

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

Leila Jalali<sup>1</sup>, Philip Bigelow<sup>1</sup>, Mohammad-Reza Nezhad-Ahmadi<sup>2</sup>, Mahmood Gohari<sup>1</sup>, Diane Williams<sup>1</sup>, Steve McColl<sup>1</sup>

<sup>1</sup>School of Public Health and Health Systems, <sup>2</sup>Department 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 ( $L_{Acq}$ ,  $L_{Zcq}$ ) 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.<sup>[1]</sup> 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.<sup>[2]</sup>

Sleep disturbance is considered the most serious nonauditory effect of environmental noise exposure.<sup>[2–4]</sup> 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.<sup>[5]</sup> 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.<sup>[6–9]</sup> 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

This is an open access article distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 License, which allows others to remix, tweak, and build upon the work noncommercially, as long as the author is credited and the new creations are licensed under the identical terms.

**For reprints contact:** [reprints@medknow.com](mailto:reprints@medknow.com)

**How to cite this article:** Jalali L, Bigelow P, Nezhad-Ahmadi MR, Gohari M, Williams D, McColl S. Before–after field study of effects of wind turbine noise on polysomnographic sleep parameters. *Noise Health* 2016;18:194-205.

Access this article online

Quick Response Code:



Website:

[www.noiseandhealth.org](http://www.noiseandhealth.org)

DOI:

10.4103/1463-1741.189242

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.<sup>[10]</sup> 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.<sup>[11]</sup> Testing location is also important when studying the effects of environmental noise on sleep, as people may adapt to noise in their home setting.<sup>[12,13]</sup> 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 polysomnographical 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).<sup>[14]</sup>

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) wakeup 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<sup>[14]</sup> 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/Messtechnik, 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 Samurai 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 ( $L_{Aeq} - TIB$ ,  $L_{Zeq} - TIB$ , and  $L_{Aeq} - 1H$ ,  $L_{Zeq} - 1H$ ) 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 WTs. In addition, wind speed and temperature data, taken at 95 m height at the location of WTs, 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 WTs 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 WTs 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 observation was not significant ( $P=0.079$ ), with the mean of 15.92 (SD = 7.15) in T1 and 13.23 (SD = 5.29) in T2. The

mean of REM sleep and sleep efficiency remained unchanged after exposure. The percentage of SWS decreased after exposure; however, this change was not significant ( $P=0.145$ ). The mean of sleep latency remained unchanged and, in general, all the participants in T2 except two had SOL less than 20 min. Those two participants with long sleep latency also had long SOL in T1.

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

**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
Education	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	2	12.5
	Positive	6	37.5
Owned the land where wind turbine is located		3	18.8
Age (mean, range)		55.94 (39, 78)	

**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 awakening	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	0.284
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	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	<b>0.042<sup>a</sup></b>	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±3.02	8.06±2.96		12.01±5.50	9.75±4.27		2.30±10.98	18±8.21	
Middle age	20.17±11.03	20.33±15.82	0.758	8.21±1.68	7.68±2.12	0.837	8.93±3.16	7.61±1.33	1.00	16.67±9.27	16.22±9.31	0.146
Older adult <sup>b</sup>	53.64±28.05	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	
Distance (m)												
<1000 m	32±25.32	29.65±18.92	0.635	8.54±1.88	8.64±3.49	0.428	9.68±3.59	8.90±3.14	0.635	19±8.98	18.10±10.53	0.181
>1000 m	39.50±28.73	42.25±37.57		10.44±3.75	8.70±1.27		11.82±7.48	8.93±4.72		23±12.85	16.83±7.25	
Bedroom's floor:												
First	22.72±13.50	30.50±34.08	0.252	8.12±1.62	7.67±2.11	1.000	8.78±3.22	7.62±1.34	0.918	14.67±8.15	14.67±8.41	0.080
Second	50.35±30.66	39.36±14.57		10.71±3.38	9.92±3.21		12.67±6.71	10.57±5.02		28±7.96	21.43±9.32	
Window at bedtime												
Close	25.17±9.74	25.50±17.42	0.324	8.83±1.77	8.45±2.03	0.260	9.25±3.81	7.82±1.57	0.252	19.67±9.81	19.33±10.17	0.105
Open	42.94±32.10	38.83±32.66		9.58±3.50	8.21±2.89		11.39±6.35	8.72±3.74		20.78±11.83	14.67±6.95	

