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Wind turbine noise annoyance – an interdisciplinary three-year field study

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ABSTRACT

Concerns have been raised about the effects of wind turbine (WT) sounds on the well-being of residents. Based on stress psychological models noise annoyance is an indicator connected to well-being. Still there is a lack of interdisciplinary studies observing the impact of noise annoyance on residents over an extended time frame. To understand annoying situations more precisely than previously possible, in a three-year investigation, we analyzed annoyance reports by residents with simultaneous measurements of acoustics, ground motions as well as meteorological and operational parameters. Ground motion and sound pressure levels could not explain noise annoyance, while there are hints to a connection with amplitude modulation and rotational speed. In a regression analysis only the combination of objective and subjective factors is able to predict annoyance sufficiently, with wind speed as the most relevant physical, and the perception of the planning process as the most relevant subjective factor. To meet concerns and better understand annoyance both aspects have to be considered: fairness in the planning process as well as the operational and environmental parameters influencing noise perception.

1. Subjective and objective factors related to wind turbine noise annoyance

Wind energy is one of the most important pillars of the energy transition. Its success is dependent not only on governmental goals but also on the support of citizens, especially local residents of energy sites. in the USA, Canada or Germany, for example, around 17–20 % of wind farm (WF) projects face opposition, possibly leading to delays or planning stops (FA Wind, 2019; Stokes et al., 2023). The expected or experienced annoyance of wind turbine (WT) noise is one of the major factors related to residents' acceptance (Hübner et al., 2023). Worries about the effects of noise emissions can initiate negative social dynamics and result in long-term opposition (Songsore & Buzzelli, 2014). While the number of strongly annoyed residents is expected to be low, affected people do experience negative effects, e.g., sleeping problems or lack of concentration (Hübner et al., 2019; van Kamp & van den Berg, 2018). Consequently, the understanding of why WT sounds are perceived as annoying, i.e., as noise, is of high relevance. Over the last decade, this relevance is mirrored in the increasing research on WT immissions and their impact on residents (e. g., Bakker et al., 2012; Jalali et al., 2016; Michaud et al., 2016a; Michaud et al., 2016b; Poulsen et al., 2018a, 2018b; Turunen et al., 2021).

To explain the emergence of WT noise annoyance, laboratory and field studies are conducted. Laboratory studies offer insights into the response to acoustic characteristics of WT sounds in a controlled setting. Studies find that higher sound pressure levels (SPL) and amplitude modulated WT sounds can have effects on noise annoyance and sleep quality (Dunbar et al., 2022; Schäffer et al., 2019; Schäffer et al., 2016; Schmitter et al., 2022; Smith et al., 2020), while a direct link to physiological or other effects could not be established, also regarding infrasound (Ascone et al., 2021; Maijala et al., 2020; Rosciszewska et al., 2025). However, in laboratory studies everyday circumstances including geography, housing, weather, as well as the social context are not considered. Field studies investigate the noise perception of

Abbreviations: AM, amplitude modulation; SPL, sound pressure level; Rpm, rotations per minute; WT, wind turbine; WF, wind farm.

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residents within the context of their everyday lives. They emphasize the importance of how fair the planning and construction process was perceived, attitudes towards wind energy and the local WF, perceived landscape impacts or impacts on property value (e. g., Hoen et al., 2019; Hübner et al., 2019; Jalali et al., 2016; Michaud et al., 2016b; Pedersen et al., 2009; Pohl et al., 2018; Radun et al., 2019). These studies predominantly rely on subjective evaluations of residents. Measurements of acoustic characteristics or the assessment of the operational or meteorological circumstances of the annoying situations are mostly missing.

Only in recent years a handful of studies were conducted that analyze the circumstances of annoyance in the field by assessing residential annoyance reports in tandem with measurements of WT emissions. One of the first combined-assessment studies used diary observations by six annoyed residents, and measurements of acoustics and vibrations (i.e., what is referred to as ground motions throughout this paper) inside and outside their homes (Cooper, 2014). They found that noise annoyance was correlated to variations in power output. Also, the residents reported a sensation of the WF operation (rather than simply hearing sounds), which the authors associated with very weak vibrations. Although the study set a good example for subsequent research, the investigated hub height (69 m) is below today's standard (>100 m) and the results could differ considerably for today's WTs.

With a comparable approach, in the project TremAc (Kudella et al., 2020; Pohl et al., 2020, 2018) ground motions (i.e., the oscillation of the WT structure transmitted through the ground), as well as airborne infrasound, were found to be below the perception threshold and could not be connected to health complaints. For moments documented in noise complaint sheets, the correlation between SPL and annoyance was small, rather, variations in amplitudes were identified as the main explanation for annoyance levels. Similarly, in a project by the German Environment Agency (Schmitter et al., 2022) infrasound signals were found at multiple WT locations, but all of them below the perception threshold. Additionally, in listening experiments they found that amplitude modulation (AM) corresponded to higher annoyance levels. Hansen et al. (2021) also found that outdoor prevalence of AM correlated with annoyance levels recorded in noise diaries. Furthermore, indoor SPL, power output and wind direction were significant predictors of noise annoyance. Instead of noise diaries, Søndergaard et al. (2021) used an app with which residents reported noise annoyance. Søndergaard et al. (2021) analyzed simulated meteorological data and operational data of the WTs in connection to the noise reports. Like in TremAc (Pohl et al., 2020), they found indications for a weak relation between SPL and annoyance–but they noted large variations of dB levels within each level of annoyance rating.

Mostly, these studies assess objective measures to predict noise annoyance, while other studies have shown the importance of subjective measures as well, i.e., attitudes, fairness evaluations, etc. (see above). Both perspectives have to be considered in conjunction in order to understand noise annoyance. And the studies investigating situations that the residents consider annoying often either lack immediacy (i.e., using diary reports, which can be difficult to tie to exact times), sample size or a sample that represents those that are strongly affected by noise.

This paper presents analyses from the research project Inter-Wind (funded by the German Ministry for Economic Affairs and Climate Action). The aim of this study was to determine which psychological and physical factors contribute to noise annoyance by analyzing a case with a relatively high amount of strongly annoyed residents. Within the project a WF was investigated over the period of three years. Three measurement campaigns were conducted, gathering acoustic, ground motion, meteorological and operational data. In one campaign operational parameters were even varied systematically. A precise analysis of the situations with WT noise annoyance and of the different parameters affecting them was enabled by assessing the residents' annoyance via an app, simultaneous to the measurements.

This study brings together different strands from the project. Earlier and further results are presented elsewhere: Müller et al. (2023b) present results of a resident survey preceding the measurements and shows a high prevalence of noise annoyance in the adjacent municipality. In comparison to other residents, strongly annoyed residents evaluated the planning process as well as the distribution of benefits and burdens as more unfair. They had more negative attitudes towards wind energy in general and towards the local WF, were more noise sensitive and lived closer to the WF (yet, the difference was small, on average strongly annoyed residents lived 150 m closer to the WF). Gaßner et al. (2022) present the overall procedure and instrumentation of the measurements. It could be shown that ground motions could be attributed to WF operation (albeit being below the human perception threshold, Gaßner & Ritter, 2023). Furthermore, it was described how the geological setting affects amplitude decay of the WT induced ground motions (Gaßner et al., 2023). AM was detected and related to tones by the generator and drive train, modulated by the blade passing frequency–with indications that noise annoyance occurred more often in situations with AM (Blumendeller et al., 2023). This study connects these earlier findings and extends them to the context of multiple measurement campaigns over the course of three years. It compares situations with different levels of noise annoyance in regards to frequency spectra, operational parameters, ground motions as well as the occurrence of AM. Finally, these parameters feed into a regression analysis in order to determine which ones affect noise annoyance the most.

2. Methods

2.1. The wind farm

Owing to discussions with residents and authorities after a previous research project in the region (Hübner et al., 2020), WF Tegelberg was brought to the research team's attention as there were conflicts because of WT noise. An opposition had formed and a group of residents tried to act against the WF by contacting the authorities and by judicial means. However, the atmosphere was not as charged as to attract media attention beyond the municipality.

The WF is located in the rural, mountainous area of the Swabian Alb in southern Germany and consists of 3 WTs located near a steep slope at a distance of approximately 1 km from the municipality Kuchen. The WTs (General Electric) have a hub height of 139 m, a rotor diameter of 120 m and a rated power of 2.78 MW. The height difference between the locations of the WTs and the village is around 300 m. A railway line and a federal road run through the municipality. At the onset of the investigation in 2020, the wind farm was in operation for 31 months (since December 2017).

The WT closest to Kuchen (WT 3) is operated in noise-reduced mode during the night (22:00–06:00 local time), whereby the power output and correspondingly the maximum rotational speed is reduced. The output is reduced from 2.78 MW to 2.64 MW, which corresponds to a maximum of 12 rotations per minute (rpm) instead of 12.55 rpm.

2.2. Resident survey and noise app

To assess WT noise annoyance, a resident survey was conducted as a first step. For the recruitment of participants, information about the project was disseminated via press releases of local newspapers and announcements by local authorities. A number of 1570 addresses were randomly collected from public phone directories within a 5 km radius around WF Tegelberg. The residents were contacted in two waves from July 2020 to March 2021 via letter and a few days later via phone call. Additionally, residents were allowed to directly contact the research team and were included in the sample. This was done to increase acceptance of the study in the community. A total of 148 persons participated in the survey, including 26 volunteers who contacted the research team on their own (all of whom heard WT sounds). This accounts for a response rate of 7.77 %.

