

Association Between Industrial Wind Turbine Noise and Sleep Quality in a Comparison Sample of Rural Ontarians

by

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Abstract

Background: Wind turbines (WTs) are an emerging source of renewable energy in Ontario. One concern is that aerodynamic and mechanical noise produced by the WTs results in sleep disturbance in residents living near such facilities. However, evidence to date is primarily self-reported, with no objective measures of the impact on sleep quality currently in the literature.

Objective: The objective of this study was to determine if the presence of a grid connected WT is a risk factor for poor sleep quality and if wind turbine noise is associated with sleep parameters. The hypothesis was that individuals residing within fifteen hundred meters of a WT experience poorer sleep, compared to those who do not reside near a WT.

Methods: A daily sleep diary and actigraphy-derived measures of sleep quality were obtained from twelve participants from a WT community in rural Ontario and ten participants from a comparison community with no wind power installations. Sound level meters were used to assess the equivalent (L_{Aeq}) and maximum (L_{Amax}) sound pressure levels within the bedroom. A variety of statistical analysis were performed to determine co-variation between variables, noise thresholds for sleep disturbance, and risk for poor sleep quality.

Results: A total of 110 person-nights and 12,971 sleep epochs were observed. Participants in the exposed group lived at a mean distance of 795 m from the closest WT (range 474 m–1085 m). Although numerous actigraphy sleep parameters were poorer in the exposed group, including lower average sleep efficiency (89% vs. 92%), longer sleep onset latency (6 min vs. 4 min), and longer wake after sleep onset (42 min vs. 29 min), the differences were not statistically significant. When the data was dichotomized by quality of sleep, the prevalence of poor sleep in the exposed group was greater than in the

unexposed group (22 vs. 11 per 100 person-nights), although the results of logistic regression modeling indicated that the differences were not statistically significant (after adjustment for age and sex). Findings from the analysis of sleep epochs showed an association between awakenings and L_{Amax} (during the sleep epoch) only for noise events above 55 dBA. No significant differences in sleep parameters derived from the sleep diaries were found between the groups.

Conclusion: Both actigraphy and sleep diaries can provide valuable information to understand the impact of industrial WTs on the quality of sleep for residents living in the vicinity. This pilot study had a small sample size which reduced the likelihood of identifying differences in sleep quality between the exposed and unexposed groups. Additionally, measurements were obtained during periods of relatively low wind speeds (nightly power outputs ranged from 1 to 34 MW or 0.5 to 17% capacity) thus, limiting the generalizability of the findings. Findings of poorer mean values of numerous sleep parameters in the exposed group support the need for more extensive research in the area. Low response to noise events up to 45 dBA was an interesting finding that also merits further investigation. Assessment of WT noise is complex and noise exposure measurement requires unique methods than those used for other sources of community noise.

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For Stephanie

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*“Obstacles cannot crush me;
every obstacle yields to stern resolve.”*
—Leonardo da Vinci

Chapter 1

Introduction

1.1 General Problem Area

The current environmental situation has resulted in an expansion of renewable energy, both in use and development. Renewable energy is energy from sources which occur naturally, like sunlight, water, and wind, and are naturally replenished. The use of renewable sources of energy is not a new concept, as hydroelectric and biomass (plant matter) have been used for many years. However, the use of solar, biofuels, geothermal, and wind energies are seen as sources that are still in their infancy. Wind Turbines (WTs) generate electricity from the mechanical movement of rotor blades by the wind and the use of WTs on an industrial scale are seen as a relatively new source of renewable energy within Canada. The use of industrial wind operations, which consist of multiple large WTs (2.5 MW; ~350 ft. tall) grouped together, has grown substantially in Canada. It is becoming common place for the production of industrial wind operations to encroach on residential land, for a number of technical and logistical reasons. Due to this prac-

tice, there has been increasing debate over whether or not WTs act as an environmental health hazard. The debate has centered around issues of noise; those who oppose WTs state possible detriments to health, due to noise as a nuisance which affects the sleep of residents living in the area of an industrial wind operation.

WTs generate noise as a result of turbulence caused by rotor blades chopping through the air during rotation. The noise generated from the turbulence is characterized as a “whoosh” or “swish” noise in an audible, recurring tone. In a study conducted in The Netherlands, noise from WTs was confirmed to be easily perceived and relatively annoying, compared to aircraft, railway, and automobile traffic noises (Pedersen, van den Berg, Bakker, & Bouma, 2009). The noise generated from WTs has come under investigation, as there have been numerous accounts of health-related complaints associated with noise induced sleep disturbance by residents living in the vicinity of an industrial wind operation.

Considering the possibility of sleep disturbance as a result of exposure to wind turbine noise, the effects on health are two-fold. The primary health effect relates to the physiological need for sleep as a part of homeostasis. During waking periods, the brain is continuously at near maximum activity levels. Therefore, sleep provides the only opportunity for the recuperation of brain tissue, when activity is lowered to near zero levels (Moorcroft, 2005). Similarly, heightened levels of human growth hormone during sleep allows repair of the daily wear placed on muscle and connective tissues Horne (1983). Secondary is the stress related to loss of sleep. Stress is known to act as a psychological stressor, which can negatively impact endocrine and nervous function if stress becomes chronic (Kryter, 1972). Stress has also been shown to negatively impact sleep, due to

increases in cortisol levels (Ising, Kruppa, et al., 2004). Therefore, a vicious cycle can be created as stress leads to sleep disturbance—which in turn increases stress.

1.2 Relevance and Significance

In 2010, a report released by Ontario's Chief Medical Officer revealed that there was insufficient scientific evidence to support the claims of negative health-related effects from industrial wind operations (CMOH, 2010). While health concerns surrounding the use of industrial wind operations are mounting in Canada and around the world, to date there have been few epidemiological studies focused on the association between WT noise and sleep. Therefore, knowledge gaps exist for which data are needed to further the understanding of WT noise as a possible environmental health hazard.

An improvement in the understanding of WT noise as an environmental health hazard is relevant and significant for policy. Given the relative infancy of industrial wind operations in Canada and Ontario, the policy decisions surrounding the regulation of the wind power industry have been made with a limited amount of evidence about how WT noise affects sleep. By addressing the gaps in the understanding about WT noise, the body of knowledge used to aid policy can be strengthened. This is significant, because future policy decisions including noise exposure limits and setback distances can be made with confidence.

Wind energy, as a growing group of renewable energy sources carries a large promise for sustainability and growth of the economies of the future. That said, the implementa-

tion, as well as the technology must be fully researched with respect to the health impact industrial wind operations pose as an environmental health hazard. In Canada, industrial wind operations are an important part of the county's long-term energy strategy. In Ontario, there is a trend toward wind power generation, because of the environmental gains of using this renewable source. As the need for clean sources of energy increases, the study of the health impact of current industrial wind operations will allow this technology to be used without risk to human health moving forward.

1.3 Research Objectives

Despite the large amount of anecdotal evidence to support an association between wind turbine noise and sleep disturbance, it is unclear whether the sleep quality of residents is affected by excess noise, or if the presence of a WT alone is negatively impacting sleep. As such, the research question under investigation is to determine if the presence of a WT is a risk factor for poor sleep quality. The hypothesis is that individuals living in the vicinity of a WT experience poorer sleep, as measured by a survey and actigraphy, compared to those who do not reside near a wind turbine.

The main goal of this study is to explore the sleep of individuals who reside in the vicinity of WTs using actigraphy to and a sleep diary in comparison with a rural community that does not have WTs. Another aim of this study is to use actigraphy to investigate sleep disturbances and to estimate the prevalence of poor sleep quality. In addition, this study will permit hypothesis generation about how WTs act to affect health, through

either visual impact and amenity, or noise generation and stimulation.