<sup>a</sup>P value is significant at <0.05. <sup>b</sup>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	Time 1	Time 2	P	Time 1	Time 2	P
Men	9.92±9.93	9.0±12.61	0.604	380.33±49.13	384.20±29.28	0.328	89.97±4.52	87.91±6.95	0.230
Women	17.90±21.05	12.30±19.54		380.30±80.92	411.10±37.63		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	93.59±4.37	0.918
Older adult	22.43±24.09	16.71±22.21		385.79±92.47	421.58±32.70		83.05±6.86	84.01±5.70	
Distance m									
<1000	15.10±19.30	9.85±19.72	0.678	387.65±77.57	406.11±34.97	0.647	89.30±7.09	89.99±7.21	0.890
>1000 m	14.58±16.53	13.08±12.13		368.08±55.54	396.16±41.12		87.17±7.48	88.42±6.81	
Bedroom floor:									
First	13.05±13.36	7.50±10.46	0.657	359.61±51.11	391.56±36.91	0.351	90.82(6.16)	91.71±6.57	0.995
Second	17.29±23.17	15.64±22.87		406.93±82.96	418.0±32.18		85.51(7.47)	86.43±6.50	
Window at bedtime:									
Close	10.83±9.60	7.66±13.25	0.197	368.66±49.84	390.66±27.69	0.774	91.05(2.81)	92.27±4.88	0.881
Open	14.33±20.25	7.27±5.43		369.39±59.60	403.06±38.17		86.68(8.94)	88.49±7.51	

<sup>a</sup>Middle age considered 30–55 years and older adult considered >55 years.

**Table 5: Changes in Deep and REM Sleep Parameters Over Time by Age, Sex, Distance, Bedrooms, and Windows Situation; Wind Turbine and Sleep Study, Ontario, Canada**

Variables	Slow wave sleep		REM sleep		REM sleep latency		P-V
	Time 1	Time 2	Time 1	Time 2	Time 1	Time 2	
	P-V	P-V	P-V	P-V	P-V	P-V	
Men	5.98±6.43	4.37±5.10	19.88±4.42	20.20±7.28	87.33±44.62	83.67±41.06	0.635
Women	8.14±7.75	6.53±5.96	19.23±3.43	19.79±3.52	92.20±43.68	91.95±35.65	
Middle age <sup>a</sup>	8.60±8.37	6.94±6.62	19.88±4.74	20.32±5.05	94.00±32.07	92.73±3.50	0.042 <sup>b</sup>
Older adult	5.70±5.35	4.14±3.77	18.96±1.91	19.46±5.32	82.21±43.49	83.05±6.86	
Distance							
<1000 m	8.25±8.18	6.91±5.82	19.09±3.07	19.95±5.45	88.70±36.56	78.75±32.83	0.428
>1000 m	5.80±5.31	3.73±4.99	20.12±4.81	19.93±4.68	93.17±54.98	105.67±88.84	
Bedroom floor:							
First	9.16±8.39	6.16±6.84	19.47±4.53	20.80±4.95	78.0±25.59	90.17±30.25	0.071
Second	4.98±4.73	5.16±3.84	19.49±2.60	18.84±5.27	106.28±56.02	87.14±46.12	
Window at bedtime:							
Close	8.28±9.13	5.60±6.46	20.05±5.52	20.10±4.59	76.92±19.50	95.25±36.19	0.169
Open	7.47±5.90	6.14±5.55	18.96±2.41	20.08±5.77	96.44±53.87	83.50±40.27	

<sup>a</sup>Middle age considered 30–55 and older adult considered >55. <sup>b</sup>P-value is significant at <0.05.

