Before–After Field Study of Effects of Wind Turbine Noise on Polysomnographic Sleep Parameters

Leila Jalali¹, Philip Bigelow¹, Mohammad-Reza Nezhad-Ahmadi², Mahmood Gohari¹, Diane Williams¹, Steve McColl¹

¹School of Public Health and Health Systems, ²Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada

Abstract

Wind is considered one of the most advantageous alternatives to fossil energy because of its low operating cost and extensive availability. However, alleged health-related effects of exposure to wind turbine (WT) noise have attracted much public attention and various symptoms, such as sleep disturbance, have been reported by residents living close to wind developments. Prospective cohort study with synchronous measurement of noise and sleep physiologic signals was conducted to explore the possibility of sleep disturbance in people hosting new industrial WTs in Ontario, Canada, using a pre and post-exposure design. Objective and subjective sleep data were collected through polysomnography (PSG), the gold standard diagnostic test, and sleep diary. Sixteen participants were studied before and after WT installation during two consecutive nights in their own bedrooms. Both audible and infrasound noises were also concurrently measured inside the bedroom of each participant. Different noise exposure parameters were calculated (LAeq, LZeq) and analyzed in relation to whole-night sleep parameters. Results obtained from PSG show that sleep parameters were not significantly changed after exposure. However, reported sleep qualities were significantly (P = 0.008) worsened after exposure. Average noise levels during the exposure period were low to moderate and the mean of inside noise levels did not significantly change after exposure. The result of this study based on advanced sleep recording methodology together with extensive noise measurements in an ecologically valid setting cautiously suggests that there are no major changes in the sleep of participants who host new industrial WTs in their community. Further studies with a larger sample size and including comprehensive single-event analyses are warranted.

Keywords: Before–after study, polysomnography, sleep disturbance, wind turbine noise

INTRODUCTION

Sleep, a natural behavioral state and a vital part of every individual’s life, involves distinct characteristics and many vital physiological changes in the body’s organs that are fundamental for physical and mental health. The physiological processes involve protein biosynthesis, excretion of specific hormones, and memory consolidation, all of which prepare the individual for the next wake period.¹ Fragmented and insufficient sleep can adversely affect general health impacting daytime alertness and performance, quality of life, and health, and potentially lead to serious long-term health effects.²

Sleep disturbance is considered the most serious nonauditory effect of environmental noise exposure.³⁻⁴ Harnessing wind energy has resulted in a new source of environmental noise, and wind is one of the fastest growing forms of electricity production worldwide. Canada’s current installed capacity is over 10,000 MW, with an anticipated minimum of 55,000 MW by 2025.⁵ This growth in wind energy development is not without controversy, as health effects such as noise annoyance and sleep disturbance have been reported by residents living close to wind developments.⁶⁻⁹ Such reports are increasing in Canada and worldwide, despite the adoption of setbacks and other measures that have been effective for other sources of noise pollution.

A number of different methods have been used to assess noise effects on sleep quality, such as questionnaires, signal-led awakenings, actigraphy, and various physiological recordings obtained by polysomnography (PSG). PSG is the most

Address for correspondence: Dr. Leila Jalali, School of Public Health and Health Systems, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, Canada. E-mail: l2jalali@uwaterloo.ca

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comprehensive method of evaluating sleep and deemed the gold standard for measuring sleep. It is most often used in laboratory settings; however, with the recent emergence of portable wireless PSG systems and sleep monitoring devices, high-quality home sleep assessment has become a reality. At present, portable computerized PSG in unattended home settings is a viable alternative to laboratory-based systems for obtaining adequate sleep recordings. Sleep recordings obtained at home using portable PSG also has advantages because sleep patterns in the laboratory may not be representative of typical sleep as participants must adapt to the unfamiliar environment. Testing location is also important when studying the effects of environmental noise on sleep, as people may adapt to noise in their home setting. Moreover, in a laboratory, it is difficult to generate some types of environmental noises, and noise from wind turbines (WTs) is especially problematic because of its significant low-frequency component.

This study aims at comparing the sleep of residents before and after exposure to WT noise, using in-home polysomographical recordings and simultaneous indoor noise measurement.