Chapter 2

Literature Review

2.1 Introduction

Over the past decade, wind power has grown steadily in Canada and worldwide. As the technology has grown to an industrial scale, a research area has emerged to study WTs as a potential environmental health hazard. Attention has been given to industrial wind operations installed near inhabited areas, as residents living in the vicinity of WTs have voiced complaints regarding detrimental changes to their health following the installation of the turbines. Affects on health related to sleep disturbance represent an area of focus, due to the expanse of reports by residents. What is currently known is that individuals living in the vicinity of an industrial wind operation experience annoyance as a result of noise emissions and visual impact. The central role that WT noise emissions are presumed to hold represents a research challenge, due to the complex nature of the noise as well as the environment where WTs are sited.

2.2 Wind Turbine Noise Emissions

Quantification of the sound level propagated from WTs is central theme in the literature looking into WTs as an environmental health hazard. Published reports from Europe show that typical noise exposure levels range from 24 to 54 dBA (F. van den Berg, Pedersen, Bouma, & Bakker, 2008), while another study estimates that approximately 40% of the Dutch population is exposed to sound levels above 50 dBA (M. van den Berg, 2011). While there is agreement in the literature that sound from WT noise is audible, is it often difficult to determine if the noise is out of compliance with noise regulations, as guidelines for acoustic measurement are strict and vary between jurisdictions. In addition, background noise levels provide a challenge, because it is often difficult to determine if WTs contribute sufficient noise to background levels. In a survey of noise emissions, Maffei and Lembo (2003) measured noise from WTs at 3 dBA greater than background noise which is below the 5 dBA cut-point used in noise regulations. Furthermore, environmental factors may modulate the perception of WT noise. Road traffic can mask the noise from WTs (Pedersen, van den Berg, Bakker, & Bouma, 2010), while landscape factors have been associated with changes in sensitivity to noise (Maffei & Lembo, 2003), through reverberation and amplitude modulation.

2.3 Perceived Annoyance from Wind Turbines

Results of a cross-sectional study by Pedersen and Waye (2003) found that 30% of respondents identified themselves as “very annoyed” at estimated levels above 38 dBA.

Findings are suggestive of a positive relationship between the proportion of individuals annoyed by WT noise and increasing sound pressure levels. Respondents noted that “swish”, whistling and pulsing were characteristics that correlated with annoyance. This finding was echoed in a similar study with the finding that 16% of respondents living at sound exposures above 35 dBA were disturbed during sleep by WT noise (Pedersen & Waye, 2004). The authors state that at similar sound pressure levels wind turbine noise is perceived as more annoying than other community noise sources such as aircraft and road traffic (Pedersen, Hallberg, & Waye, 2007).

Performing an analysis of WT noise characteristics, Lee, Kim, Choi, and Lee (2011) have concluded that a combination of sound pressure level and amplitude modulation both significantly contribute to noise annoyance. Epidemiologic data have confirmed this finding, as individuals who reside in rural areas with complex (hilly or rocky) terrain are at greater risk of perception and annoyance compared to individuals residing in rural areas with flat ground and those in suburban areas (Pedersen & Waye, 2007). Viewing attitude towards WTs, defined as “attitudes to wind turbines in general and to their impact on the landscape” has been found to be positively associated with annoyance (Pedersen et al., 2009). Therefore, a positive correlation is believed to exist between individuals who are able to view WTs from their homes and their annoyance with the perceived noise. However, adding to the complexity is the finding that annoyance is lower among residents who stand to make economic gain (Janssen, Eisses, Pedersen, & Vos, 2009). In summary, annoyance from WT noise appears to be a function of loudness, characteristics of the noise, and personal sensitivity.

2.4 Health Effects from Wind Turbines

The principal area of focus for research into the health effects related to WTs is sleep disturbance. Self-reported sleep disturbance has been outlined in case reports from various countries including the United Kingdom (Bowdler, 2011). Survey data from the United States by Bittner-Mackin (2003) support the findings from case-reports, showing that over 60% of respondents said their sleep had been disturbed due to noise from WTs. In a cross-sectional study from New Zealand, Shepherd, McBride, Welch, Dirks, and Hill (2011) measured Health-Related Quality of Life as an outcome measure for sleep disturbance and found lower scores for individuals residing within two kilometres of a WT compared to matched controls. In another study by Nissenbaum, Aramini, and Hanning (2011), individuals residing within fifteen hundred metres scored worse on two scales measuring sleep quality, compared with a control group. The authors note that sleep must have been sufficiently disrupted over a period of days for a significant difference in sleep quality to develop. Although reports illustrate an association between sleep disturbance and noise exposure from WTs, limitations within these studies, as described below, have limited the strength of the conclusions.

First, the majority of research uses subjective measures to report on sleep as a primary effect. The validity of the results in these studies is questionable, because self-reported data do not provide the strongest evidence. Second, studies making use of survey data are prone to bias. Specifically, recall bias is known to exist in studies estimating exposures using subjective measures and would result in an inaccurate assessment of sleep disturbance. Risk of bias is highlighted in the evidence which suggest that people may

have difficulty assessing their own sleep, especially those suffering from sleep disorders (Lockley, Skene, & Arendt, 1999) as well as age and gender effects (Reyner, Horne, & Reyner, 1995). Therefore, no clear consensus has emerged surrounding the impact of WT noise on sleep and an improved method of sleep assessment is required to increase the strength of the conclusions.

2.5 Objectively Measured Sleep Quality

In order to assess the primary effects of environmental noise on sleep, a method of measuring sleep is required. Measurements can be performed subjectively, using a questionnaire aimed at the psychological, or behavioural aspects of sleep aspects of sleep, or objectively, with the focus on the physiological aspects of sleep. Many laboratory experiments use polysomnography (PSG), considered as the gold standard of sleep measurement, to obtain objective measures of sleep. However, the use of PSG is hindered in field research, as the machinery is expensive and not practical for use in the homes of study participants. As an alternative, field studies in this area have relied on actigraphy as a method of objectively measuring sleep.

The use of actigraphy in the sleep research is based, in part, on the finding that physiological responses occur as a result of alteration in the normal sleep pattern (Eberhardt, Stråle, & Berlin, 1987). For actigraphy for to function, body movements must occur as a result of sleep pattern changes. As a behavioral response to physiologic changes, body motility has been correlated to changes in the EEG-pattern (Griefahn & Spreng, 2004;

Pirrerera, De Valcka, & Cluydts, 2010). As a result, actigraphy has been used for over 30 years in the study of wake/sleep patterns. Over the same time period, however, the validity of measures from actigraphic systems has been debated, as follows.

In 1995, Sadeh, Hauri, Kripke, and Lavie (1995) reviewed the role of actigraphy in the evaluation of sleep disorders and concluded that actigraphy could provide useful information and a “cost-effective method for assessing specific sleep disorders...[however] methodological issues have not been systematically addressed in clinical research and practice.” Since this time, actigraphic technology has changed dramatically and has been used in many different studies on sleep. Recent reviews have shown actigraphy correlates well with PSG in the identification of wake/sleep, with reported agreement between 80% and 96.5% (Acebo, 2006; Ancoli-Israel et al., 2003). In addition, actigraph validation against PSG for sleep onset latency showed a correlation between 0.53 and 0.92 depending on the definition of sleep onset latency used (Ancoli-Israel et al., 2003). The stability of the correlation coefficients have been shown to increase with increasing time period (Van de Water, Holmes, & Hurley, 2011), with recommendation that five nights of data collection be the minimum to obtain reliable measures (Sadeh & Acebo, 2002). Therefore, actigraphy presents a useful method to measure sleep in situations where PSG is not suitable. Through the careful control of artifacts, data quality can be maintained at a reasonable level (Acebo, 2006). Also, details on the scoring algorithm used should be provided as this is needed information for comparison of the results with other studies (Morgenthaler et al., 2007).