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

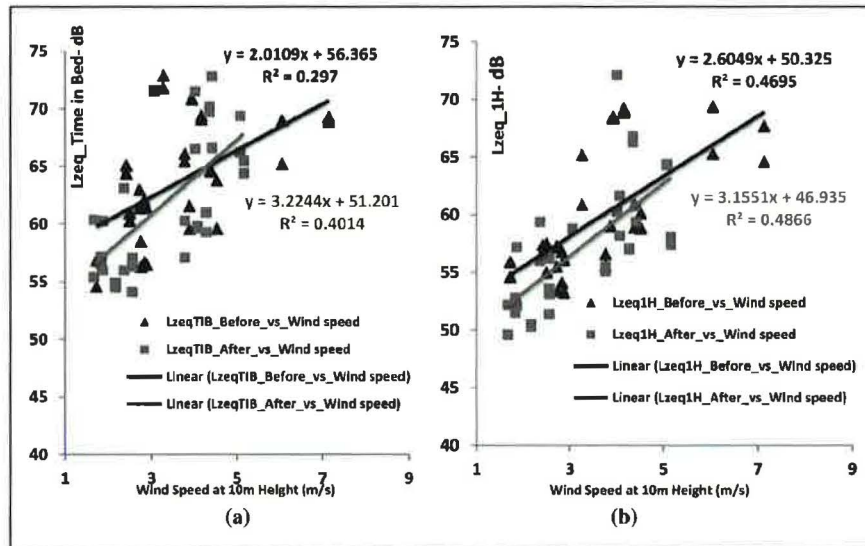
The means of wind and temperature data from 10:00 pm to 8:00 am for each night were used in the analysis. The means of wind speed, at height of 10 m, were not significantly different ( $P=0.559$ ) between T1 and T2 periods of observation: 3.64 m/s (SD=1.19) in T1 and 3.33 m/s (SD=1.39) in T2. The mean 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 ( $P<0.001$ ).

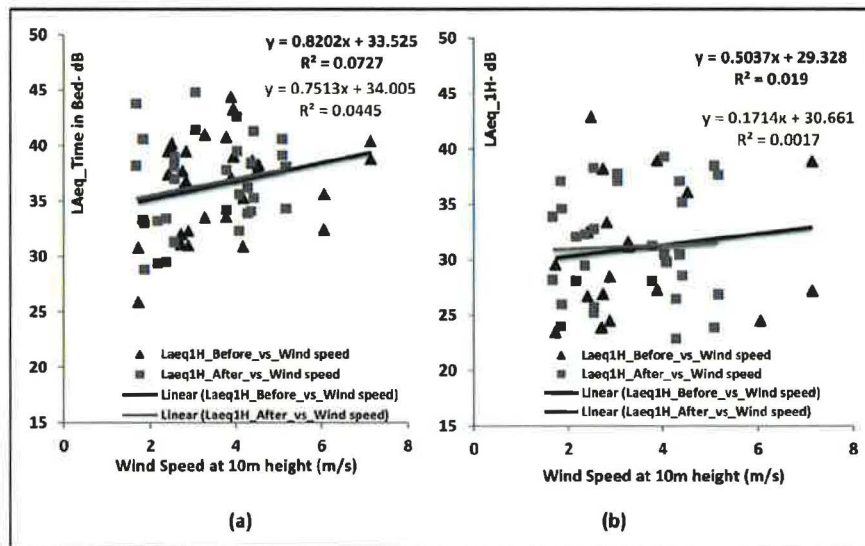
Figures 2a and b show the A-weighted noise exposure for TIB and 1H for T1 and T2 of observation versus wind speed at the height of 10 m. Increasing trends in the noise level are observed by increasing wind speed; however, none of the findings were significant. For TIB, the slope of noise is 0.75 for 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



**Figure 1:** (a) Time 1 (before exposure) and Time 2 (after exposure) Z-weighted equivalent noise for “time in bed” versus wind speed at the height of 10 m. (b) Time 1 (before exposure) and after Time 2 (after exposure) Z-weighted equivalent noise exposure for 1H versus wind speed at the height of 10 m