**METHODS**

**Participant and study design**

This research employed a multidisciplinary approach and prospective cohort design with subjective sleep diaries, and synchronous measurement of physiological sleep signals and indoor noise. Participants were recruited from Ontario, Canada, in an area where WTs were scheduled to be installed in near future (June 2014). Five Vestas V100-1.8 MW turbines, with hub heights of 90 m and rotor diameters of 100 m, were planned to be installed in open and flat agricultural fields. Turbines had an estimated power of about 26 million kW per year. Residents who lived within 2000 m radius from the underconstruction turbines and met further criteria required for valid and reliable home sleep assessment (over 18 years of age, general good health, no known sleep disorder, no children under 5 years of age living in the same household, no regular nightshift work, not being regularly disturbed during the night by other noise sources such as traffic or trains, no regular use of sleeping pills, and no hearing loss (one or both ears, self-reported, not confirmed by audiometry)) were eligible for participation. The study was conducted in two time periods. The first time of data collection (T1) was conducted postturbine erection but preoperation to avoid construction noise effects on sleep quality (May to June 2014). The second time of data collection (T2) occurred after the turbines became operational and it happened from September to October to minimize seasonal and temperature effects. Participants were also asked to fill a rescreening form before T2 to point out any changes to sleep environment as well as health condition that might affect the sleep compared with T1.

Participants slept for two consecutive nights in their own bedroom with the recording equipment and were encouraged to follow their normal sleeping habits. A trained sleep technician along with a researcher with expertise in acoustical assessment installed the noise measurement instrumentation, performed all PSG sensor applications, checked for signal impedances, and performed calibrations and instrument diagnostic tests. These visits were scheduled so as not to interfere with participants’ habitual bedtime routine. The participants were free to have the bedroom window in their usual position (open or closed during the night). In each case, the position of the bedroom window was noted by the researcher. Polysomnographic recordings were obtained from a Somte PSG (Compumedics, Melbourne, Australia) sleep system. As the first nights served for adaptation of participants, only results from the second nights were analyzed. The start and stop of sleep recordings were preset by the technician according to each participant’s reporting of expected bedtime and final awakening. Sleep data were stored on a computer using a PSG digital system.

Participants were also provided with sleep diaries and asked to enter information over a period of one week. These diaries enabled participants to record their times of going to bed, attempting to fall asleep, waking up and getting out of bed, nocturnal awakenings, and daytime napping periods. In addition, subjective ratings of sleep quality, depth of sleep, mood and stress level, and how rested participants felt were recorded. Participants also answered a series of behavioral questions such as whether they slept with the windows open, and if they used earplugs or other sleep aids. The designed diary had two sections: one filled at bedtime and another in the morning.

Sleep-related physiologic signals were obtained by six electroencephalograms (EEGs) (C3/A2-C4/A1, O3/A2-O4/A1, F3/A2-F4/A1), positioned according to the 10–20 international electrode placement system, right and left electrooculograms, five electromyograms (EMGs; submental, anterior tibialis), and left and right electrocardiograms (ECGs). To screen for breathing-related sleep disorders such as central or obstructive sleep apnea as well as periodic leg movements, the following data were also collected: finger pulse rate, oxygen saturation (finger pulse oximeter), nasal air flow (nasal cannula), respiratory movements (two piezoelectric belts), body position, and leg movements.

Each PSG recording was scored manually (using Profusion 3 software from Compumedics) and blindly (regarding noise exposure and distance) by an experienced sleep technician in 30-s epochs according to the standard developed by the American Academy of Sleep Medicine (AASM). From these data, the following sleep parameters were derived:

1. Sleep period (SLP), defined as the time elapsed from sleep onset to final awakening;
2. Sleep onset latency (SOL), defined as the period of time between reported lights out.
and 2 min of unbroken sleep; (3) time spent in stages one and two (S1, S2); (4) rapid eye movement (REM); (5) slow wave sleep (SWS); (6) wake up time after sleep onset (WASO), defined as total amount of time awake excluding SOL; (7) total sleep time (TST), which is SLP minus WASO; (8) sleep stage changes to a lighter stage (SSC), that is, S1 to wake, S2 to S1 or wake, SWS to S2, S1 or wake, REM to S2, S1 or wake; (9) apnea–hypopnea index; (10) periodic limb movement index (PLM); and (11) arousal index. An arousal is defined as an abrupt and transient shift of EEG frequencies consisting of alpha, theta, and/or frequencies greater than 16 Hz. In this study, arousals were classified according to the criteria published in AASM[14] and divided into spontaneous (SP) arousals, respiratory-event (RE)-related arousals (arousals following apnea or hypopnea), and arousals associated with PLMs (LM arousals). Only the SP arousals were hypothesized to be related to noise; hence, the other types of arousals were scored but not directly analyzed with regard to noise exposure.