To test possible self-selection bias a non-responder analysis was conducted, assessing possible influencing factors on WT noise annoyance: 208 residents contacted via phone call refused to participate in the survey but answered a short interview. Both the responders as well as the non-responders rather strongly approved of WFs in general (M > 3 each) but differed in their judgment of the local WF: On average, respondents approved of the local WTs less (M = 0.20, SEM = 0.20) than the non-respondents (M = 1.44, SEM = 0.12, medium effect size). Additionally, respondents felt more annoyed by WT noise than non-respondents (M = 2.18, SEM = 0.15 versus M = 0.57, SEM = 0.08, large effect size). This result indicates that residents were more likely to participate when they felt more negatively affected by the local WF.

The participants gave consent to data collection, being contacted again for follow-up surveys and the publication of results that do not allow for inference about the individual participant. They were interviewed according to a standardized questionnaire via telephone. The survey questionnaire was based on previous studies on stress effects of WT emissions (Pohl et al., 1999; Pohl et al., 2018; Pohl et al., 2021). It assessed stress indicators concerning WT emissions, especially due to noise annoyance. These stress indicators included somatic and psychological symptoms associated with WT emissions.

The residents' general level of WT noise annoyance was assessed on a 5-point scale. The individual response scale levels can be viewed in Table 10 in the appendix. To overcome the shortcomings of the common single item annoyance assessment, stress reactions were integrated into the annoyance assessment to define strong annoyance. Residents are defined as strongly annoyed by WT sound, when they are at least somewhat (≥ 2) annoyed and experience one or more stress symptoms at least once per month due to the sounds (Hübner et al., 2019; Pohl et al., 2018). The term "strongly annoyed residents" is not to be confused with "highly annoyed residents" according to ISO/TS 15666 (2003), as the former includes an assessment of stress responses, which is not present in the latter. For comparison, annoyance was additionally assessed according to ISO/TS 15666 (2003) on a 5-point verbal scale referring to the previous 12 months.

Furthermore, the questionnaire covered a range of non-acoustic influencing factors on noise annoyance, e.g., attitude towards wind energy in general and towards the local WF (–3 "very negative" to + 3 "very positive"), perception of the distribution of benefits and burdens (–3 "very unfair" to + 3 "very fair"), perceived change in property value (–2 "decreased a lot" to + 2 "increased a lot"), perception of the planning process (0 "not at all fair" to 4 "very fair") and noise sensitivity (1 "not at all noise sensitive" to 6 "very noise sensitive"). For more details on the survey, see Müller et al. (2023b).

The participants were given the opportunity to use an app to report when they heard WT sounds during the following measurement campaigns. In the first measurement campaign (T1) participants were asked to report every time they heard annoying WT sounds. For the second and third campaign (T2, T3), residents were asked to make a report every evening before they went to bed, independent from whether they heard WT sounds in that moment or not. In addition to that, they were allowed to always make a report when they wished. They were also allowed to report about other times than the current situation, so they could retrospectively report situations when they did not have their phone at hand. In order to ensure some level of accuracy about the reported times, however, the analyses in this study only consider reports that were submitted no more than two hours after the moment that was described. In the app they were asked whether they heard WT sounds and how annoying these were in that moment. They were also asked where the sounds were heard, what activity they interfered with, and whether measures were taken to counteract them. Use of the app was voluntary and users received no financial compensation for their reports. The residents were asked to use the app for the entire duration of the acoustic, meteorological and ground motion measurements in each measurement campaign. Additionally, in T2 and T3 they had a weekly scheduled phone call by the research team, asking them a couple of questions about the WF (not reported in this paper). At this opportunity, each week they were reminded to use the app.

2.3. Measurements and instrumentation

Three interdisciplinary measurement campaigns with noise reports, acoustic, meteorological, and ground motion measurements were carried out at WF Tegelberg as part of the Inter-Wind project (Fig. 1). Ground motion and acoustic measurements were performed at the emission and the immission site. All details regarding the instrumentation and first measurement campaign can be found in Gaßner et al. (2022). During T1 immission measurements were performed inside and outside the four houses of strongly annoyed residents. For T2 and T3 the grounds of a public open-air swimming pool were used (at a time of year when it was not used by the public). There, measurements could be performed inside a clubhouse of the German Lifesaving Association for indoor measurements as well as outside on a lawn, resulting in similar conditions to the measurements at residencies (see also Blumendeller et al., 2023). In all three measurement campaigns the WTs were shut down at specified times at night in order to assess background noise, which also provides the opportunity to observe effects due to abrupt changes in the WT operation.

The WF operator's SCADA (Supervisory Control and Data Acquisition) data for all WTs (i.e., wind direction, wind speed and temperature at hub height) was made available. In Addition, data was available from the nearby WINSENT test field (Rettenmeier et al., 2021): In approximately 2.4 km distance meteorological measuring masts are equipped to measure wind speed and direction, air temperature, air humidity, air pressure and precipitation at different heights. Several remote sensing devices such as two Doppler wind lidars, measuring air movement, and a ceilometer, detecting cloud cover, are installed in the vicinity of the test site.

Between the three measurement campaigns there were some differences in the boundary conditions. The measurement campaigns were carried out at different times of the year (Table 1), resulting in different meteorological conditions and variations in wind direction and wind speed (Fig. 2). In T1 and T3 the wind direction was predominantly westerly, especially in T3. During T2 mostly southeastern wind was detected. Additionally, in T2 and T3 there was a higher proportion of peak wind speeds than in T1. In T1 there were shutdowns during the night, in order to measure background noise levels. In T2, on the other hand, the WT closest to Kuchen (WT3) was out of operation due to repair work during the entirety of the measurement campaign. T3 had the longest joint measurement period, as different operating modes were tested (Müller et al., 2023a) and long-term measurements were necessary to record fluctuations in the accompanying conditions. During the test of operational modes all three WTs were operated at 2.64 MW for four weeks, and for another four weeks at 2.28 MW.

2.4. Data analysis

In order to obtain an overview of the acoustic data for all three locations (inside, outside and at the WF), spectrograms were calculated. The power spectral density (PSD) of the acoustic data is calculated for intervals of 10 s. The PSD indicates the distribution of the sound pressure at different frequencies. Furthermore, the A-weighted equivalent-continuous sound pressure level (L_{Aeq}) was calculated for each 10-minute period. This value indicates the sound pressure, averaged across all frequencies. To analyze infra- and low-frequency sound the frequency range 1–200 Hz is considered.

Another acoustic parameter that is analyzed in relation to annoyance is amplitude modulation (AM). Amplitude modulated WT sound can be defined as the change in the level of the audible WT sound over time, where the blade passing frequency is the modulating signal for the sound fluctuation. The difference between peak and trough of the SPL time-series is called AM depth. The detection of AM is based on the method

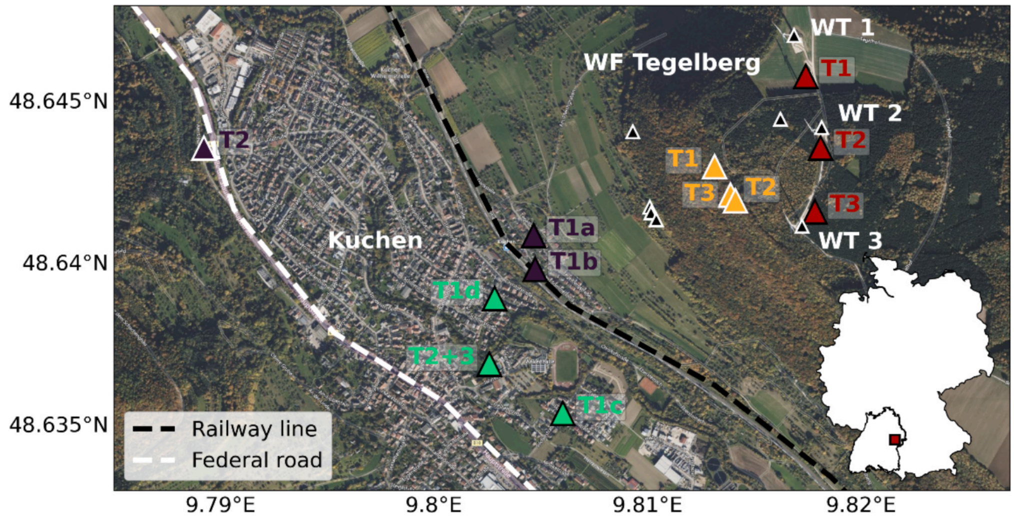

Fig. 1. Overview of measurement sites at WF Tegelberg and the municipality of Kuchen during the three measurement campaigns (T1–T3). Triangles with black edges mark sites where sound and ground motion were measured simultaneously. White edges indicate locations where only ground motion data was measured. Dark blue markers indicate sites located in close proximity (< 100 m) to one of the major traffic routes.

Table 1
Measurement campaigns at WF Tegelberg and the corresponding data evaluation periods.

	Start	End	Duration
T1	2020/10/22	2020/12/16	56 days (8 weeks)
T2	2022/04/07	2022/05/11	35 days (5 weeks)
T3	2022/11/21	2023/02/12	84 days (12 weeks)

of the Amplitude Modulation Working Group (Bass et al., 2016). First, different tones that are amplitude modulated are identified by visual inspection, since AM can be recognized by the peaks around the carrier tone, which are spaced at the BPF (modulation frequency). Then, the algorithm calculates AM values for different frequency bands, in this study the frequency band of 50–200 Hz was identified as the most relevant. To reduce uncertainty, data points were excluded when rotational speed was below 4 rpm as well as during rainfall and air humidity above 99 %. AM has already been investigated for the T1 and T2 campaigns (Blumendeller et al., 2023). For more details on the methodology the reader is referred to this publication.