**Figure 2:** (a) Time 1 (before exposure) and Time 2 (after exposure) A-weighted equivalent noise for “time in bed” versus wind speed at the height of 10 m. (b) Time 1 (before exposure) and Time 2 (after exposure) A-weighted equivalent noise exposure for 1H versus wind speed at the height of 10 m

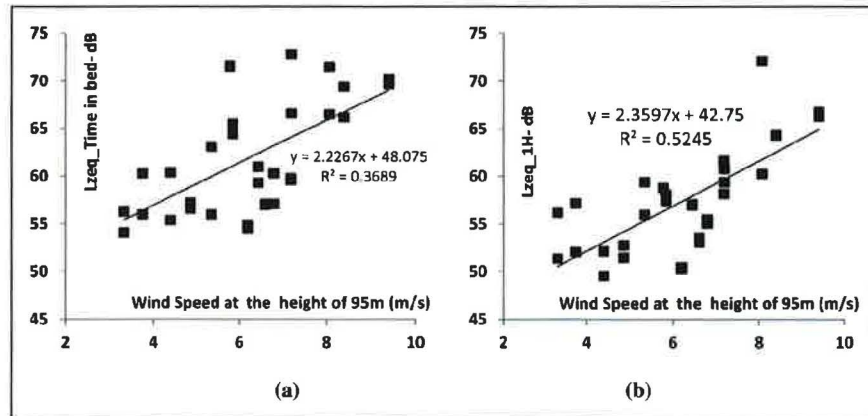
exposure ( $L_{Aeq} - TIB$ : Spearman’s  $r = -0.047$ ,  $P = 0.862$ ,  $L_{Aeq} - 1H$ : Spearman’s  $r = -0.353$ ,  $P = 0.180$ ,  $L_{Zeq} - TIB$ : Spearman’s  $r = -0.230$ ,  $P = 0.392$ ,  $L_{Zeq} - 1H$ : Spearman’s  $r = -0.080$ ,  $P = 0.769$ ).

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

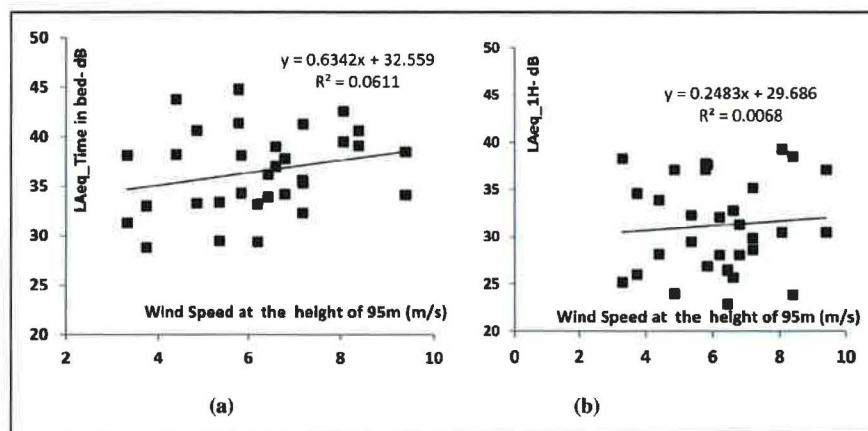
91 dB that is about 34 dB variation on the amplitude of the noise signal.