Noise exposure assessment

A noise measurement system was placed in participant’s bedroom to record both audible and low-frequency noise for the duration of their sleep. The system was programmed to turn on and off automatically at the start and end of each period. The indoor microphone was fitted with a windscreen and mounted on a microphone stand in the bedroom at a location close to the participant’s head, at the same height as the sleeping person and 1 m horizontally from the participant’s head. A Soundbook analyzer (MK1) (Sinus/Mestechik, Germany) was used with a G.R.A.S 40AZ low-frequency microphone. The whole system is capable of measuring noise in the 0.5 Hz to 20 KHz frequency range. The system was calibrated before and after each recording using a known frequency (250 Hz) and sound pressure level (SPL) (114 dB) source. The results of the sound measurements and recordings were transferred from the Soundbook to a personal computer. Further processing and calculations were performed using the software package Samuari 2.6.

Indoor noise was measured at two participants’ residences, varying each night, for total of 16 nights before and 16 nights after operation of the turbines. In total, 64 sets of data were collected. For each night and each residence, noise data were recorded for 10 h. For each participant, two cuts of full data were analyzed. The first cut was noise measurement for the period that the participant was in bed (TIB, from lights off to lights on). The second cut was noise measurement for one hour (1H) during the night at a point when inside spikes (eg, coughing, snoring, and dog barking) were minimal. Z and A-weighted parameters for TIB and 1H noise (LAeq – TIB, LZeq – TIB, and LAeq – 1H, LZeq – 1H) were measured for each night, respectively. Frequency band for Z-weighted noise parameters was from 5 Hz to 20 KHz. The sound analyzer was time synchronized to the sleep recording instrumentation.

In addition to noise measurements, weather, temperature, and wind speed data were collected from the companies that had weather stations close to the location of the study. Wind speed data, taken at 10 m height, was used for before and after analysis of noise versus wind speed, from the closest weather station to the WT. In addition, wind speed and temperature data, taken at 95 m height at the location of WT, were used for after turbine operation analysis. The wind speed data at the height of 95 m is average of wind speed at the location of five turbines. It provides more accurate insight into the relationship of the measured indoor noise and wind speed at the height of 95 m where the turbine blades are interacting with wind and generating low-frequency noise.

Participants’ noise sensitivity and attitude to WT were measured on a 5-point scale ranging from “not at all sensitive” to “very sensitive” and “very positive” to “very negative,” respectively. Noise sensitivity and attitude were dichotomized into “not sensitive” and “sensitive” (1–3 vs 4–5, respectively), and attitude into “not negative” and “negative” (1–3 vs 4–5, respectively).

This study was reviewed and received ethics clearance by the University of Waterloo Research Ethics Committee, Waterloo, Ontario, Canada, and written consent was obtained from all participants prior to the study. A certified sleep technician performed, monitored, and scored all PSG recordings.

Statistical analysis

All analyses were performed using SPSS, Version 22 for the Windows 8 operating system (IBM Corp). Normality assumption were examined using Shapiro–Wilk tests and descriptive statistics, including means and standard deviations (SDs), were performed on a number of dependent and independent variables for sleep parameters. Comparisons before and after exposure for objective sleep variables that could be treated as continuous variables (sleep duration, number of awakenings) were performed by paired t tests or the Wilcoxon signed rank test, as appropriate. For subjective sleep ratings, McNemar tests were used. For normal data, an independent samples t test was used to compare the means of variables for two independent groups. Nonparametric tests such as Mann–Whitney test was used to compare mean differences of measures in two independent groups. Spearman’s rank correlation coefficients were calculated to determine the strength of the relationship between the noise exposure parameters and the sleep parameters. The threshold level for statistical significance was established at P < 0.05.