To evaluate the ground motion root mean square (rms) amplitude values are evaluated at 10-minute intervals. Of the three components (vertical, North-South, East-West) only the vertical component is considered here. The frequency range 5.6 Hz to 80 Hz was used for the evaluation, which is relevant for human perception (DIN4150-2, 1999). In T1 the sampling frequency was set to 100 Hz, resulting in a frequency range of 0.05–50 Hz (Gaßner et al., 2022; Gaßner & Ritter, 2023). In the following campaigns higher sampling rates of 400 Hz (T2) and 200 Hz (T3) were used to record frequencies of up to 200 Hz and 100 Hz, respectively.

2.5. Statistical analyses

To analyze group differences for interval-scaled variables, descriptive statistical values, such as the arithmetic mean (M) and standard error of the mean (SEM) were used. For nominal-scaled variables, absolute and relative frequencies (%-values) are reported.

A multiple regression analysis was run for each measurement campaign to predict the noise annoyance. As the β weights indicate the relationship strength between each factor and noise annoyance we understood them as effect sizes (Nieminen et al., 2013), and a cut-off of > 0.15 was used to indicate an influential predictor. A power analysis with G*Power, assuming an alpha error probability of 0.05 and a large effect size (based on Hübner et al., 2019; Michaud et al., 2016b), showed that for a power level of 0.95 a sample size of 55 would be required. X^2 tests for inferential analysis of frequency distributions were used. Mean values of two groups were compared via t-tests. In the case of unequal variances, Welch's t-tests were chosen. The data analysis and description is based on the principles of Abt (1987). Therefore, reported p values of the two-tailed significance tests serve a descriptive purpose to characterize the extent of group differences. Since the analysis is not a confirmatory data analysis, no alpha adjustment was made, despite multiple significance tests. We consider p values of 0.05 or less as statistically significant. Furthermore, the effect size parameters d and w were calculated to report practical significance (Cohen, 1988). The effect size categories (small, medium, large) mentioned in the results section are related to statistically significant group differences.

3. Results

3.1. Resident survey

In the resident survey 148 residents were interviewed. About a third (n = 54, 36.5 %) reported not to hear WT sound, 16 (10.8 %) did hear WT sound but were not annoyed by it. Another third (n = 49, 33.1 %) was categorized as strongly annoyed (i.e., annoyance ≥ 2 and symptoms due to WT sounds). For comparison, following the ISO/TS 15666 (2003), 36 residents (24.3 %) were categorized as highly annoyed.

On average, the residents who heard WT sounds rated the planning process as not fair, and the distribution of benefits and burdens as somewhat unfair, as they assumed their property value to have slightly decreased since WT erection (Table 2). While the attitude towards wind energy in general was, on average, positive, the attitude towards the WF Tegelberg was slightly negative. Residents who did not hear WT sounds viewed all of these more positively. On average, residents who heard WT sounds described themselves as slightly not noise sensitive, and they lived 1.36 km to the nearest WT, whereas residents who did not hear lived on average in 2.6 km distance (with large variations in this group).

3.2. App reports

In total, n = 638 app reports were evaluated across all three measurement campaigns at WF Tegelberg, which were submitted by a total of 24 different residents. Three users participated in all three campaigns,

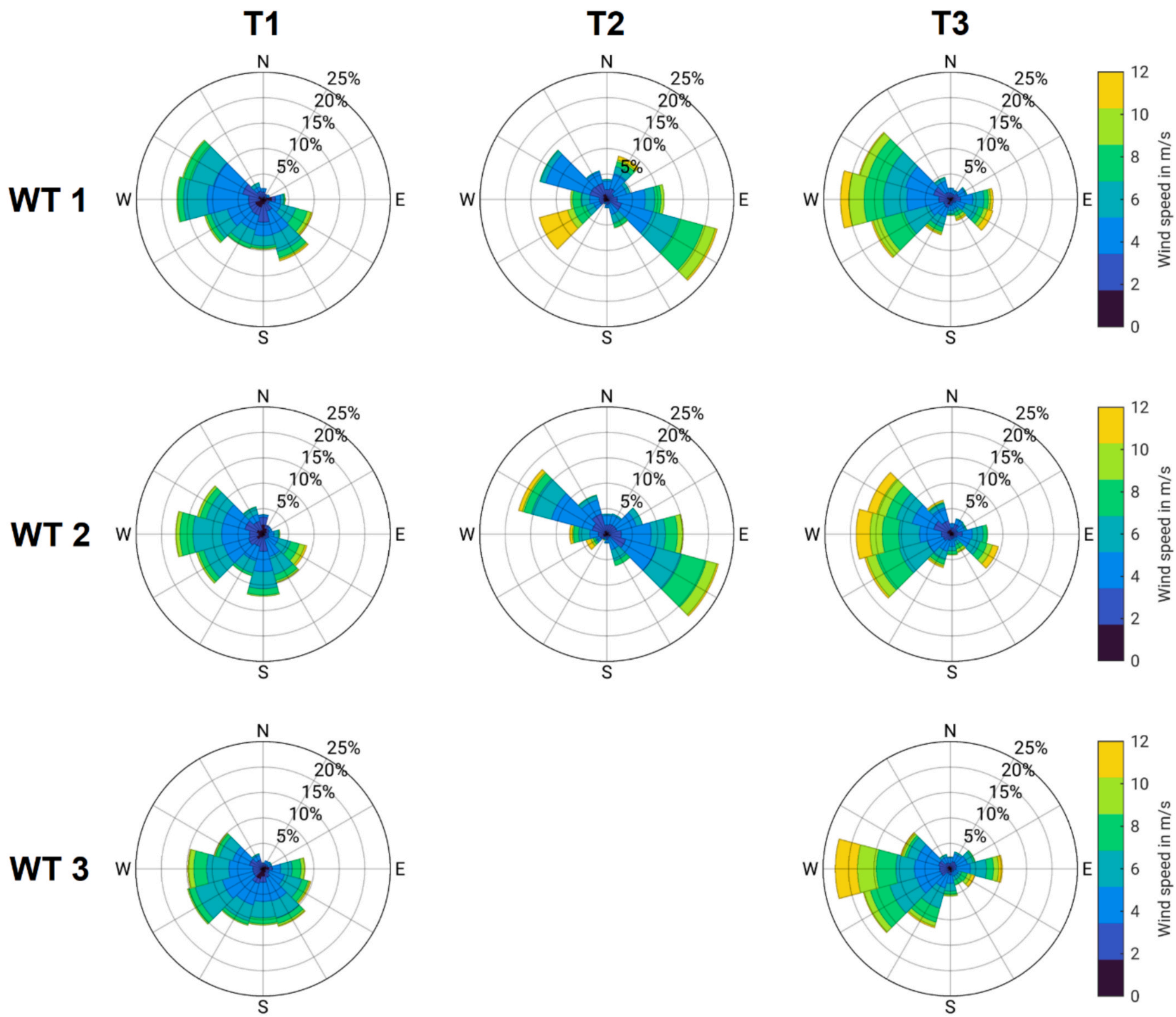

Fig. 2. Comparison of wind speed and direction distribution at the individual WTs during measurements at WF Tegelberg. WT 3 was not in operation during campaign T2.

six participated in two campaigns, 15 participated in only one campaign, respectively. The app users were only part of the sample that was surveyed in the interviews. There were no statistically significant differences between the users and the rest of the sample in terms of the extent of their long-term WT noise annoyance or attitudes towards the WF (Table 3). However, it was found that there was a higher proportion of strongly annoyed and highly annoyed individuals among the users than among the non-users. The app users were therefore negatively affected to a higher degree, but applied a comparable standard to the WT noise annoyance rating as the rest of the sample.

In T1, reports were only made when WT sounds were heard. For T2 and T3 a regular time was set for the residents to make app reports, so that also a larger proportion of reports was submitted when no sounds were heard (66 % in T2, 52 % in T3, Table 4). The extent of how annoying they rated situations with WT noise varied between the measurement campaigns: when residents heard WT sounds, they reported being, on average, moderately annoyed in T1, somewhat annoyed in T3, and between slightly and somewhat annoyed in T2. That means there is a large effect size for the comparison of T1 and T2, otherwise the effect sizes are medium.

In all three measurement campaigns, 70–80 % of the reports were made during evening and night hours (between 18:00–06:00 local time). In terms of time, the reports from T1 are the most meaningful, as in T2 and T3 it was specified to make a report every evening, whereas there was no time specification in T1. In T1, 29 % of the noise reports were between 18:00–22:00 and 41 % between 22:00–06:00 local time (UTC + 1). When hearing WT sounds, residents were inside the building for 54 % of the reports and outside, in the immediate vicinity of their home, for 46 %.

3.3. Annoyance and sound pressure levels (SPL)

For periods where acoustic data was available, the acoustic and WT operating data from all measurement campaigns were grouped, according to the reported annoyance levels and whether or not WT sounds were heard (Table 5).

Detailed information on the spectral composition of the WT sound during annoyance reports was obtained by narrowband analysis of the acoustic data recorded at three microphone positions. The categorization was carried out according to the criteria specified in Table 5

Table 2
Key characteristics of residents who hear WT sounds.