### Associations between noise exposure and sleep parameters

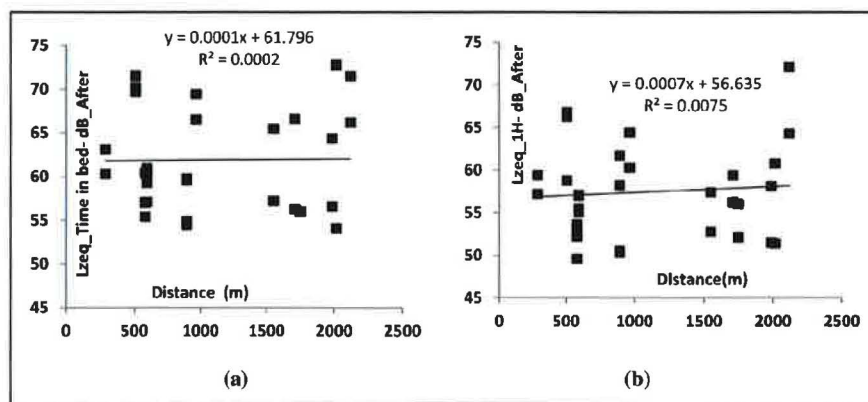
The Spearman’s rank correlation coefficients were used for the associations between average noise difference ( $L_{Aeq} 2 - L_{Aeq} 1$ ) and sleep factors difference in T1 and T2 of study. Noise difference correlated with the difference in the number of awakenings ( $r = 0.605$ ,  $P = 0.001$ ), SSC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



**Figure 3:** (a) Time 2 (after exposure) Z-weighted equivalent noise for “time in bed” versus average wind speed at the height of 95 m. (b) Time 2 (after exposure) Z-weighted equivalent noise for 1H versus average wind speed at the height of 95 m



**Figure 4:** (a) Time 2 (after exposure) A-weighted equivalent noise for “time in bed” versus average wind speed at the height of 95 m. (b) Time 2 (after exposure) A-weighted equivalent noise for 1H versus average wind speed at the height of 95 m



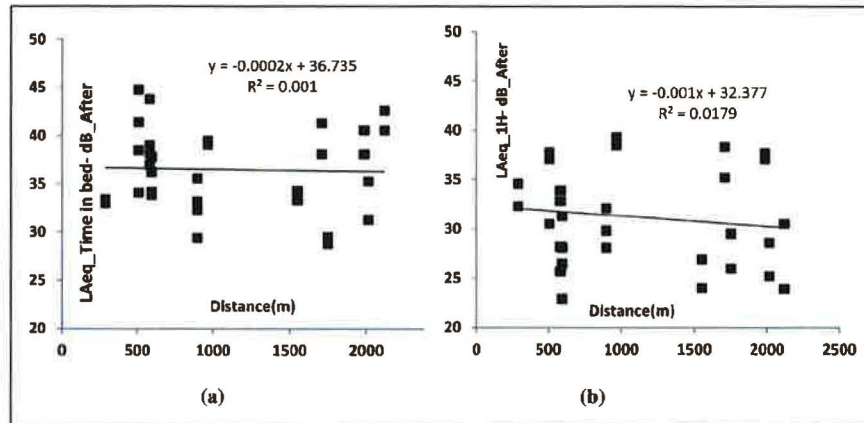
**Figure 5:** (a) Time 2 (after exposure) Z-weighted equivalent noise versus distance from the closest wind turbine for “time in bed.” (b) Time 2 (after exposure) Z-weighted equivalent noise versus distance from the closest wind turbine for 1H