In addition, an event-related analysis was performed on a few participants at different distances from the WT and with different levels of wind speed. A time period of 60 s (two sleep epochs) after a high level of noise was screened for sleeper reactions.

Results

Table 1 shows the demographic characteristics of the participants. Ten women and six men with a mean age of
55.9 years participated in the study. All participants lived on farms or in single detached houses; 87.5% could see at least one WT from their dwelling, and 62.5% lived at a distance of less than 1000 m from the nearest turbine. Regarding the noise sensitivity, 12.5% of participants were “rather or very sensitive” to noise.

Table 2 compares different sleep factors from T1 and T2 observation. All scorings were judged to be of sufficient quality to provide reliable sleep staging and EEG arousal data. Calculation of SOL relied on the participant’s reporting of lights out. There were no significant differences between measured sleep factors in T1 and T2 observations. Neither sleep discontinuity factors (WASO, duration of S1 sleep, SSC and the number of awakenings) nor sleep quantity factors (TST and duration of S2 sleep) showed any significant changes after the new exposure. The difference between mean number of arousal indices in T1 and T2 of changes after the new exposure. The difference between (TST and duration of S2 sleep) showed any significant and the number of awakenings) nor sleep quantity factors (WASO, duration of S1 sleep, SSC measured sleep factors in T1 and T2 observations. Neither of lights out. There were no significant differences between.

Regardless of exposure presence, sleep efficiency, arousal index, SSC, and WASO in both T1 and T2 of observation were strongly related to age; older adults (>55) had lower sleep efficiency (P < 0.001), higher number of arousals (P = 0.041), higher number of SSC (P = 0.016), and longer awakening (P < 0.001) than middle-age group (30–55 years old). The distribution of all sleep factors did not significantly differ between men and women.

Tables 3–5 compare changes of sleep factors over time based on age, sex, distance, bedroom, and window situation. REM sleep latency is decreased in middle age but increases in older adults after exposure (P = 0.042); SSC also changed in different ways for men and women, with men having more SSC after exposure than women (P = 0.042).

Sleep quantity and sleep quality were compared using sleep diary data from before and after exposure. Total sleep time (P = 0.472), number (P = 0.126), and length (P = 0.062) of awakenings and sleep latency (P = 0.942) did not change significantly after exposure. However, reported quality of sleep significantly declined after exposure (P = 0.008). Participants also reported higher levels of stress before bedtime (P = 0.039) and in the morning (P = 0.064), and

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**Table 1: Demographic Characteristics of Participants in Wind Turbine and Sleep Study, Ontario, Canada**

| Variable                  | N   | %   |
|---------------------------|-----|-----|
| Gender                    |     |     |
| Male                      | 6   | 37.5|
| Female                    | 10  | 62.5|
| Marital status            |     |     |
| Married/common law        | 14  | 87.4|
| Separated or widow        | 2   | 12.6|
| Occupation                |     |     |
| Full-time employment      | 8   | 50  |
| Retired                   | 5   | 31.3|
| Part-time/self-employment | 3   | 18.7|
| Post-Graduate college/university | 13  | 81.2|
| High school diploma/less than secondary | 3   | 18.8|
| Own their home            |     |     |
| Yes                       | 16  | 100 |
| Rented or others          | 0   |     |
| Distance to nearest turbine |   |     |
| <1000 m                   | 10  | 62.5|
| >1000 m                   | 6   | 37.5|
| Turbine visibility        |     |     |
| Yes                       | 14  | 87.5|
| No                        | 2   | 12.5|
| Bedroom facing wind turbine |   |     |
| Yes                       | 14  | 87.5|
| No                        | 2   | 12.6|
| Bedroom location          |     |     |
| First floor               | 9   | 56.3|
| Second floor              | 7   | 43.8|
| Double glass window       |     |     |
| Yes                       | 13  | 81.3|
| Not answered              | 3   | 18.7|
| Noise sensitivity          |     |     |
| Not or slightly sensitive | 12  | 75  |
| Rather or very sensitive  | 2   | 12.5|
| Not answered              | 2   | 12.5|
| Attitude to turbines      |     |     |
| Negative                  | 8   | 50  |
| Neither negative or positive |   | 12.5|
| Positive                  | 6   | 37.5|
| Owned the land where wind turbine is located | 3 | 18.8|
| Age (mean, range)         | 55.94 | (39, 78) |