In the objective measurement of sleep, there are a number of primary effects reported in the literature when describing the impact of noise on sleep. Many studies report

changes in sleep onset latency (SOL) as this is the variable responsible for a reduction in total sleep time and poor subjective sleep quality as a result of noise disturbed sleep (Öhrström, Björkman, & Rylander, 1990). Increased SOL, due to exposure to road traffic noise, has been reported in several studies (Eberhardt et al., 1987; Griefahn & Spreng, 2004). Conversely, many studies did not find a significant difference in objective and subjective measurements of SOL (Marks & Griefahn, 2007; Öhrström, Hadzibajramovic, Holmes, & Svensson, 2006; Öhrström & Skånberg, 2004).

Given the contradictory results, it is interesting that the operational definition of SOL is rarely defined as this definition is highly relevant. Current use of SOL varies between studies from the first occurrence of sleep stage N2 (the second of five stages as measured by PSG) (Pirrer et al., 2010), the first minute beginning two minutes of continuous sleep (Blood, Sack, Percy, & Pen, 1997), or the first 20 minute block with more than 19 minutes of sleep as defined by the Cole-Kipke scoring algorithm for actigraphy (Öhrström & Skånberg, 2004). To improve causal conclusions around sleep disturbance, a clear definition of SOL is needed for future studies. This will increase the compatibility of the results between and across studies of sleep disturbance from WTs and other environmental noise sources.

2.6 Subjectively Measured Sleep Quality

Sleep can be assessed subjectively through the use of sleep questionnaires or sleep diaries. These tools are less expensive than objective measurement, are simple for study

participants to complete, and can be used in laboratory or field research. Subjective measures of sleep differ from objective measures in that objective measures focus on the physiological aspects of sleep, while subjective measures provide information on perceived sleep quality. Comparing a sleep questionnaire, to assess overall sleep quality, with a three day sleep diary in quiet and noisy areas, [Öhrström and Skånberg \(2004\)](#) found good consistency between both measurement tools for sleep parameters, including sleep onset latency, awakenings, sleep quality, and tiredness in the morning. This finding suggests that important information about sleep can be obtained through the use of a questionnaire or survey, allowing for the investigation of large population samples.

Caution is needed when evaluating results from subjectively assessed sleep as the interpretation of sleep variables is not always straightforward. As subjective measurement relies on the individual to correctly recall events from the previous night, errors and omissions can occur. A review of subjective assessment by [Pirrer et al., 2010](#) found that subjective reports of awakenings are generally an underestimation compared with objectively assessed awakenings. This could be due to the fact that the recollection of an awakening is a requirement for reporting, which is often absent. Comparisons with PSG recordings estimate that the minimum time required for an awakening to be remembered is four minutes ([Johns & Doré, 1978](#)). Also, the presence of mediating factors can affect how an individual perceives sleep. In a study of subjective sleep, [Carter \(1996\)](#) described that recall of information following sleep depends attitude towards the noise source, but also the amount of time awake and the degree of sleep disturbance. The presence of mediating factors must be taken into consideration when attempting to measure sleep with subjective measures.

2.7 Quantification of Environmental Noise Emissions

In the investigation of environmental noise and sleep, noise assessment provides a measurement of exposure. To obtain the greatest estimate of exposure, indoor noise assessment is required as this is the noise which is perceived by the individual (Pirrera et al., 2010). Alternatives that have been used involve calculation of the equivalent sound pressure level from an outdoor measure (Eberhardt & Akseleson, 1987), but the use of outdoor measurement for noise assessment has been reported as a limitation in many studies (Eberhardt & Akseleson, 1987; Öhrström et al., 2006; Öhrström & Skånberg, 2004), raising questions about the relevance if its use. The relevance of outdoor noise measurement has been tested by Pirrera, De Valcka, and Cluydts (2011) who found a low correlation between noise measurement taken indoors and outdoors. In addition, bedroom location proved to be a mediating factor for outdoor measurement, but not for indoor measurement. The authors concluded that caution must be taken when outdoor noise assessment is used in the relationship between road traffic noise and sleep. It is clear the use of indoor measurement should be the focus of future research on noise and sleep. However, the research setting along with the available resources and equipment will ultimately shape the method used for noise assessment.

Another issue is the choice of time frame used in the assessment of noise exposure. The World Health Organization (WHO) has published noise guidelines for Europe and recommends an eight hour A-weighted equivalent noise measurement (L_{Aeq}) for exposure assessment of continuous noise (World Health Organization, 1999). Many studies have made use of a time frame between 23:00 and 7:00 for L_{Aeq} as part of the assess-

ment of exposure, as this represents the normal sleep time of healthy adults (Griefahn, Marks, & Robens, 2006; Öhrström et al., 2006; Öhrström & Skånberg, 2004). However, in studies of aircraft noise, the probability of awakening was better correlated to the maximum sound pressure level per event (L_{Amax}) (Basner, Samel, & Isermann, 2006; Passchier-Vermeer, Vos, Steenbekkers, van der Ploeg, & Groothuis-Oudshoorn, 2002). This result was replicated by Kaku, Hiroe, Kuwano, and Namba (2004) who report that the L_{Amax} of a road traffic event is an important influence on sleep along with L_{Aeq} . The WHO has included these findings in the guidelines for noise, indicating that L_{Amax} be used in the study of instantaneous sleep changes and L_{Aeq} for use with long-term effects (Kim & Van den Berg, 2010). In this way, L_{Aeq} and L_{Amax} can be seen as complimentary and should be reported together to provide a comprehensive analysis of noise exposure on sleep.

2.8 Mediating Factors

Complicating the research of environmental noise on sleep is the presence of mediating factors which influence nighttime reactions to noise. Noise sensitivity has been discussed as an endogenous factor as it seems to play an important role in the evaluation of subjective sleep. Job (1999) has provided a useful definition of noise sensitivity as, "the internal states (be they physiological, psychological, or related to life style or activities conducted) of any individual which increase their degree of reactivity to noise in general." This definition suggests that physiological reactivity, hearing acuity, attitudes and

beliefs towards the noise, and vulnerability by stressors other than noise are components of noise sensitivity (Job, 1999). This phenomenon has been observed in a field study of sensitive and non-sensitive individuals from noisy and control neighbourhoods, where Öhrström et al. (1990) found noise sensitivity was correlated to disturbance of subjectively measured sleep by noise. This result suggests that noise sensitive individuals may have a lower threshold for noise during sleep and highlights noise sensitivity as a predictor for subjectively measured sleep disturbance. However, few studies have seen an influence of noise sensitivity on physiological reactions during sleep (Marks & Griefahn, 2007; Marks, Griefahn, & Basner, 2008).

In addition, the time of night exposed to the noise stimulus has been shown to be an important factor towards noise sensitivity. The thresholds for noise seem to be lowest during the early stages sleep, eventually leveling towards the morning hours (Griefahn & Spreng, 2004). Poor subjective sleep quality and daytime sleepiness have been reported for sleep disturbance in the early part of the night and just before awakening (Muzet, 2007). Therefore, choice of time frame used to define sleep hours should consider the degree of noise sensitivity present in the study population. In addition, the impact of time of night exposed to noise could extend beyond subjective appraisal of sleep, as aircraft noise in the early evening has been correlated with the use of non-prescription sleep aids or sedatives (Franssen, van Wiechen, Nagelkerke, & Lebret, 2004), which indicates a behavioural link between time of night and noise sensitivity.

2.9 Research Setting

Research surrounding the relationship between noise exposure and sleep was initially only performed in the laboratory setting, as the technology required to perform sleep measurement was too large and not practical for use in field studies. Over the past three decades, the technology with which sleep is assessed has progressed, allowing the research of sleep to be conducted in the home environment. Movement of the research setting from the laboratory to the field has allowed for the investigation of sleep from a population perspective. However, the choice of research setting presents an array of advantages and disadvantages for researchers to consider.