## DISCUSSION

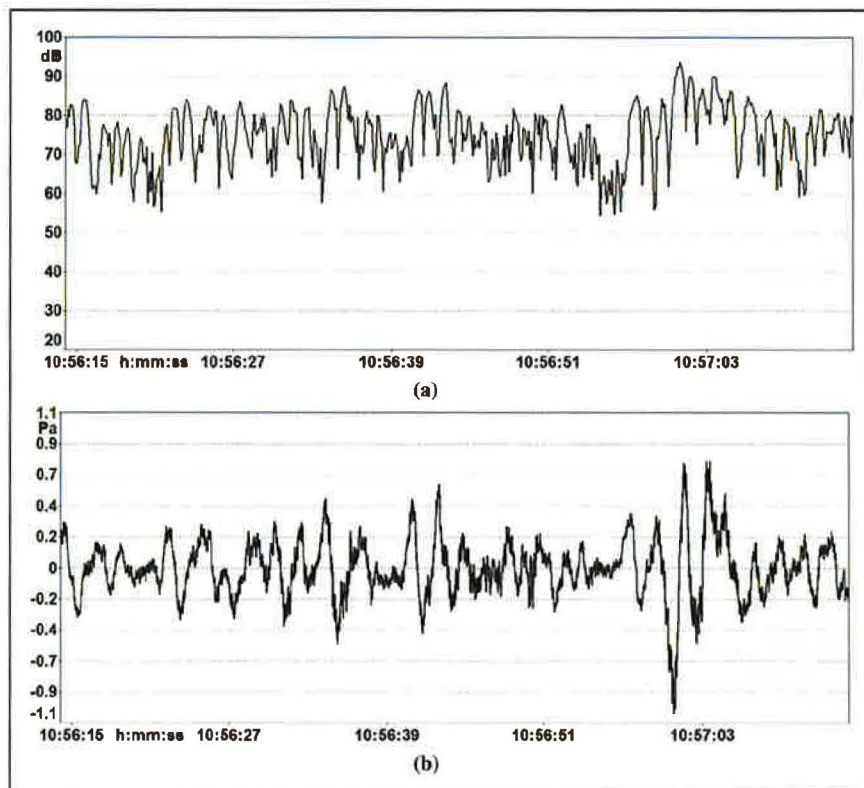
A detailed analysis of the individual sleep epochs measured by PSG in the present study showed no major changes in the sleep of

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





**Figure 6:** (a) Time 2 (after exposure) A-weighted equivalent noise versus distance from the closest wind turbine for “time in bed.” (b) Time 2 (after exposure) A-weighted equivalent noise versus distance from the closest wind turbine for 1H.



**Figure 7:** (a and b) Time variation of turbine noise (raw data) in Pascal and peak of Z-weighted data in dB, indoor and 550 m distant, showing low-frequency noise waveform swings

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.<sup>[15]</sup> 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.<sup>[16]</sup> 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;<sup>[17,18]</sup> 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.*<sup>[17]</sup> 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.<sup>[18]</sup>

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.*<sup>[19]</sup> 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.*<sup>[12]</sup> 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.*<sup>[20]</sup> 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 [Figure 9]. 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<sup>[21]</sup> used a