	Residents who hear WT sound (M, SEM)	Residents who do not hear WT sound (M, SEM)	Test statistics
Process fairness[0–4]	0.55 (0.19)	1.57 (0.21)	t(61.51) = 4.56, $p < 0.01$, $d = 0.97$
Distributive fairness [−3 – +3]	−1.76 (0.17)	–.10 (0.25)	t(142) = 5.92, $p < 0.01$, $d = 1.02$
Assumed change in property value [−2 – +2]	–.46 (0.09)	0.00 (0.03)	t(96.17) = 3.99, $p < 0.01$, $d = 0.74$
Attitude towards wind energy in general [−3 – +3]	1.31 (0.15)	1.76 (0.17)	t(143) = 1.80, $p = 0.07$, $d = 0.31$
Attitude towards local WF [−3 – +3]	–.80 (0.19)	1.45 (0.19)	t(133.04) = 8.30, $p < 0.01$, $d = 1.35$
Noise sensitivity [1–6]	2.98 (0.15)	2.43 0.21)	t(143) = 2.14, $p = 0.03$, $d = 0.37$
Distance to nearest WT [m]	1355.98 (31.24)	2606.00 (182.54)	t(57.18) = 6.77, $p < 0.01$, $d = 1.46$

Table 3
Comparison of app users and non-users (M, SEM, %) via *t*-test and X^2-test.

	App users (n = 24)	Non-users (n = 124)	Test statistics
WT noise annoyance [0–4]	2.46 (0.31)	2.08 (0.17)	t(93) = 1.09, $p = 0.28$, $d = 0.26$
Noise annoyance, last 12 months (ISO/TS) [0–4]	2.21 (0.30)	1.87 (0.17)	t(93) = 1.01, $p = 0.32$, $d = 0.24$
Attitude towards WF [−3 – +3]	–.68 (0.38)	0.19 (0.18)	t(141) = 1.92, $p = 0.06$, $d = 0.44$
Number of strongly annoyed due to WT sound	14 (58 %)	35 (28 %)	$X^2(1) = 8.23$ [CI: 1.45, 8.76], $p < 0.01$, $w = 0.24$
Number of highly annoyed (ISO/TS)	12 (50 %)	24 (19.4 %)	$X^2(1) = 10.26$ [CI: 1.67, 10.41], $p < 0.01$, $w = 0.26$

Table 4
Number of app reports with and without WT sounds, degree of WT noise annoyance for app reports with WT sounds, and number of residents, who reported annoyance.

	Without WT soundabsolute number (%)	With WT soundabsolute number (%)	Noise annoyance (0–4; M, SEM)	Number of residents
T1	0 (0 %)	104 (100 %)	2.88 (0.08)	11
T2	124 (65.6 %)	65 (34.4 %)	1.49 (0.15)	14
T3	180 (52.2 %)	165 (47.8 %)	2.21 (0.08)	20

Table 5
Data points used to evaluate the annoyance from the app-documentation. Criteria are an annoyance rating of 2–4 (*sound + annoyed*) or 0 (*sound + not annoyed* or *no sound heard*).

	T1	T2	T3
Sound heard + annoyed	79	25	115
Sound heard + not annoyed	1	17	5
No sound heard	0	113	159

exemplary for the T3 measurement campaign (Fig. 3). Different SPL values across the frequency spectrum up to 200 Hz are recognizable for different degrees of annoyance, with higher values at the WF site for reports with annoyance. Outside and inside the building, these differences are less pronounced for frequencies above 10 Hz. To determine background levels, shut-down periods during the night with hub height wind speeds matching those of the data points in Table 5 were considered. By only considering night-time ambient noise was minimized.

Analysis of frequency spectra at times associated with annoyance reports (with annoyance levels 2–4) at the WF site shows a relationship between annoyance levels and rotational speed variations (see Fig. 4a)). For this analysis, the acoustic data was selected for the night-time (between 20:00 and 23:50 UTC), with rotational speed of WT 3 between 8 rpm and 12 rpm. In particular, operation at rated rotational speed (12 rpm) corresponds closely to reports with annoyance. Similar results are observed for measurement positions at the building 1 km away from the WF (Fig. 4b) and c)). Particularly in the frequency range below 20 Hz, clear SPL fluctuations can be recognized.

The 1/3 octave spectrum (see Fig. 5a)) allows a comparison with the human hearing threshold as described in DIN45680 (1997) and Møller and Pedersen (2004). Although SPL deviations below 20 Hz can be observed across different sound levels, the SPLs in this frequency range are below the hearing threshold and only exceed it at about 50 Hz in the building. As differences can also be observed above the hearing threshold, the audible low-frequency sound is more likely to be associated with annoyance.

Fig. 5b) and c) show SPLs for the frequency range from 1 to 200 Hz and Fig. 5d) and e) for the frequency range from 20 Hz to 10 kHz, both A-weighted and unweighted (Z-weighted), for the three measurement positions and categorization criteria. Slightly higher SPLs are observed at the WF at times with annoyance level 2–4 than at times without annoyance and audible WT sound. The A-weighted SPLs at distances of more than 1 km are in a similar range both outdoors and indoors for all criteria, with no substantive differences observed. There are slight deviations in the Z-weighted SPLs of the low-frequency SPL (Fig. 5c)). This implies that the low-frequency sound is more related to annoyance, but frequency spectra provide higher information value regarding noise rating and WT sound (Blumendeller & Cheng, 2023).

3.4. Annoyance and amplitude modulation

Table 6 shows for which app reports AM was detected during the T2 and T3 campaigns. In T1, due to unfavorable weather conditions (i.e., rain, high humidity) at the times of app reports, too few data points were available to analyze AM meaningfully. During T2, AM was detected in 24 cases out of 189 reports, and during T3, in 45 cases out of 345. Specifically, for reports with an annoyance level of at least 2 ("somewhat annoyed"), AM was detected in 32 % (T2) and 27 % (T3) of the reports. Consequently, the proportion of reports with AM was highest among these reports. X^2 testing confirms an association between AM detection and the degree to which WT sound was perceived as annoying, with a small to medium effect size.

To obtain an overview of how app reports are distributed, residents' complaints regarding different levels of annoyance are shown together with AM depth and WT data from T3 (see Fig. 6). The level of annoyance varies notably in the presence of AM, noise annoyance is also reported with no AM present. Most noise reports occur at rated rotational speeds, during up-winds, and are evenly spread across wind speeds between 7 and 12 m/s as well as electrical power output between 40 % and 100 %. This trend persists even when AM is not detected. While there was more crosswind from southeast during T2, the other trends were similar in both campaigns.

3.5. Annoyance and ground motions

Mean amplitudes for ground motions were set in relation to the resident reports (Fig. 7). For both campaigns data from the public swimming pool within the municipality were used and measurements at WT 2 for campaign T2 (Fig. 7a) and near WT 3 for campaign T3 (Fig. 7b).

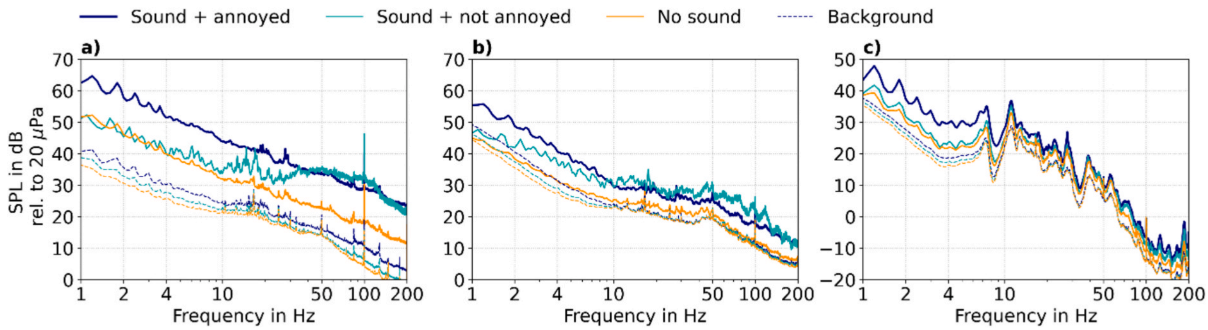

Fig. 3. Averaged narrowband octave spectra, selected for the three criteria according to Table 5 at a) the WF, b) outside and c) inside the building during the T3 campaign.

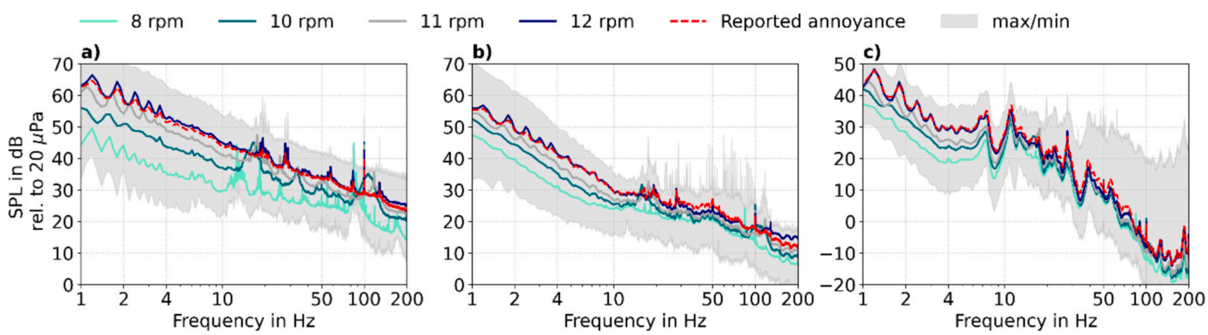

Fig. 4. Narrowband spectra at a) the WF, b) outside and c) inside the building during the T3 campaign. Data is selected for the night time (from 20:00–23:50 UTC), rotational speeds of WT 3 between 8 rpm and 12 rpm and compared to the spectrum during annoyance reports with "somewhat" to "very" annoyance levels (red line).