There are advantages and disadvantages to conducting sleep research in the laboratory setting. The principle advantage of laboratory experiments is a controlled environment, leading to precise measurement on effect and allowing for dose-response relationships to be explored. Also, experimentation in the laboratory environment allows for the use of polysomnography (PSG)—the gold standard for sleep assessment. The main disadvantage with laboratory experiments is the greater variability of reported sleep disturbances with experimentally induced noise compared to field studies (Pearsons, Barber, Tabachnick, & Fidell, 1995). Also, extrapolation of laboratory results to everyday situations is often difficult and in some cases inappropriate. Furthermore, technological advancements have made it possible to measure sleep in the field setting.

Field experiments have advantages, such as generalizability (Pirrera et al., 2010). Field studies allow for the assessment of sleep in the homes of the subjects, which increases compliance and decreases attrition, producing results which can be transferred

to target populations. Also, field studies allow for investigations of the environment itself and for comparisons between different environments. While the following evidence highlights the advantages of studying sleep in the field, this setting is not without its disadvantages. The disadvantages of field experiments relate to the inability for the researcher to control the environment. The most commonly discussed weaknesses of field studies include the possibility of confounding, and the development of coping mechanisms among subjects. Possible confounders include blindness, deafness, diagnosed sleep disorders, pregnancy, and working night-shifts (Öhrström et al., 2006; Vallet, Gagneux, Blanchet, Favre, & Labiale, 1983). As described by Fields (1984), in situations of noise intrusion of sleep, people tend to develop coping mechanisms as a way to deal with the disturbance in a positive manner. The development of coping mechanisms increases the difficulty with which the effects of noise on sleep are evaluated.

2.10 Future Direction

The study of industrial wind operations as a potential environmental health hazard is a complex and evolving research field, due to the presence of multiple risk factors, each of which presenting a unique field of study. From the literature published to date, there is a consensus that noise emitted from WTs is audible and perceived as annoying for residents in the vicinity. Furthermore, an understanding of the potential harmful effects of noise on sleep has been observed in studies of road, rail, and aircraft noise.

When performing research on WT noise in relation to sleep, it is important to obtain

an indoor measure of noise, as this will show what is actually perceived in the bedroom. Ultimately, the choice of research setting will determine the noise assessment method and location of measurement required for the investigation. Clarification of the sleep parameters, such as SOL and sleep efficiency is needed when assessing sleep to provide an understanding of the impact of noise on sleep. Attention to confounding and mediating factors, described previously, is needed as these may influence individual reactions to noise during the night.

Chapter 3

Methods

3.1 Study Area & Participants

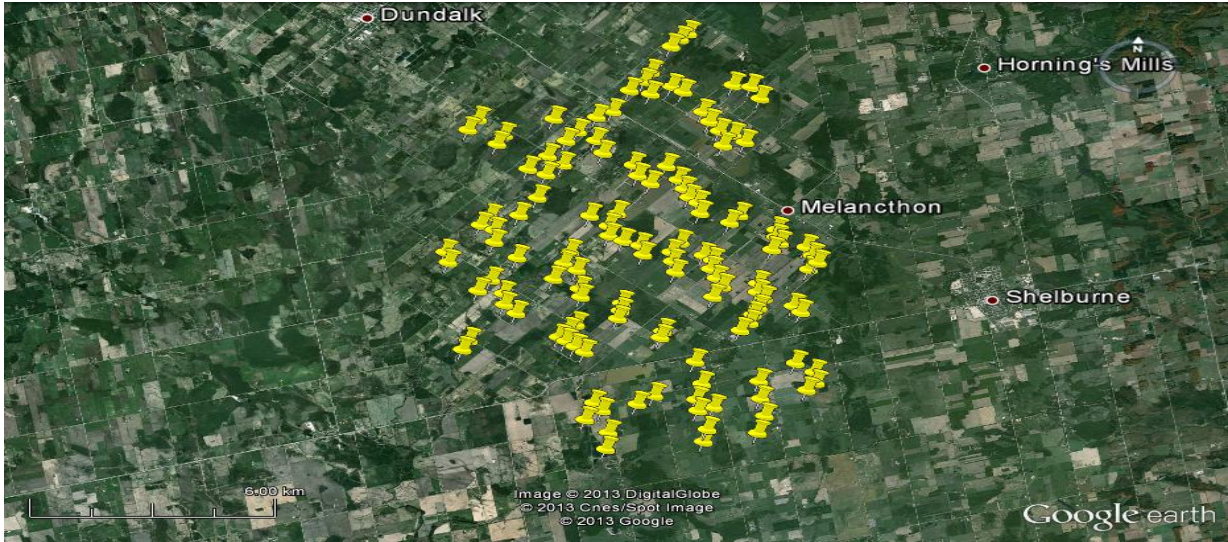
The present study used a comparison sample design to explore the impact of wind turbine noise on sleep measured with actigraphy. Two rural Ontario communities were purposefully selected as study sites: a community containing an industrial wind operation as the exposed group, and a control community which does not have WTs. Selection of the exposed community involved criteria such as the size of the wind operation, residential proximity to the wind operation, and community perception of industrial wind operations in general. The control community was selected in an area which also housed a renewable energy source, anaerobic digestion (biogas), to account for possibility of confounding by annoyance. A summary of the study sites used in this study is provided in table 3.1. The study protocol was reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo.

Table 3.1: Geographic summary of exposed and unexposed areas from which participants were recruited.

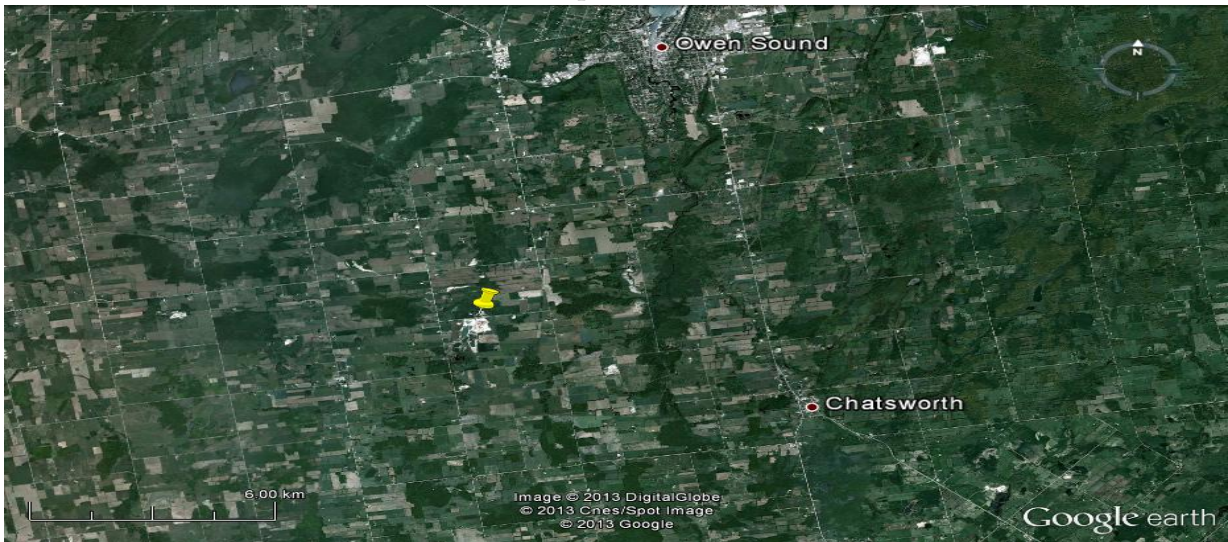
	Exposed Area	Unexposed Area
<i>Location</i>	Melanchton, ON	Georgian Bluffs, ON
<i>Population density per km²</i>	9.1	17.2
<i>Area (km²)</i>	311	604
<i>RET Type</i>	Wind (133 x 1.5 MW)	Biogas (1000 m ³)
<i>Capacity</i>	199.5 MW	100 kW/hr
<i>Date of installation</i>	2006/03	2011/01

Recruitment of study participants began with identification of candidate residences. Potential candidates for participation in the exposed group were those residents identified as living within fifteen hundred metres of a WT. Candidates in the unexposed group were those residents within thirty-five hundred metres of the anaerobic digestion facility. Mapping software was used to identify candidate households and Global Positioning System (GPS) coordinates were recorded using a cellular device following recruitment to ratify the distance from the household to the nearest renewable energy source. Following the identification of candidate residences, the researcher went door-to-door to recruit participants.