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**Table 2: Comparison of Mean Sleep Factors at Time 1 and Time 2 of Observations, Wind Turbine and Sleep Study, Ontario, Canada**

| Sleep factors     | Time 1 (Mean ± SD) | Time 2 (Mean ± SD) | P value |
|-------------------|--------------------|--------------------|---------|
| Wake after sleep onset (WASO, min) | 34.81±25.95 | 34.37±26.92 | 0.950 |
| Stage 1 of sleep (%) | 16.25±7.54 | 16.16±6.96 | 0.953 |
| Sleep stage changes (SSCs)/h | 9.25±2.78 | 8.66±2.80 | 0.444 |
| Number of awakenings | 20.50±10.37 | 17.63±9.19 | 0.145 |
| Sleep efficiency (SE)% | 88.5±7.06 | 89.40±6.87 | 0.634 |
| Sleep period (SLP, min) | 415.12±71.64 | 437.07±53.44 | 0.281 |
| Total sleep time (TST, min) | 380.31±68.80 | 402.13±36.44 | 0.226 |
| Stage 2 of sleep% | 56.94±9.45 | 58.17±6.70 | 0.526 |
| Slow wave sleep (SWS)% | 7.33±7.14 | 5.72±5.58 | 0.145 |
| REM sleep% | 19.47±3.70 | 19.94±5.02 | 0.728 |
| Spontaneous arousal/h | 10.48±5.25 | 8.91±3.65 | 0.179 |
| Respiratory arousal | 3.39±4.42 | 2.72±3.53 | 0.298 |
| Limb movement arousal | 0.53±1.81 | 0.1±0.25 | 0.001 |
| REM sleep latency | 90.37±42.60 | 88.84±36.62 | 0.871 |
| Sleep latency (min) | 14.91±17.73 | 11.06±16.88 | 0.371 |
### Table 3: Changes of Sleep Discontinuity Factors Over Time by Age, Sex, Distance, Bedrooms, and Windows Situation; Wind Turbine and Sleep Study, Ontario, Canada

| Variables         | Wake after Sleep Onset | Sleep Stage Changes | Spontaneous Arousal | Number of Awakenings |
|-------------------|------------------------|---------------------|---------------------|----------------------|
|                   | Time 1 | Time 2 | P value | Time 1 | Time 2 | P value | Time 1 | Time 2 | P value |
| Men               | 34.67±30.16 | 32.25±20.69 | 0.958 | 8.58±2.43 | 9.65±2.43 | 0.042* | 7.93±3.96 | 7.51±1.86 | 0.428 | 20.83±10.24 | 17±11.47 | 0.706 |
| Women             | 34.90±24.85 | 35.65±31.07 | 9.66±2.02 | 8.06±2.96 | 12.01±5.50 | 9.79±4.27 | 1.00 | 8.83±3.16 | 7.61±1.33 | 16.67±9.27 | 16.22±9.31 | 0.146 |
| Middle age        | 8.51±15.82 | 8.21±1.68 | 0.378 | 9.68±3.49 | 10.58±5.02 | 2.3010.98 | 19±8.98 | 19.43±9.43 |
| Older adult<sup>a</sup> | 53.64±28.18 | 52.43±28.33 | 10.60±3.43 | 9.91±3.22 | 12.47±6.87 | 10.58±5.02 | 25.43±10.17 | 19.43±9.43 |

*P value is significant at <0.05. *Middle age considered 30–55 years and older adult considered >55 years.