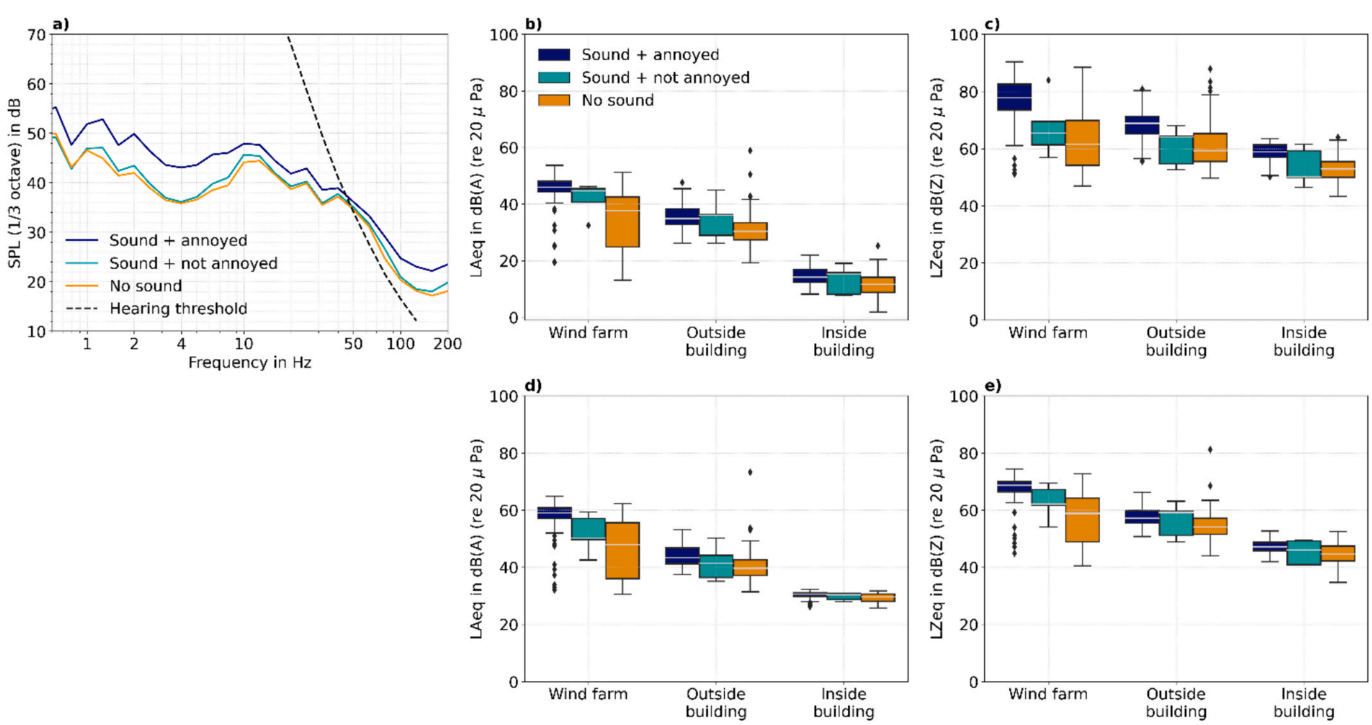

Fig. 5. a) averaged 1/3-octave spectra inside the building, b) $L_{A,eq10min}$ (frequency range 1–-200 Hz), c) $L_{Z,eq10min}$(frequency range 1–-200 Hz), d) $L_{A,eq10min}$ (frequency range 20 Hz–10 kHz) and e) $L_{Z,eq10min}$ (frequency range 20 Hz–10 kHz). Data is selected for the three criteria according to Table 5 during the T3 campaign. Boxplots show median, first and third quartile as well as the interquartile range.

Table 6
Frequency of amplitude modulation (AM, 50–200 Hz) detection for app reports with or without perceived WT sound and different annoyance levels. Expected frequency if AM detection and annoyance level were independent of each other (values in brackets). The range of AM depth for the reports with AM.

T2	App reports				Test statistic
	No sound	Annoyance < 2	Annoyance ≥ 2	Total	
AM not detected	115 (108.3) 92.7 %	29 (29.7) 85.3 %	21 (27.1) 67.7 %	165	$X^2(2) = 14.13$, $p < 0.001$, $w = 0.27$
AM detected	9 (15.7) 7.3 %	5 (4.3) 14.7 %	10 (3.9) **32.3 %**	24	
Maximum AM-depth (dB)	3–6	3–5	3–7	3–7	
T3	No sound	Annoyance < 2	Annoyance ≥ 2	Total	
AM not detected	172 (156.5) 95.6 %	40 (39.1) 88.9 %	88 (104.3) 73.3 %	300	$X^2(2) = 31.52$, $p < 0.001$, $w = 0.30$
AM detected	8 (23.5) 4.4 %	5 (5.9) 11.1 %	32 (15.7) **26.7 %**	45	
Maximum AM-depth (dB)	3–7	3–7	4–6	3–7	

The median values (white circles in Fig. 7) during campaign T2 vary substantially across all degrees of annoyance and no trend can be identified either for the measurements at the WF or in the town. Campaign T3 shows a tendency in the amplitudes in the vicinity of WT 3, which increase from degree of annoyance 0–2, but are the same for degree of annoyance 3–4 as for degree of annoyance 2. The median amplitudes of the measurements in the town are similar for all degrees of annoyance in campaign T3. All rms-amplitudes are in the range of 1 µm/s, which is far below 100 µm/s, taken as a reference for perceivable vibrations (DIN4150-2, 1999). Within the community, ground motions are mainly dominated by anthropogenic and traffic noise, which mask the comparably weak wind turbine signals (Gaßner & Ritter, 2023).

3.6. Annoyance and operational data

Fig. 8 shows the WT operating conditions under which app reports were received during the three measurement campaigns. Beside rotational speed and wind direction, power output and pitch angle difference are related to the app reports. The pitch angle difference describes how much the rotor blades are rotated out of optimal position, i.e., optimal position is described with 0°, any other angle results in aerodynamic deceleration. This active angle adjustment mechanism is used to limit the power output of the WT at nominal wind speed. This parameter is also analyzed, as stall effects at the rotor blade can occur at certain pitch angles and wind speeds, influencing the sound generation at the blade (e. g., Tonin, 2018).

In all three campaigns reports with annoyance ≥ 2 were predominantly logged during rotational speeds above 8 rpm. While no relation to wind direction is discernible during T1 and T2, in T3 annoyance was mostly reported during western winds, i.e., crosswind to upwind for most residents. While noise annoyance occurred at all power output levels, the reports mostly occurred with a pitch angle difference indicating below-rated WT operation (0°). However, during T3, a considerable number of noise reports were also recorded at slightly higher pitch angles, i.e., when power output had to be limited to rated power. Considering the hour up to the time of a noise report, sounds were more often heard when pitch angle changed during that hour ($X^2(1) = 30.08$, $p < 0.001$, $w = 0.30$), however, it could not be confirmed that noise annoyance was stronger in these moments.

For all three measurement campaigns two rotational patterns coincided the most with app reports reporting WT noise annoyance (i.e., at least somewhat annoyed, ≥ 2). These were: constant high rotational speed of 10–12.5 rpm of at least one WT during the hour preceding the annoyance report, and a high variability (i.e., high standard deviation) of the rotational speed (see Table 7). As the high variability is supposed to depict all kinds of variability the residents can perceive, both differences between the three WTs as well as differences in time during the hour leading up to the noise report are considered. These two patterns made up more than 60 % of all reports with at least somewhat annoyance during all three measurement campaigns.

The correlation between rotational speed and noise annoyance reports varied, with no correlation in T1, a small correlation in T2 ($r = 0.25$) and medium in T3 ($r = 0.46$). For wind speed the correlation with annoyance reports was higher in all three campaigns: small in T1 ($r = 0.15$), medium in T2 ($r = 0.38$), and large in T3 ($r = 0.53$).

3.7. Regression analysis

To determine how strong the influence of various factors is on WT noise annoyance, multiple regression analyses were performed–-for all app reports with WT sounds of all three measurement campaigns (Table 8). The factors, which were identified in the previous sections to be associated with WT noise annoyance, were used as predictors (bivariate correlations are displayed in Table 9). For the physical parameters either the average value of the hour preceding the app report was calculated or the highest value (maximum / modus) within that

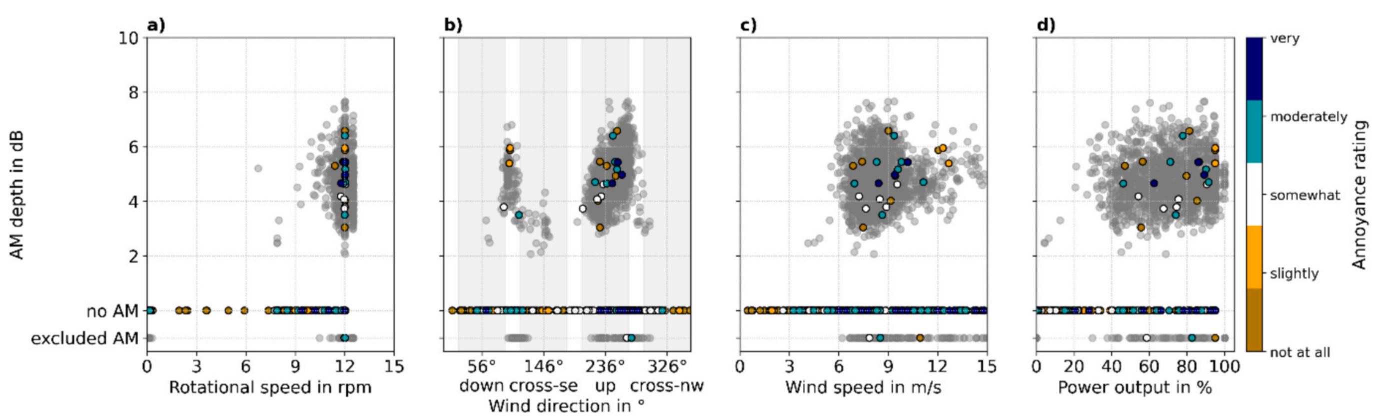

Fig. 6. All AM depth data from the building location for T3 (WT3) at times of resident reports. a) Rotational speed, b) wind direction (se: southeast, nw: northwest), c) hub height wind speed and d) power output in gray with color coded annoyance levels from residential noise reports.