Door-to-door recruitment took place between September 26th and 27th, 2012 in the exposed group and October 26th and 27th, 2012 in the unexposed group. During recruitment the interviewer provided information about the study, highlighted the potential risks, and informed the participant about their responsibilities (Appendix B). Those who agreed to participate were asked a brief health assessment to screen for potential mediating factors (Appendix C). This assessment was used to identify exclusion criteria



(a) Exposure area



(b) Unexposed area

Figure 3.1: Satellite image of the exposed (top frame) and unexposed (bottom frame) areas showing renewable energy sources, as marked by pins. Selection criteria involved residents within 1,500 metres of a WT in the exposed area and within 3,500 metres of the anaerobic digester in the unexposed area.

such as self-reported sleep disorders (including those related to WTs), diagnosed sleep-disorder, symptoms suggestive of a sleep-disorder (e.g. heavy snoring, leg jerk, gasping for breath), psychiatric disorders, cognitive impairment, use of medication known to alter sleep, and medical conditions which alter an individual's daily independence. Candidates that met the criteria for participation were asked to give their written consent and were included in the sample (Appendix A).

An overview of the participant recruitment for the study is summarized in figure 3.2. In total, a combined 106 residences were visited during the four days of recruitment. This consisted of 50 residences visited in the exposed community and 56 residences visited in the unexposed community. The amount of non-response (i.e. residents who were not home or did not answer) was 21 in the exposed community and 31 in the unexposed community, which left a total of 54 respondents and a response rate of 50.9%. Of the remaining 54 individuals, 14 declined to participate from the exposed group, and 13 declined participation from the unexposed group. The final sample consisted of 13 participants from the exposed group and 10 participants from the unexposed group (figure 3.1), yielding a sample of 23 participants and a participation rate for this study of 42.6%. One participant from the exposed group was lost due to non-compliance and another completed only the sleep diary. All participants were Caucasian non-Hispanic, over the age of 18 years, and resided in the community where they were recruited. Participants in the exposed group resided at a mean distance of 794.6 metres from the nearest WT and unexposed group participants resided a mean distance of 2,931 metres from the anaerobic digestion facility. A description of the participant demographics can be seen

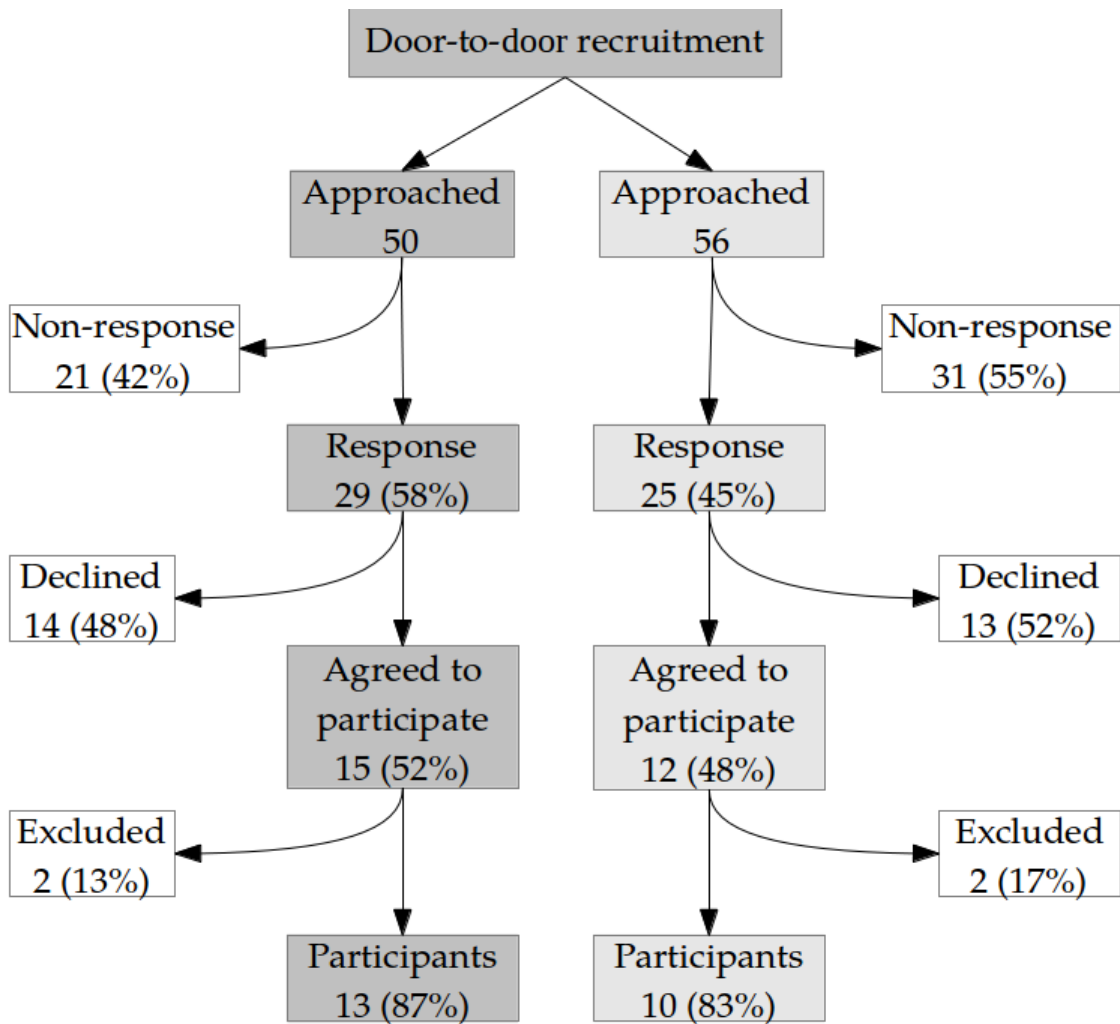


Figure 3.2: Flowchart describing recruitment process and numbers which contributed to the construction of the cohort. The left-hand side refers to the exposed group, while the right-hand side refers to the unexposed group.

in table 3.2.

Table 3.2: Characteristics of study participants who made up the comparison sample.

		Unexposed	Exposed	<i>p-value</i>
Gender				0.39 ^a
Females	N	7	5	
	% of group	70	45.5	
	% of all subjects	33.3	23.8	
Males	N	3	6	
	% of group	30	54.5	
	% of all subjects	14.3	28.6	
Age	Mean	41.4	60.36	0.04 ^b
	SD	13.39	12.06	
	Min	18	42	
	Max	59	82	
Distance From Source (m)	Mean	2931.6	794.55	
	SD	1015.63	263.08	
	Min	1157	474	
	Max	3857	1085	

^a Wilcoxon-Mann-Whitney test

^b Fisher's exact test

3.2 Sleep Assessment

3.2.1 Objective Sleep Measurement

Actigraphy was employed for the measurement of objective sleep measures in this study. The study used the GT3X+ (ActiGraph, Inc.) type actigraphs to detect body movements during sleep and record the data for computer analysis. The actigraphs were worn according to the manufacturer's specifications and worn the wrist of the non-dominant

arm for the duration of the five night trial. Actigraphs were collected following the conclusion of the five night trial and the data was uploaded to a computer for analysis.