### Table 4: Changes in Sleep Quality Parameters Over Time by Age, Sex, Distance, Bedrooms, and Windows Situation; Wind Turbine and Sleep Study, Ontario, Canada

| Variables         | Sleep latency | Total sleep time | Sleep efficiency |
|-------------------|---------------|------------------|------------------|
|                   | Time 1 | Time 2 | P value | Time 1 | Time 2 | P value | Time 1 | Time 2 | P value |
| Men               | 9.92±9.93 | 9.0±12.61 | 0.604 | 380.3±49.13 | 384.2±29.28 | 0.328 | 89.97±4.52 | 87.91±6.95 | 0.230 |
| Women             | 17.90±21.05 | 12.30±19.54 | 0.660 | 380.3±80.92 | 411.10±37.53 | 0.918 | 87.62±8.34 | 90.29±7.04 |
| Middle age<sup>a</sup> | 9.06±8.16 | 6.67±10.71 | 0.470 | 376.05±49.15 | 389.17±34.39 | 0.623 | 92.73±3.50 | 93.95±4.37 | 0.918 |
| Older adult<sup>a</sup> | 22.43±24.09 | 16.71±22.21 | 0.657 | 385.79±92.47 | 421.58±33.70 | 0.853 | 83.05±6.86 | 84.01±5.70 |

*Middle age considered 30-55 years and older adult considered >55 years.
also reported feeling more sleepy ($P = 0.013$) in the morning and throughout the day ($P = 0.014$) after exposure.

Of participants, 90.1% in T1 and 96.1% in T2 believed that outside noise did not wake them up and no one reported waking up to close their windows because of the outside noise (33.7% of participants in T1 and 44.8% of them in T2 slept with open windows).

**Noise and wind data analysis**

The means of wind and temperature data from 10:00 pm to 8:00 am for each night were used in the analysis. The means of wind speed, at height of 10 m, were not significantly different ($P = 0.559$) between T1 and T2 periods of observation: 3.64 m/s (SD = 1.19) in T1 and 3.33 m/s (SD = 1.39) in T2. The mean of wind speed at hub height for exposure nights was 6.48 (SD = 1.84) m/s, with a range of 3.70–9.40 m/s. The cut-in wind speed for the turbines was 4 m/s. The average A-weighted noises measured in T1 and T2 observation were not significantly different with means of 36.55 dBA (SD = 4.18) in T1 and 36.50 dBA (SD = 4.20) in T2 for TIB ($P = 0.959$) and mean of 31.52 dBA (SD = 5.16) in T1 and 31.23 dBA (SD = 4.91) in T2 for 1H ($P = 0.740$). The average Z-weighted noises measured in T1 and T2 observation were also not significantly different with means of 63.78 dBZ (SD = 25.75) in T1 and 61.93 dBZ (SD = 36.07) in T2 for TIB ($P = 0.218$) and mean of 59.93 dBZ (SD = 27.33) in T1 and 57.44 dBZ (SD = 28.49) in T2 for 1H ($P = 0.090$).

Figures 1a and b show the Z-weighted noise exposure for TIB and 1H for T1 and T2 of observation versus wind speed at the height of 10 m. Increasing trends in the noise level are observed by increasing wind speed and slope of noise at T2 is higher than T1 for both TIB and 1H noise equivalent; for TIB, the slope of noise is 3.22 ($P < 0.001$) for T2 versus 2.01 for T1 ($P = 0.001$), and for 1H noise, the slope of noise is 3.15 ($P < 0.001$) at T2 versus 2.60 at T1 ($P < 0.001$).

Figures 2a and b show the A-weighted noise exposure for TIB and 1H for T1 and T2 of observation versus wind speed at the height of 10 m. Increasing trends in the noise level are observed by increasing wind speed; however, none of the findings were significant. For TIB, the slope of noise is 0.75 for T2 ($P = 0.247$) versus 0.82 for T1 ($P = 0.136$), and for 1H noise the slope of noise is 0.17 ($P = 0.823$) at T2 versus 0.32 ($P = 0.638$) at T1.

Figures 3 and 4 demonstrated the Z-weighted and A-weighted noise exposure at T2 for TIB and 1H versus wind speed at the height of 95 m, respectively. The slopes of Z-weighted noise versus wind speed are 2.23 for TIB ($P < 0.001$) and 2.36 for 1H ($P < 0.001$). The slopes of A-weighted noise versus wind speed noise are 0.63 for TIB ($P = 0.171$) and 0.24 for 1H ($P = 0.650$).