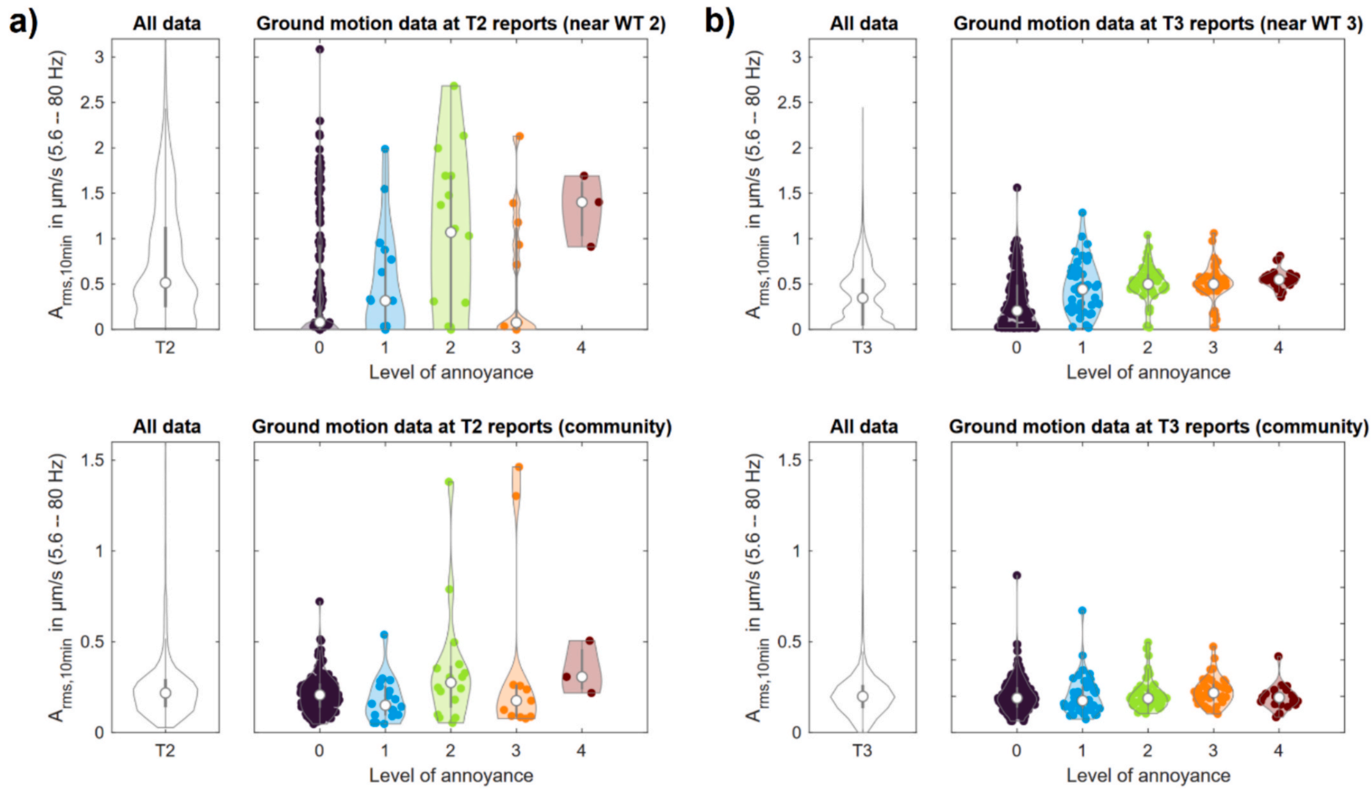

Fig. 7. Comparison of the distribution of ground motion rms-amplitudes with level of annoyance ratings for campaigns a) T2 and b) T3. White circles indicate median values, thick lines show the range between first and third quartile, thin lines the interquartile range.

time frame was used in the model. Only using objective measurement data, explained variance was low ($R^2_{adj} = 0.06–0.37$). When subjective data from the residents was also considered, the regression models for T2 and T3 were able to explain annoyance substantially ($R^2_{adj} =$ 0.60–0.69). For T1, on the other hand, the explanatory power remained low.

Wind speed as well as perceived process fairness were relevant predictors, both in T2 as well as T3. In T1, however, an influence of wind speed was not found. The perceived process fairness could not be included in the regression model of T1 because there was too little variance in the assessments of the app users. However, it did play a role insofar as almost all reports in T1 were made by residents who rated the planning and construction process as not at all fair. Furthermore, in T2 higher levels of WT noise annoyance were accompanied by larger AM depth, a more negative attitude towards the WF, and a smaller living distance to the WF. In T3 whether the resident was identified as strongly annoyed in the resident survey in 2020 was associated with higher levels of noise annoyance. It was the strongest predictor in T3, followed by process fairness, which, in turn, was the strongest predictor in T2. Despite the p value indicating significance of atmospheric stability in T3, the β weight was below the defined threshold (> 0.15) for an influential predictor. All other factors were negligible in their influence on WT noise annoyance (e.g., rotational speed or its variability). That means that their influence on annoyance is predominately explained by the highlighted significant factors. Adding the remaining factors does only marginally improve the explained annoyance further.

Reasons for the low explanatory power of T1 can be found in the composition of the group of app users. In T1, there were mainly reports of high levels of annoyance and from a small group of residents (so only a connection to a limited spectrum of annoyance can be established). In addition, two groups with different response tendencies can be identified among the app users. Two users made a total of 70 reports and were thus responsible for the majority of the reports. The remaining nine users made a total of 34 reports. While noise annoyance correlated positively with wind speed (r = 0.54) and not with rotational speed in the first group, both correlations were negative in the other group (r = –0.31). If both groups are considered together, these effects overlap for these and other variables and lead to a low degree of explained variance. In the regression of T1, the relatively high but negative β weight of the variable "strongly annoyed in 2020″ is unusual. One would have expected a positive β weight, i.e., that strongly annoyed residents would rate the noise as more annoying. Due to the different correlation patterns of the two subgroups described above, the interpretations of the β weights are questionable.

4. Discussion

The interdisciplinary analysis made it possible to identify specific factors associated with annoyance as well as those not related to annoyance. At WF Tegelberg an unusually high percentage of people were strongly annoyed by WT noise. While percentages of 1.1 % to a maximum of 9.9 % of residents strongly annoyed by WT noise were found in comparable studies (Hübner et al., 2019; Pohl et al., 2018; Pohl et al., 2021), 33.1 % were identified at WF Tegelberg.

The analyses have shown that the ground motion signals from the WTs in the adjacent municipality are low and below the perception threshold. This is consistent with findings from TremAc–where this was investigated for softer soil layers (Kudella et al., 2020). Nguyen et al. (2020) also found very low vibrations and speculate that residents might falsely attribute some wind-induced vibrations inside dwellings to the WF. Furthermore, measurement data at a distance of over 1 km from the WF have shown that the SPL measured in the infrasound range (1–20 Hz) are below the human hearing threshold. This is consistent with earlier studies (e. g., Tonin, 2012; Van den Berg, 2005; Zajamšek et al., 2016) and the infrasound level seems below the impact level on human organisms (Krahé et al., 2020; Poulsen et al., 2018a, 2018b). An association between the sound heard and the annoyance experienced could not be sufficiently explained by SPL: At a distance of 1 km from the WF,