Following the return of the actigraphs, data was downloaded to a computer using the provided USB cable and analyzed using ActiLife (ActiGraph, Inc.) version 5.11 software for the Windows 7[®] operating system. Analysis of the wake-sleep stages was made according to the ActiLife software, using the Cole-Kripkie scoring algorithm for actigraphy (Cole, Kripkie, Gruen, Mullaney, & Gillin, 1992). Sleep measures obtained from the analysis for use in this study include: sleep onset latency (SOL), wake after sleep onset (WASO), total sleep time (TST), time in bed (TIB), number of awakenings, and sleep efficiency (SE). SOL was defined according to the ActiLife algorithm as the time to the start of the first complete minute scored as sleep. Number of awakenings was defined as the number of blocks of adjoining wake episodes. WASO was defined as the number of wake minutes after sleep onset. TST was defined as the total amount of time scored as sleep. TIB was defined as the time between first attempting sleep to the final awakening. Finally, SE was defined as the amount of time allocated to sleep which was actually spent sleeping, expressed as a percentage.

3.2.2 Subjective Sleep Measurement

Sleep diaries were used to provide an additional source of sleep data and to assist with actigraphic measurement of sleep. The sleep diary (Appendix D) asked participants to enter information regarding the time they went to bed, the time they fell asleep, and the time they woke up. Additional sleep variables include the number of awaken-

ings and a ranking of their perceived sleep quality on a six point scale. A series of behavioural question asked participants if they slept with the windows open, and if they used ear-plugs or other sleep aids. Observations documented on sleep diaries assisted the computer scoring algorithm, by providing checkpoints at certain sleep periods, such as sleep start time and rise time. Furthermore, the subjective data obtained from the sleep diaries were used in comparison with actigraphic data for the purpose of measuring how well participants recalled sleep events.

3.3 Noise Exspoure Assessment

Sound level meters were used to obtain estimates of noise exposure for exposed and unexposed groups. Casella CEL-633 type sound level meters (Casella CEL, Inc.) were placed inside the bedroom and recorded sound pressure levels for each night of the trial. Sound pressure levels were surveyed in the home of one participant in each group for each of the five nights to ascertain noise exposure for exposed and unexposed groups. Noise assessment was based on the WHO recommendation of an eight hour equivalent A-weighted sound level (L_{Aeq}) (Kim & Van den Berg, 2010) along with L_{Amax} for the investigation of sleep state changes. This study employed a time frame between 23:00 and 07:00 for the assessment of noise exposure to match the usual sleep pattern of healthy adults (Acebo, 2006; Öhrström et al., 1990).

The configuration of the sound level meters used in the study can be seen in figure 3.3. Sound level meters were placed with the microphone at an inclination of 45° and a height



Figure 3.3: Image describing the set-up of the sound level meter used for noise exposure assessment. Not shown: AC adapter used to power the device.

of approximately 75 centimeters (30 inches) from the ground, so that the microphone was roughly at the height of the participants ear when lying in bed. Sound level meters were placed along the side of the bed in a location which allowed access to an electrical outlet to power the device. Settings were selected to enable the devices to turn on and off automatically for each observation night beginning at 23:00 and ending at 7:00 the following morning. Sound level meters were calibrated to 1 kHz at 114 dB before the first observation and following the final observation.

3.4 Statistical Analysis

Statistical analysis of the study data was performed using SAS software version 9.2 of the SAS system (SAS Institute Inc., Cary, NC, USA) for the Windows 7[®] operating system. Descriptive statistics, including means and standard deviations were calculated provide an overview of the measurements; these include age, sex, and sleep parameters. Student's *t*-test and Wilcoxon-Mann-Whitney rank sum tests were used to compare mean WASO, SOL, TST, TIB, sleep ratings, number of awakenings, and sleep efficiency between groups. A summary of the variables used in this study is seen in table 3.3.

Co-variation between noise exposure, WASO, SOL, TST, sleep efficiency, sleep rating, and number of awakenings was assessed using Spearman's rank correlation tests with a similar analysis performed on the data obtained through the sleep diary. In addition, nightly sound pressure level and wind speed were analyzed for conformity against sleep variables. Finally, a detailed analysis of the actigraphic sleep data was performed. The

Table 3.3: Variables used in objective and subjective measurement of sleep.

	Variable	Data Type
Actigraphy	Awakenings	Ordinal
	Sleep Efficiency (SE)	Interval
	Sleep Onset Latency (SOL)	Interval
	Sleep Quality	Nominal
	Total Time In Bed (TIB)	Interval
	Total Sleep Time (TST)	Interval
	Wake After Sleep Onset (WASO)	Interval
Sleep Diary	Sleep Behaviours	Nominal
	Sleep Rating	Ordinal
	Sources of Awakening	Ordinal
	Time Into Bed	Interval
	Time Out of Bed	Interval
	Time of Sleep Start	Interval

method looked at the actigraphic recording to see if a binary score of ‘awake’ occurred in the same 60-second epoch as a noise event of sound pressure level ≥ 45 dBA calculated for each subject from measured sound pressure levels, among sleeping subjects. The proportion of this occurrence was calculated and labeled as noisy (n). The occurrence of ‘awake’ in all other epochs was labeled as quiet (q). Chi-square tests were performed to determine the association between awakenings and noisy periods. Logistic regression analysis was used to obtain estimates of the odds ratio, adjusted for covariates like age, and gender for the dependent variable sleep quality. Sleep efficiency was converted to a binary variable to evaluate sleep quality. For the purpose of this analysis, good sleep refers to sleep efficiency of 85% and greater; poor sleep quality as sleep efficiency below 85% (Salin-Pascual et al., 1992). For all statistical tests, a value of $p < 0.05$ was considered

statistically significant.

Chapter 4

Results

4.1 Overview

The data obtained for use in this study were collected between September 26–October 10, 2012 for the exposed group and October 27–November 6, 2012 for the unexposed group. In total, 95 person-nights of data were collected from 21 participants. This total contains 50 person-nights from 11 participants in the exposed group and 45 person-nights from 10 participants in the unexposed group.

Compliance within the study was good, as 205 of a possible 215 person-nights were observed with both measurement tools, yielding an overall compliance rate of 95.34%. The compliance rate for actigraphy was 90.48% (95 of a possible 105 person-nights) and compliance was similar between exposed (90.90%) and unexposed (90.00%) groups. The most common reasons for non-compliance included participant forgetting to wear the actigraph to bed, failure of the actigraph strap, and comfort. All 22 participants completed their sleep diary for each of the 5 study nights, yielding a compliance rate for the

sleep diary of 100%.

4.2 Sleep Assessed by Wrist Actigraphy

Results of the five night sleep assessment using wrist actigraphy are shown in table 4.1. The values represent the average of the five nights for exposed and unexposed groups for each person. Results indicate that the exposed group performed worse on each of the actigraphic measures of sleep, with the exception of total sleep time and number of awakenings; however, there were no significant differences between groups across observed sleep variables. Measured total sleep time for both groups was above 7 hours (420 minutes) and sleep efficiency was above 85%. Time in bed and total sleep time showed the largest amount of variation within the groups at approximately 200 minutes between the lightest and heaviest sleepers. A visual representation of the data is shown in figure 4.1.

Additional analysis of sleep made use of individual sleep epochs used in actigraphy over the course of the night to examine awakenings during each minute of the night in relation to sound pressure levels. Over the 5 night sleep assessment, a total 12,971 sleep epochs were analyzed within the exposed group with 3117 (24%) of those identified as noise epochs having a maximum sound pressure level of 45 dBA or greater. Table 4.2 shows the results of the analysis of sleep epochs stratified across the five study nights and for noisy (NE) and quiet (QE) epochs. The total proportion of awakenings in noisy epochs (n) was 9.5% and the proportion of awakenings in quiet epochs (q) was 9.1%.

Table 4.1: Sleep assessed by actigraphy for exposed (N = 11) and unexposed (N = 10) groups averaged over the five study nights. Results show mean, standard deviation, 95% confidence intervals, and ratio of means for all measured variables.

