.

The results stress the importance of considering *time-dependent factors* and *local environmental conditions* when designing and implementing noise mitigation strategies. The findings from this study offer valuable guidance for improving wind turbine planning and operations:

- **Localized mitigation:** Develop strategies tailored to site-specific conditions, such as adjusting operations during wind directions and speeds that heighten annoyance.
- **Time-dependent noise curtailment:** The peaks in annoyance during the late evening and the start and end of the night emphasize the importance of addressing quieter periods when turbine noise is more noticeable. In situations requiring noise curtailment, annoyance may be more effectively reduced by applying additional noise reduction at the start of the night, when residents are going to bed, rather than sustaining a lower level of noise reduction throughout the entire night.
- **Long-term monitoring:** Feedback patterns reveal that annoyance levels tend to stabilize over time as residents adapt to turbine operations. Long-term monitoring can help identify trends and inform mitigation measures that address persistent issues.
- **Community engagement:** Enhance communication and accessibility through tools like the interactive noise forecast app to gather meaningful feedback and improve interventions.

By addressing these perspectives, future wind turbine projects can better balance the need for sustainable energy production with the concerns of nearby residents, ensuring effective noise management and community satisfaction.

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