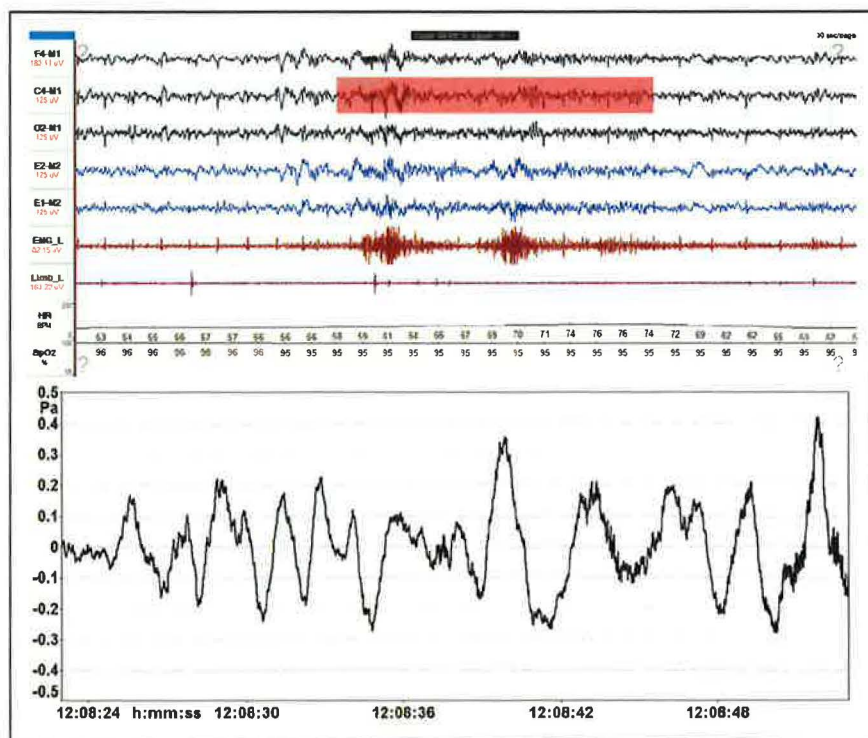
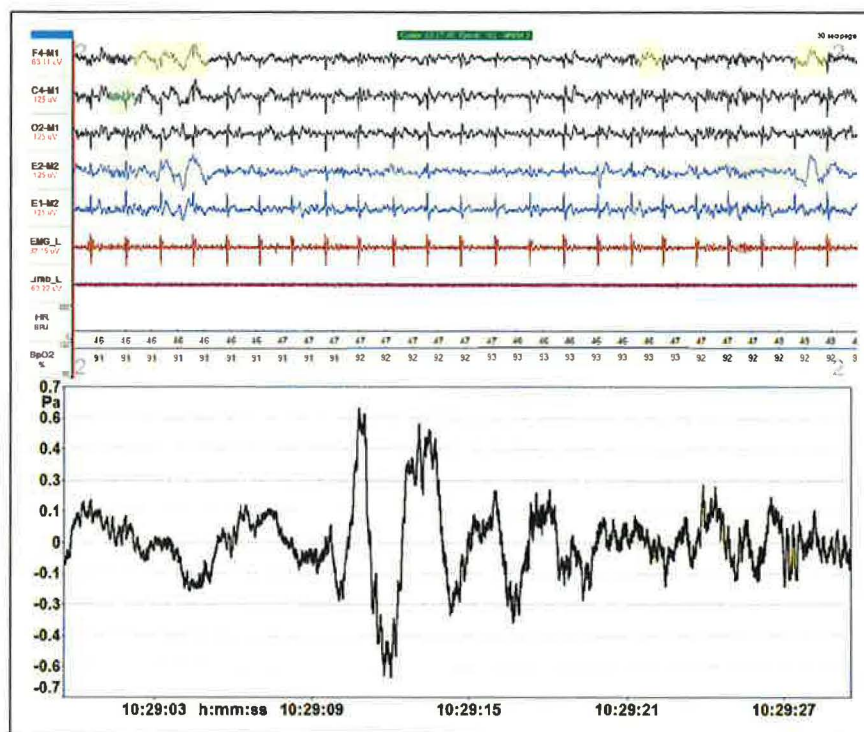


Figure 8: Sleeper's reactions to a single noise event at a distance of 1986m from the turbine



**Figure 9:** Sleeper's reactions to a single noise event at a distance of 967 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.*<sup>[22]</sup> 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.<sup>[23,24]</sup> Self-reported sleep disturbance may also be associated to the indirect effects of individual differences such as visual and attitudinal factors.<sup>[25]</sup> 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.<sup>[26]</sup> 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.<sup>[27]</sup> 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.

### Acknowledgements

The authors would like to gratefully and sincerely thank Professor Mathias Basner for his guidance in developing the study design and deeply acknowledge his thoughtful review and important insights on the manuscript. They would also acknowledge the support they received throughout the study from Ontario Research Chair in Renewable Energy Technologies and Niagara Health Region, and are grateful to the volunteers who participated in this study.

### Financial support and sponsorship

Ontario Research Chair in Renewable Energy Technologies and Niagara Health Region.

### Conflicts of interest

There are no conflicts of interest.