		Unexposed	Exposed	Ratio	<i>p-value</i> ^a
Sleep Efficiency	Mean(SD)	91.92(4.09)	89.09(5.35)	0.97	0.188
	95% CI	(89.00,94.85)	(85.50,92.69)		
Sleep Onset Latency (Min)	Mean(SD)	4.31(2.25)	6.36(1.82)	1.39	0.236
	95% CI	(3.40,7.23)	(4.53,10.22)		
Wake After Sleep Onset (Min)	Mean(SD)	28.79(1.90)	42.10(1.65)	1.40	0.147
	95% CI	(20.16,47.36)	(30.49,64.05)		
Total Sleep Time (Min)	Mean(SD)	443.42(47.74)	447.05(53.63)	1.01	0.871
	95% CI	(409.26,477.57)	(411.03,483.08)		
Time In Bed (Min)	Mean(SD)	482.49(53.10)	501.70(48.32)	1.04	0.399
	95% CI	(444.50,520.47)	(469.24,534.16)		
Awakenings	Mean(SD)	13.46(1.51)	14.01(1.48)	1.04	0.792
	95% CI	(9.93,19.05)	(10.88,19.33)		

^a One-way student's *t*-test using unequal variance

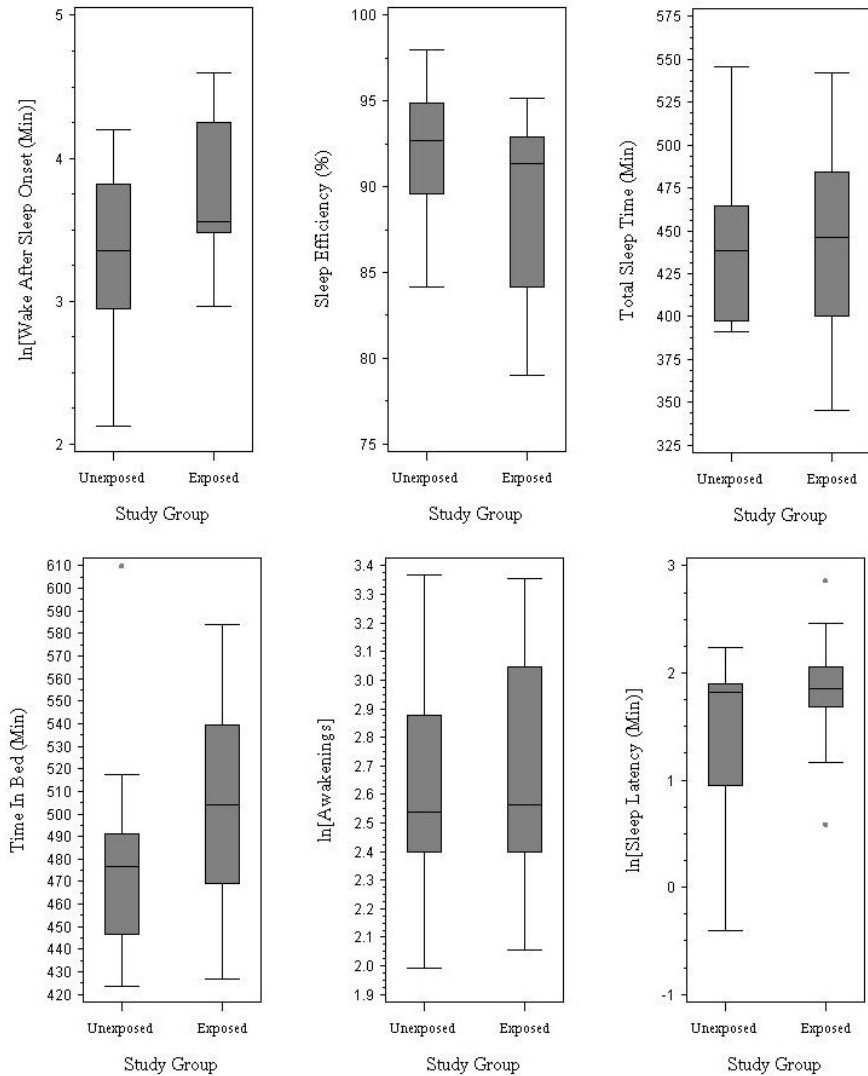


Figure 4.1: Box-and-whisker plots of sleep variables measured by actigraphy for exposed and unexposed groups. The bottom and top of boxes are located at the 25th and 75th percentiles. Central horizontal lines indicate median values. Whiskers are drawn from the boxes to extreme values less than or equal to 1.5 interquartile ranges. Any other extreme values are marked with a dot.

Results indicate that for subjects in the exposed group, noise events were attributable (n - q) for 0.4% of awakenings scored by actigraphy, or 1 in 250 noise epochs resulted in an awakening within the same epoch. Chi-square analysis did not reveal an association between awakenings and noisy periods ($\chi^2 = 0.65$; $p = 0.42$).

Results between study nights showed that a greater proportion of awakenings exist in noisy epochs compared with quiet epochs. However, the effect of noise on awakening was low and chi-square analysis did not reveal an association. The exception being night 2, where an association between awakenings and noisy periods was observed ($\chi^2 = 6.9$; $p < 0.05$). Here, the difference in the proportion of awakenings between noisy and quiet epochs was 2.6%, or 13 in 50 awakenings attributable to noise events. Further analysis shown in figure 4.2 shows that a relationship between maximum sound pressure level and proportion of awakenings observed exists only for noise events above 55 dBA.

Table 4.2: Actigraphy results for all 60-second sleep epochs by study night showing proportion of assessed awakenings in noisy and quiet epochs within exposed subjects.

Night	Noise Condition			Quiet Condition			Total		
	Events ^a	NE ^b	n ^c	Events ^a	QE ^d	q ^c	Events	Epochs	t
1	71	620	11.5%	268	2346	11.4%	339	2966	11.4%
2	74	867	8.5%	131	2216	5.9%	205	3083	6.7%
3	43	400	10.8%	200	1718	11.6%	243	2118	11.5%
4	56	601	9.3%	188	2163	8.7%	244	2764	8.8%
5	53	629	8.4%	105	1411	7.4%	158	2040	7.8%
Total	297	3117	9.5%	892	9854	9.1%	1189	12971	9.2%