Figures 5 and 6 identify the relationship between distance from the closest WT and noise levels ($L_{Aeq}$, $L_{Zeq}$) for TIB and 1H. Results of Spearman’s correlation indicate that there is no significant correlation between distance and inside noise after
exposure ($L_{Aeq} - TIB$: Spearman’s $r = -0.047$, $P = 0.862$, $L_{Aeq} - 1H$: Spearman’s $r = -0.353$, $P = 0.180$, $L_{Zeq} - TIB$: Spearman’s $r = -0.230$, $P = 0.392$, $L_{Zeq} - 1H$: Spearman’s $r = -0.080$, $P = 0.769$).

Figure 7a and b provides an example of typical low-frequency waveform swing measured inside the bedroom at a distance of 550 m from the turbines at T2. All the noise recordings were observed to identify nonrelevant peak noise levels. For this particular example, the measured peak of noise is 0.7 Pa that is approximately equivalent to SPL of 91 dB. The peak of noise signal varies from 57 to about 91 dB that is about 34 dB variation on the amplitude of the noise signal.

**Associations between noise exposure and sleep parameters**

The Spearman’s rank correlation coefficients were used for the associations between average noise difference ($L_{Aeq} 2 - L_{Aeq} 1$) and sleep factors difference in T1 and T2 of study. Noise difference correlated with the difference in the number of awakenings ($r = 0.605$, $P = 0.001$), SSC difference ($r = 0.600$, $P = 0.001$), arousal difference ($r = 0.551$, $P = 0.004$), and percentage of S2 difference ($r = -0.499$, $P = 0.009$).
DISCUSSION

A detailed analysis of the individual sleep epochs measured by PSG in the present study showed no major changes in the sleep of participants residing near new industrial WTs in their community. The analysis considered the possible effects on whole-night sleep parameters, sleep discontinuity (increased number and length of awakenings, number of sleep stage changes, and length of shallow...
sleep), sleep quantity and quality (reduced total sleep time, reduced stage 2, and REM and SWS sleep), and sleep efficiency. Previous noise–effect studies have regarded SSC as the primary indicator for disturbed sleep. The number of SSCs per hour, measured in this present study, remained unchanged after exposure. The effects on sleep obtained by sleep diary support findings from PSG with regard to sleep quantity, whereas perceived sleep quality measured by sleep diary decreased after exposure to WTs.

A total of 640 night-hours of indoor noise measurement on 32 nights were performed, at different distances and locations, before and after turbine operation. Results of the noise measurement showed that average noise levels during the exposure period were low to moderate, with an average of 31.29 dBA in 1H with minimal indoor spikes. The mean of inside noise levels did not significantly change after turbines operation. Outside sound monitoring also was performed at four residential houses before and after exposure. The outside...
sound levels ranged between 40 and 45 dBA before and 38 and 42 dBA after the turbines became operational. These results also indicate that the wind farm project resulted in no significant changes in the ambient SPLs in the surrounding area.

Previous studies, investigating the relationship between sleep and WT noise, mostly had cross-sectional designs and were based on self-reported symptoms. Only two studies measured objective sleep parameters in relation to WT sound exposure. In general, the current findings are consistent with the results of those two objective studies, however, their study designs were different with the current study and both used actigraphy for measuring sleep and did not compare the sleep data before and after exposure. Lane et al. studied 11 exposed and 10 unexposed individuals to WTs, respectively, and found no significant changes for the worse in sleep parameters in the exposed group. Results of a very recent large study, conducted by Health Canada, provided the most comprehensive assessment of the association between exposure to WT noise and sleep and showed that outdoor WT noise levels near participants’ homes were not associated with sleep factors measured by actigraphy, such as sleep efficiency, the rate of awakenings, duration of awakenings, total sleep time, or sleep latency.

Sleep disturbances are often indicated by body movements, which are easier to record and much easier to evaluate than polysomnogram. The current study relied on polysomnogram that recorded and evaluated according to internationally accepted criteria and it provides information about sleep depth, and reliably detected EEG arousals. Basner et al. showed that for low maximum SPLs and chronic exposure situations with partial adaptation, the strongest association between noise and effects on sleep was observed for EEG arousals. In the present study, the mean of spontaneous arousal indices did not change significantly after exposure.