## REFERENCES

- Munzel T, Gori T, Babisch W, Basner M. Cardiovascular effects of environmental noise exposure. *Eur Heart J* 2014;35:829-36.
- Lin F, Brown L, Kim R, Schwela D, Kephelopoulous S. Conclusions [Burden of disease from environmental noise: Quantification of healthy years life lost in Europe]. World Health Organisation, 2011.
- Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, Stansfeld S. Auditory and non-auditory effects of noise on health. *Lancet* 2014;383:1325-32.
- Muzet A. Environmental noise, sleep and health. *Sleep Med Rev* 2007;11:135-42.
- Canadian Wind Energy Association [Internet]. Canadian Wind Energy Association. 2016 [cited 2016 May 2]. Available at: <http://canwea.ca/>
- Nissenbaum M, Aramini J, Hanning C. Effects of industrial wind turbine noise on sleep and health. *Noise Health*. 2012;14:237.
- Onakpoya I, O'Sullivan J, Thompson M, Heneghan C. The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies. *Environ Int* 2015;82:1-9.
- Pedersen E, Persson WK. Perception and annoyance due to wind turbine noise: A dose-response relationship. *J Acou Soc Am* 2004;116:3460.
- Shepherd D, Welch D, Hill E, McBride D, Dirks K. Evaluating the impact of wind turbine noise on health-related quality of life. *Noise Health*. 2011;13:333.
- Myktyyn I, Sajkov D, Neill A, Mc Evoy R. Portable computerized polysomnography in attended and unattended settings. *Chest* 1999;115:114-22.
- Agnew H, Webb W, Williams R. The first night effect: An EEG study of sleep. *Psychophysiology* 1966;2:263-6.
- Aasvang G, Overland B, Ursin R, Mowm T. A field study of effects of road traffic and railway noise on polysomnographic sleep parameters. *J Acou Soc Am* 2011;129:3716.
- Pearsons K. Predicting noise-induced sleep disturbance. *J Acou Soc Am* 1995;97:331.
- American Academy of Sleep Medicine; Iber C. The AASM manual for the scoring of sleep and associated events: Rules, terminology and technical specifications. *Am Acad Sleep Med* 2007.
- Basner M, Samel A. Effects of nocturnal aircraft noise on sleep structure. *Beeintrachtungen der Schlafstruktur durch nachtlischen Fluglarm*. *Somnologie*. 2005;9:84-95.
- Ramakrishnan R, Seharwat V. Evaluation of sound propagation from wind. ICSV22. Florence; 2015 [cited 2016 May 2]. Available at: [http://iaav.org/archives\\_icsv\\_last/2015\\_icsv22/content/papers/papers/full\\_paper\\_296\\_20150504153904130.pdf](http://iaav.org/archives_icsv_last/2015_icsv22/content/papers/papers/full_paper_296_20150504153904130.pdf); 2015:12-6.
- Lane JD, Bigelow PL, Majowicz SE, McColl RS. Impacts of industrial wind turbine noise on sleep quality: Results from a field study of rural residents in Ontario, Canada. *J Environ Health* 2016;79:8-12.
- Michaud D, Feder K, Keith S, Voicescu S, Marro L, Than J, *et al.* Effects of wind turbine noise on self-reported and objective measures of sleep. *Sleep* 2016;39:97-109.
- Basner M, Glatz C, Griefahn B, Penzel T, Samel A. Aircraft noise: Effects on macro- and microstructure of sleep. *Sleep Med* 2008;9:382-7.
- Basner M, Müller U, Elmenhorst EM. Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep* 2011;34:11-23.
- Basner M. Nocturnal aircraft noise exposure increases objectively assessed daytime sleepiness. *Somnologie – Schlafforschung und Schlafmedizin*. 2008;12:110-7.
- Jackowska M, Dockray S, Hendrickx H, Steptoe A. Psychosocial factors and sleep efficiency. *Psychosomatic Med* 2011;73:810-6.
- Petrie K, Broadbent E, Kley N, Psych D, Moss-Morris R, Home R, Rief W. Worries about modernity predict symptom complaints after environmental pesticide spraying. *Psychosomatic Med* 2005;67:778-82.
- Taylor J, Eastwick C, Wilson R, Lawrence C. The influence of negative oriented personality traits on the effects of wind turbine noise. *Personality Individual Differences* 2013;54:338-43.
- Jalali L, Nezhad-Ahmadi M, Gohari M, Bigelow P, McColl S. The impact of psychological factors on self-reported sleep disturbance among people living in the vicinity of wind turbines. *Environ Res* 2016;148:401-10.
- Guastella A, Moulds M. The impact of rumination on sleep quality following a stressful life event. *Personality Individual Differences* 2007;42:1151-62.
- Van den Berg G. Effects of the wind profile at night on wind turbine sound. *J Sound Vibration* 2004;277:955-70.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.