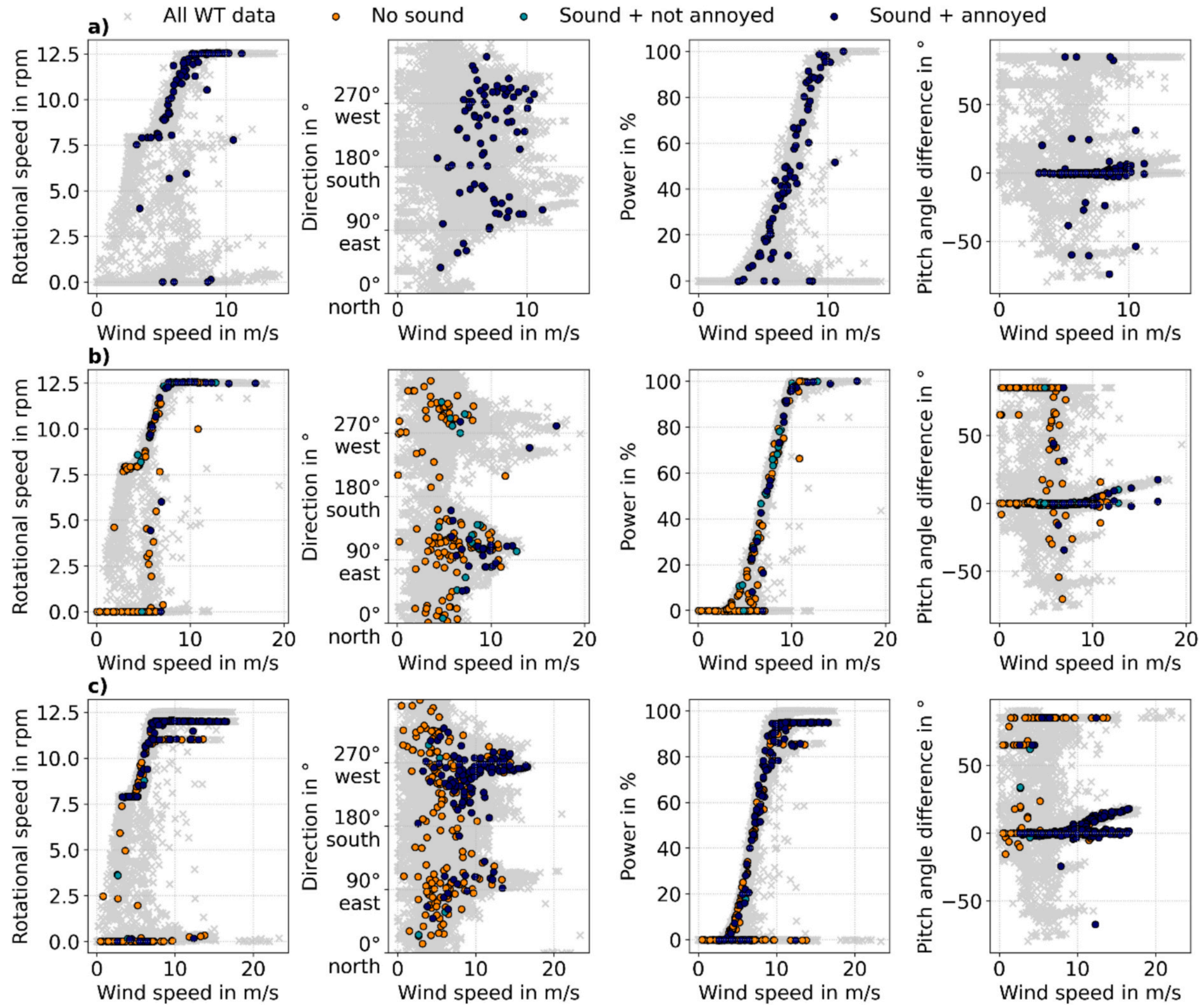

Fig. 8. Comparison of app reports with WT operational data (rotational speed, wind direction, power in percent and pitch angle difference) for a) T1, b) T2 and c) T3.

Table 7
Rotational patterns during app reports with annoyance ≥ 2 ("somewhat annoyed"). For each report the preceding hour is considered: the 10-minute interval which included the time of the report and the five preceding intervals.

Rotational pattern	T1	T2	T3
	Frequency (%)		
Constant medium rotational speed (7–10 rpm) of all 3 WTs	9 (9.6 %)	0 (0.0 %)	3 (2.5 %)
Constant high rotational speed (10–12.5 rpm) of at least 1 WT	32 (34.0 %)	16 (51.6 %)	72 (60 %)
Very low variability (SD < 1)	15 (16.0 %)	2 (6.5 %)	13 (10.8 %)
Low variability (SD 1–2)	10 (10.6 %)	4 (12.9 %)	5 (4.2 %)
Medium variability (SD 2–3)	1 (1.1 %)	1 (3.2 %)	5 (4.2 %)
High variability (SD > 3	27 (28.7 %)	8 (25.8 %)	22 (18.3 %)
Total	94 (100 %)	31 (100 %)	120 (100 %)

Note: In T2 only two WTs were in operation.

no systematic differences in the averaged, A-weighted SPL were found between situations with and without noise annoyance. This confirms a pattern that has already been found elsewhere (Michaud et al., 2016b; van Kamp & van den Berg, 2021).

A weak association, however, was found between annoyance and AM. When residents heard sounds and classified them as annoying, these sounds were more likely to be characterized by AM (with AM depth of more than 3 dB) than when there was no annoyance. Some laboratory studies suggested that such a relationship exists (Schäffer et al., 2018, 2019; Schmitter et al., 2022). So far, however, there are only a few field studies that quantify this relationship (see e. g., Hansen et al., 2021; Nguyen et al., 2022). Additionally, the app reports suggest that the time of day plays a role for annoyance. The annoyance was particularly high in the evening and at night. Especially before going to bed, WT sound was often experienced as annoying. The clearest indications for this conclusion are the reports from the first measurement campaign. It has to be taken into consideration, though, that these reports are skewed towards the views of a small group of residents who made significantly more reports than the others. However, it is consistent with statements of the larger sample in the pre-survey (Müller et al., 2023b) and with other studies (Hansen et al., 2021; Michaud et al., 2016b; Pohl et al., 2018).

The analyses indicate that the identification of rpm patterns is relevant for understanding annoyance situations. Annoyance situations were not only characterized by high rotational speeds, but also by strong fluctuations in rotational speed. Further analyses showed, however, that the correlation between annoyance and wind speed was stronger than that between annoyance and rotational speed. The regression analyses suggest that when annoyance is predicted on the basis of wind speed, rotational speed does not provide additional information that significantly improves the prediction. This is surprising as one might expect

Table 8
Multiple regression analysis explaining WT noise annoyance for all app reports with WT sounds (T1–T3).

	T1		T2		T3	
	B (95 % CI)	β (*p*)	B (95 % CI)	β (*p*)	B (95 % CI)	β (*p*)
Average wind speed[a]	0.108 (–.04, 0.26)	0.239 (0.151)	0.103 (0.03, 0.18)	**0.277** **(0.005)**	0.090 (0.03, 0.15)	**0.293** **(0.004)**
Western wind (yes / no)	–[b]	–[b]	–[b]	–[b]	0.195 (–0.11, 0.50)	0.097 (0.205)
Average rotational speed[a]	–0.024 (–0.16, 0.11)	–0.076 (0.719)	–0.025 (–0.09, 0.04)	–0.083 (0.466)	0.003 (–0.05, 0.05)	0.010 (0.911)
Variability of rotational speed[a]	0.027 (–0.13, 0.18)	0.066 (0.726)	0.014 (–0.10, 0.13)	–0.026 (0.805)	0.052 (–0.03, 0.13)	0.097 (0.187)
L_{Aeq} 20–10 000 Hz, immission outside, hourly average	0.001 (–0.04, 0.05)	0.008 (0.956)	0–.027 (–0.06, 0.00)	0–.165 (0.089)	0.054 (–0.01, 0.12)	0.199 (0.078)
Maximum AM depth 50–200 Hz, immission outside	–[c]	–[c]	0.106 (0.01, 0.21)	**0.180** **(0.039)**	0.038 (–0.03, 0.11)	0.078 (0.290)
Gamma Class (Modus), 25–97 *m*	–0.168 (–0.42, 0.08)	–0.175 (0.180)	–0.200 (–0.46, 0.06)	–0.127 (0.128)	–0.197 (–0.38, –0.01)	**–0.141** **(0.036)**
Attitude towards WF	–0.084 (–0.38, 0.22)	–0.090 (0.578)	–0.233 (–0.38, –.07)	**–0.371** **(0.005)**	0.012 (–0.20, 0.22)	–0.011 (0.908)
Perceived process fairness	–[d]	–[d]	–0.016 (–0.03, –0.01)	**–0.433** **(0.001)**	–1.781 (–2.53, –1.03)	**–0.400** **(<0.001)**
Strongly annoyed in 2020(yes / no)	–0.690 (–1.53, 0.15)	–0.284 (0.106)	–[e]	–[e]	1.505 (0.85, 2.16)	**0.453** **(<0.001)**
Noise sensitivity	0.283 (–0.02, 0.59)	0.320 (0.066)	0.010 (–0.15, 0.17)	0.015 (0.900)	–0.109 (–0.27, 0.05)	–0.133 (0.182)
Distance to closest WT	0.000 (–0.001, 0.002)	0.052 (0.724)	–0.001 (–0.002, 0.000)	**–0.362** **(0.003)**	<0.001 (–0.001, 0.001)	0.002 (0.982)
	$R^2_{adj} = 0.067$, n = 69–104, all VIF < 2.95		$R^2_{adj} = 0.686$, n = 62, all VIF < 3.10		$R^2_{adj} = 0.603$, n = 107–149, all VIF < 3.20	

Note: β Values in bold face denote factors with significant influence on noise annoyance ($p < 0.05$).
[a] Considering all operating WTs (T1, T3: 3 WTs, T2: 2 WTs).
[b] Wind direction not considered, no association to noise annoyance in this measurement campaign.
[c] Too few detections of amplitude modulation.
[d] Variance too low, 94 % of reports "not at all fair".
[e] Very high correlation between attitude and strong annoyance ($r = –.83$). Not included to avoid multicollinearity.

sound generation to be directly tied to rotor blade rotation. A reason might be that the upper limit of rotational speed can be reached at wind speeds of 7 m/s. Wind speed can vary a lot above that threshold and possibly affect sound generation and propagation. Additionally, part of what residents perceive as WT noise possibly might be, in fact, wind sounds. The influence of wind speed on annoyance even proved to be consistently stronger than the influence of all other physical parameters across all measurement campaigns.