Failing to find an association between noise exposure and any of the sleep parameters might be because of the relatively low level of indoor noise. Adaptation to moderate levels of noise is possible because of the more continuous character of the noise; Aasvang et al. also found that people were more easily habituated to continuous traffic noise compared with intermittent rail road sounds. Some adaptation processes might have happened to compensate for sleep disruption throughout the night and produce no or minimal global effect on sleep. Basner et al. suggested that traffic noise events may cause awakenings in study participants, but these awakenings replaced the majority of awakenings that would otherwise have spontaneously occurred.

An event-related analysis was performed on three participants at different distances from the WTs and with different levels of wind speed. The results varied; in some observations, arousals were immediately captured after WT noise events (high peak level of noise), as shown in Figure 8, and in some, no changes were observed in participants’ physiological signals. The reactions of participants to noise was nonspecific, as is the case in most studies, and it was unclear whether these reactions were induced by noise or spontaneous. Basner used a

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Figure 8: Sleeper’s reactions to a single noise event at a distance of 1986 m from the turbine
formula in his study to calculate sleep reactions induced by noise. However, in the current study, the numbers of noise events were limited and mostly moderate, and drawing a conclusion would have needed more rigorous and detailed analyses with larger sample size.

Discrepancies between subjective and objective evaluations of sleep, such as those found in this study, are not surprising and have been previously explained in other studies. Jackowska et al.\[^{22}\] pointed out that people’s judgments of sleep efficiency are associated with psychosocial stress and affective responses. Concern about environmental changes, especially those associated with new but nonperceptible exposures, such as low-frequency noise, appear to act as a trigger for such reports of ill health.\[^{23,24}\] Self-reported sleep disturbance may also be associated to the indirect effects of individual differences such as visual and attitudinal factors.\[^{25}\]

Further research into the effects of WTs on sleep quality, emotions such as preconstruction and postconstruction anxiety, and fear for health is warranted.

Several points need to be considered; because of the field study design, there was a lack of control, both with regard to the exposure levels and wind speed, and with other possible sources of variation that might affect results.

A potential source of bias for repeated measure studies is “order effects” in which repeated uses of a diagnostic test such as PSG influence dependent variables. In the current study, contrary to expectation, the mean arousal index in T1 was higher than the same index in T2 of observation ($P = 0.079$). This result might be related to “order effect,” and participants might get used to the system after frequent uses, and there is no way to control for it.

Slight improvement in sleep and lower arousal index in T2 may also be explained by possible lower stress and anxiety after turbine operations. Any new WT development could be a source of concern as residents do not know the outcome, and could lead local people to ruminate about this new change. Rumination, such as worry, functions as a source of presleep cognitive arousal and interferes with sleep quality, perhaps causing sleep-related difficulties.\[^{26}\] After WTs operation, most probably residents accepted this new change in the community and they found the turbines less disturbing than anticipated.

Some operational characteristics of WTs may also have impacted the study. Exposure to WT sound occurs irregularly, and people living in the vicinity of turbines are not exposed every night; examination of sleep quality in one night may be affected by WT noise and sleep quality in the nights preceding data collection. Moreover, several other factors impact measurement and exposure to WT noise, including characteristics of the participant’s home, weather conditions, local flora and topography, and the number of and layout of the turbines. Larger wind farms tend to generate more noise than smaller ones, as several WTs in the same vicinity can lead to increased pulse sounds, with increased SPLs of 5 dB.\[^{27}\] It is also common for old turbines to operate at a fixed speed, or perhaps at one or two fixed speeds, depending on the wind speed. However, new turbines are fully variable in blade
rotational speed and so are able to operate at the most efficient rotational speed across a wide range of wind speeds. The result of this technological improvement is that at low speeds of rotation in light winds, noise emissions are lower. Further research is needed to evaluate sleep quality in residents living adjacent to older WTs.

The strength of this study is that it involved baseline noise and infrasound monitoring and objective and subjective sleep assessments during turbine construction and follow-up during the operation period. This study is the first published study of WT-related sleep disturbances assessed using polysomnographic techniques while simultaneously collecting inside SPLs. Further studies should be performed involving the simultaneous field collection of PSG and noise signals but with a large sample size and including comprehensive single-event analyses.

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Conflicts of interest
There are no conflicts of interest.

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