Most relevant, the occurrence of annoyance situations could only be understood substantially by combining objective and subjective factors. Note that the relation between being, in general, strongly annoyed and the annoyance in specific situations with WT sounds was at most only medium sized ($r = 0.32$, β = from non-significant to 0.45). In other words, even strongly annoyed residents make distinctions between different situations, that were defined by the observed physical factors. Moreover, the present results emphasize and corroborate the relevance of perceived fairness (e. g., Ellis & Ferraro, 2016; Firestone et al., 2020; Hoen et al., 2019; Hübner et al., 2019; Wolsink, 2007). The measurement campaigns provide evidence that the perception of planning process fairness had an influence on how annoying the sounds were perceived. That means that a foundation for the negative perception of noise can be laid even before the WF is in operation, depending on how the plans are made and executed, as well as how fairly the benefits and burdens are distributed. The literature suggests that, although the possibility of financial participation can be beneficial, it can also be interpreted as bribery if the affected parties already have a negative attitude (Walker & Baxter, 2017). A fair process, on the other hand, is also more likely to lead to a fairer distribution (Gross, 2007). Which participatory practice is perceived as just can be different and is dependent on the local context (Campos et al., 2025). For example, it is important to bear in mind that participation opportunities are often more accessible for the hosting municipality (Dällenbach & Wüstenhagen, 2022), while neighboring municipalities might be just as or even more affected.

The combination of different disciplines and the synchronization of different measurements allowed for a new level of analysis in the present project. Outside of research projects, in the practice of regular WT operation, a similar procedure might be too laborious. However, an analysis of specific annoyance situations in cooperation with those affected, combined with acoustic, readily available meteorological data, and the operational data of the WTs, can be used to analyze problems and find solutions to mitigate them.

4.1. Limitations

There are differences in the boundary conditions of the campaigns, which especially affect the regression analyses (see section 2.1). Namely, T2 was performed at a different time of the year, resulting in different meteorological conditions, and had one WT out of operation during the entire campaign. In T3, on the other hand, the effect of varying operating modes was tested (Müller et al., 2023a), resulting in periods with reduced maximum rotational speeds of the WTs. There are also similarities, though. In particular, wind speed and perceived process fairness played an important role in two and three measurement campaigns, respectively, showing their consistent impact, despite varying conditions.

In this study meteorological data was assessed at the WF and at a measuring site nearby. In order to achieve a more precise characterization of wind direction, wind speed and temperature, especially in the vicinity of residents, meteorological measurements would have benefited from being carried out at the immission locations. The complex conditions in different types of terrain can be recorded more accurately with more measuring points.

The proportion of strongly annoyed residents in this sample is notably higher than in comparable studies, nevertheless the percentage of 33.1 % should not be over-emphasised. As a convenience sample of residents who heard WT sounds was included in the analyses and the non-response analysis shows that the response sample was more likely to be negatively affected, stressed individuals were likely oversampled in this study. Furthermore, some app users had more weight in the analyses as they were more diligent in making noise reports. While they had been given the instruction to make a report every day, the majority skipped days regularly. This issue can, most likely, not be avoided entirely, but was mitigated to some degree in T2 and T3 by calling the participants every week, reminding them about the app. A monetary incentive was not present in this study, but might have provided additional benefit.

In the municipality Kuchen, a railway line runs through the town, on which trains run regularly day and night. These have an influence, specifically, on the measurement data at the residential buildings. By analyzing a day with an available train timetable these signals could be identified and distinguished from WT signals. In Blumendeller (2024) it was shown that train passages lead to higher sound pressure and ground motion amplitudes at the building positions compared to signals from the WTs. Nevertheless, train signals are restricted in time and have a broad frequency range while signals associated to the WTs are continuous and clearly identifiable due to their distinct frequencies.

With regard to road traffic, no relevant influence on the measurement data at the buildings could be determined, as the busy roads were either too far away or the measurement locations were shielded from road traffic.

This study investigated one WF over the course of three years. Yet, it can deliver no comparison to the situation before the WF was there. Long-term studies that accompany the commissioning of the WTs can help to gain a comprehensive understanding of the development of annoyance. Comparing the situation before and after the commissioning of a WF is of particular value to show when the onset of annoyance is, how it diffuses among the population, and whether it increases or decreases over time.

5. Conclusion

By measuring physical parameters one can capture different signals, but not how people experience them. Therefore, an interdisciplinary approach is recommended, in order to be able to analyze and reduce noise annoyance from WTs: the combination of acoustic, meteorological, ground motion and operational data with subjective assessments by residents. With this approach, situations with WT annoyance could be described, associations could be shown, e.g., to wind speed, rotational speed or AM. However, only when also considering the individual preconceptions of the residents, annoyance could be substantially explained. The attitude to the WF and planning process fairness had a strong influence on how annoying the WT sounds were perceived.

As the perception of the planning process is closely linked to subsequent noise annoyance, the potential of a holistic planning culture for prevention should be emphasized. Typically, this means a participation beyond formal procedures with all affected stakeholder groups, and early information that is open and honest about benefits and burdens and how much can be and already is decided. In cases where mitigation measures are necessary, a differentiated annoyance analysis is recommended, working together with those affected. This can result in a beneficial situation for both those affected and the operator: questioning the affected and getting annoyance reports (e.g., via an app) can be used to specifically identify situations that are perceived as more annoying than others, such as certain weather and wind conditions. Specific mitigation measures then can be developed, targeting these situations, and thus both reducing annoyance and increasing energy yield compared to unspecific approaches, e.g., general rpm reductions.

CRediT authorship contribution statement

Florian J.Y. Müller: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Esther Blumendeller:** Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Laura Gaßner:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Po Wen Cheng:** Supervision, Resources, Project administration, Funding acquisition. **Joachim Ritter:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Johannes Pohl:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gundula Hübner:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

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.

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Appendix

Table 9
Bivariate correlations between WT noise annoyance and regression predictors (T1–T3).

	T1		T2		T3	
	r (CI)	p	r (CI)	p	r (CI)	p
Average wind speed[a]	0.26 (0.07, 0.44)	0.004	0.19 (–0.08, 0.40)	0.071	0.53 (0.34, 0.58)	<0.001
Western wind (yes / no)	–0.07 (–0.26, 0.13)	0.483	–0.04 (–0.28, 0.20)	0.736	0.43 (0.22, 0.48)	<0.001
Average rotational speed[a]	–0.01 (–0.21, 0.19)	0.456	–0.03 (–0.26, 0.22)	0.400	0.28 (0.12, 0.41)	<0.001
Variability of rotational speed[a]	0.14 (–0.06, 0.32)	0.088	0.21 (–0.10, 0.38)	0.052	0.04 (–0.16, 0.14)	0.309
L_{Aeq} 20–10 000 Hz, immission outside, hourly average	0.02 (–0.23, 0.26)	0.446	–0.12 (–0.35, 0.14)	0.175	0.52 (0.35, 0.59)	<0.001
Maximum AM depth 50–200 Hz, immission outside	–[b]	–[b]	0.19 (–0.09, 0.38)	0.074	0.16 (–0.05, 0.26)	0.029
Gamma Class (Modus), 25–97 *m*	–0.22 (–0.40, –0.02)	0.014	0.10 (–0.15, 0.34)	0.216	–0.24 (–0.33, 0.02)	0.006
Attitude towards WF	–0.14 (–0.33, 0.07)	0.094	–0.73 (–0.83, –0.59)	<0.001	–0.32 (–0.43, –0.15)	<0.001
Perceived process fairness	–[c]	–[c]	–0.51 (–0.65, –0.27)	<0.001	–0.44 (–0.53, –0.27)	<0.001
Strongly annoyed in 2020 (yes / no)	–0.09 (–0.28, 0.11)	0.181	0.59 (0.40, 0.73)	<0.001	0.32 (0.15, 0.43)	<0.001
Noise sensitivity	0.15 (–0.04, 0.34)	0.064	0.57 (0.35, 0.70)	<0.001	0.16 (0.03, 0.33)	0.025
Distance to closest WT	–0.01 (–0.21, 0.18)	0.445	–0.38 (–0.58, –0.16)	0.001	0.04 (–0.14, 0.17)	0.332

[a]Considering all operating WTs (T1, T3: 3 WTs, T2: 2 WTs).
[b]Too few detections of amplitude modulation.
[c]Variance too low, 94 % of reports "not at all fair".

Table 10
Questionnaire scale values.

Scale	Scale values						
Noise annoyance (annoyed by WT noise)	0 Not at all	1 Slightly	2 Somewhat	3 Moderately	4 Very		
Annoyance Stress Scale	0 No sounds heard	1 Sounds heard, no annoyance	2 Slightly annoyed, no symptoms	3 ≥somewhat annoyed, no symptoms	4 ≥somewhat annoyed, ≥1 symptom/month		
Noise annoyance (ISO scale)	0 Not at all	1 Slightly	2 Moderately	3 Very	4 Extremely		
Process fairness (process was fair)	0 Not at all	1 Slightly	2 Somewhat	3 Moderately	4 Very		
Property value change since WT erection	–2 Decreased a lot	–1 Decreased	0 No change	1 Increased	2 Increased a lot		
Noise sensitivity ("I am noise sensitive")	1 Strongly disagree	2 Disagree	3 Disagree somewhat	4 Agree somewhat	5 Agree	6 Strongly agree	
Distributive fairness	–3 Unfair	–2	–1	0 Neither nor	1	2	3 Fair
Attitude	–3 Negative	–2	–1	0 Neither nor	1	2	3 Positive

Data availability

The data that has been used is confidential.

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Glossary

Amplitude modulation: The change in the level of a sound signal over time, where there is a different signal modulating the fluctuation of the first one.

Amplitude modulation depth: In a sound pressure level time series, the difference between peak and trough of the amplitude modulated sound signal.

Atmospheric stability: patterns of different air layers. Neutral layering refers to a well mixed atmosphere. Stable layering refers to different air layers staying mostly separate. Instable layering refers to a situation where different air layers quickly change position, usually leading to wind gusts.

Sound pressure level: The local pressure of a sound wave relative to the ambient atmospheric pressure.

Pitch angle: Angle of a wind turbine rotor blade. The angle affects wind flow and, therefore, rotational speed.