^a Number of one minute epochs scored as awake by actigraphy

^b Number of one minute epochs with $L_{Amax} \geq 45$ dBA

^c Proportion of awake counts which occur in noisy(n) & quiet(q) epochs

^d Number of one minute epochs with $L_{Amax} < 45$ dBA

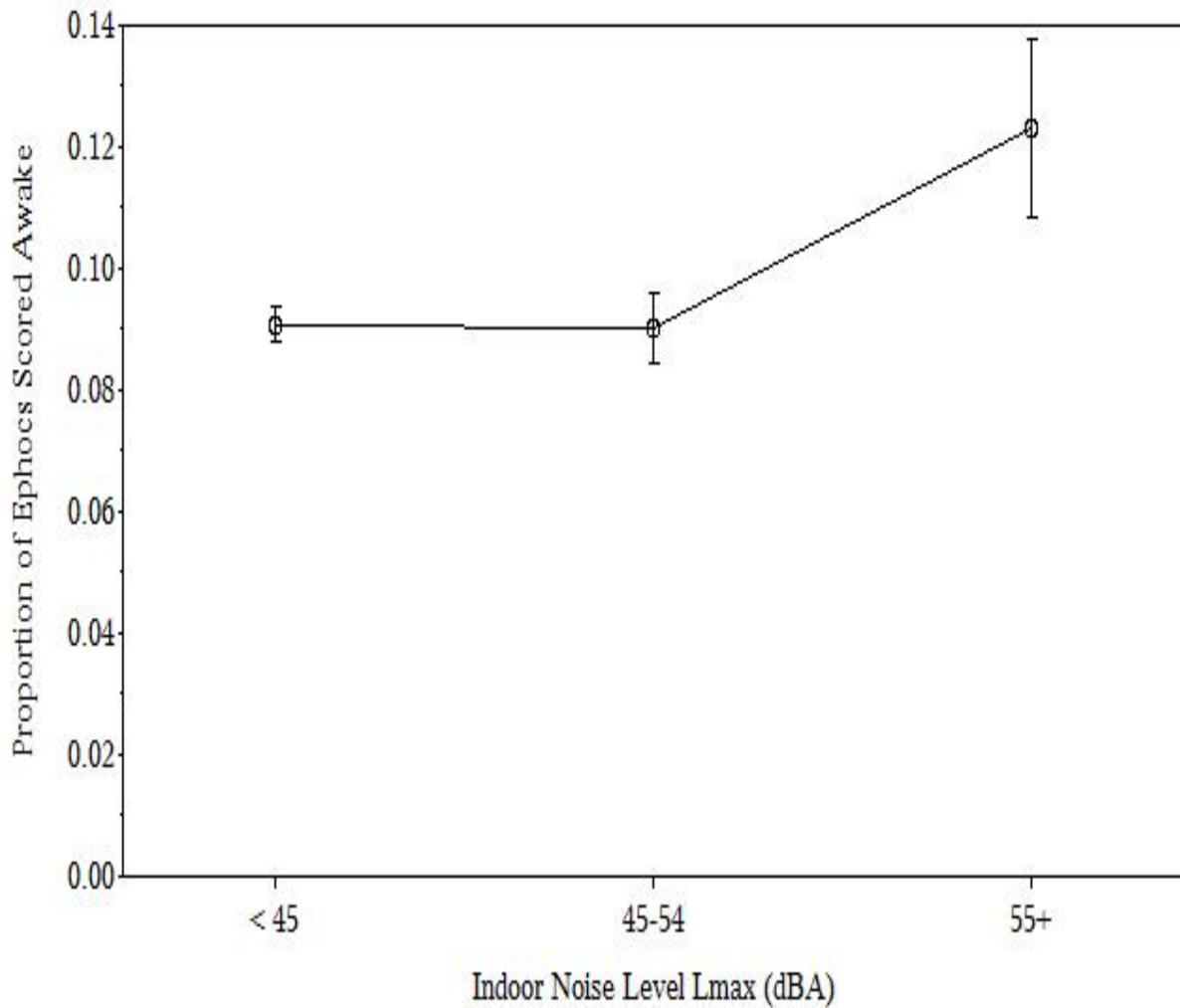


Figure 4.2: Proportion of epochs, with 95% confidence intervals, scored as awake by actigraphy with increasing maximum sound pressure level (dBA) measured indoors. **Note:** Outdoor correction is roughly 20 dB greater.

4.3 Relationship Between Wrist Actigraphy Measures

Spearman’s rank correlation coefficients (r_s) between sleep variables assessed by actigraphy are shown in table 4.3. Sleep variables were generally well correlated with the majority showing statistical significance. The strongest correlation was seen between variables wake after sleep onset and sleep efficiency ($r_s = -0.96$), with wake after sleep onset also correlated with sleep onset latency ($r_s = 0.57$) and number of awakenings ($r_s = 0.74$). Sleep onset latency showed a significant correlation with sleep efficiency ($r_s = -0.71$), but did not correlate with number of awakenings ($r_s = 0.36, p = 0.1$). The variables time in bed and total sleep time did not show significant correlations with the other sleep variables, with the exception of time in bed and number of awakenings ($r_s = 0.63$).

Table 4.3: Spearman’s rank correlations between sleep variables as assessed by actigraphy.

	SOL	WASO	Awakenings	TST	TIB
SOL	1				
WASO	0.57*	1			
Awakenings	0.36	0.75*	1		
TST	-0.0052	-0.16	0.28	1	
TIB	0.23	0.34	0.63*	0.83*	1
SE	-0.71*	-0.96*	-0.63*	0.26	-0.22

* $p < 0.05$

4.4 Sleep Assessed by Sleep Diary

Results of the daily sleep diary are shown in table 4.4. The values represent the average of the five nights for exposed and unexposed groups for each person. The table shows a significant difference in time of retiring to bed, with those in the the exposed group retiring an hour earlier on average than those in the unexposed area, 22:00 and 23:06 respectively. Similarly, subjects from the exposed group reported going to sleep an hour earlier (22:19) than the unexposed group (23:19); however, there was no significant difference in the time subjects reported getting out of bed. There was no significant difference in mean reported sleep rating between the exposed (3.4) and unexposed (3.3) groups ($p = 0.38$). Reported sleep quality across study nights varied more in the unexposed group, between 2.82 (night 3) to 3.63 (night 2) compared with the exposed group reporting between 3.16 (day 3) to 3.58 (nights 2 and 5).

Causes of awakening varied slightly between the two groups. *Use of bathroom* followed by *child or partner* were the most commonly reported sources of awakening for subjects in the exposed group, while subjects in the unexposed group listed *other* and *child or partner* as the most frequent causes of awakening. There was a difference in the number of awakenings described as *other*, as those in the unexposed group reported 37 more events than those in the exposed group. The most frequent descriptions of *other* sources of awakening included “dogs barking”, “discomfort”, and “restlessness”. No reference was made to wind turbines or wind turbine noise as a source of awakening among subjects in the exposed group. Orientation of bedroom windows was different between groups, with subjects in the unexposed group reported to have slept with the

windows closed on 96.4% of the person-nights compared to 56.7% of the person-nights among the exposed group. Masking noise was used 13.3% of the person-nights in the exposed group and 5.5% of the person-nights in the unexposed group.

4.5 Relationship Between Sleep Diary Measures

Table 4.5 shows the Spearman's rank correlation coefficients for the variables measured through the sleep diary. To prevent information surfeit, only correlations with $p < 0.05$ are shown. Subjective sleep rating was negatively correlated with the variables awakenings caused by pain ($r_s = -0.46$), number of awakenings ($r_s = -0.69$), and wake after sleep onset ($r_s = -0.46$). Sleep rating was positively correlated with time out of bed ($r_s = 0.54$). Also, time out of bed was positively correlated with time of sleep start ($r_s = 0.50$) and negatively correlated with waking events caused by pain ($r_s = -0.60$). Relationships within the sleep diaries that approached significance ($p < 0.25$) included sleep rating with sleep latency ($r_s = -0.37$, $p = 0.1$), and awakenings by a child or partner ($r_s = -0.37$, $p = 0.08$); time out of bed with use of bathroom ($r_s = -0.26$, $p = 0.25$); and sleep latency with awakenings caused by pain ($r_s = -0.43$, $p = 0.054$).

4.6 Comparison of Objective and Subjective Sleep Measurements

The relationship between objective and subjective sleep measures are described using Spearman's rank correlation coefficients in table 4.6. Subjectively measured sleep

Table 4.4: Response to sleep diaries averaged across the five study nights for exposed and unexposed groups.

		Unexposed	Exposed	<i>p-value</i> ^a
Time Into Bed	Mean(SD)	23:06(1.14)	22:00(0.82)	0.025
	Min	21:06	20:42	
	Max	01:42	23:15	
Time of Sleep Start	Mean(SD)	23:19(1.08)	22:19(0.85)	0.03
	Min	21:42	21:00	
	Max	01:51	23:24	
Time Out of Bed	Mean(SD)	07:06(0.54)	06:42(0.79)	0.19
	Min	06:21	05:36	
	Max	07:51	07:54	
Sleep Rating (0-6)	Mean(SD)	3.24(0.59)	3.38(0.77)	0.64
	Min	2.2	2.2	
	Max	4.2	4.6	
<i>Reported Sources of Awakening</i>		Unexposed	Exposed	
Use of Bathroom		16(12.8%)	53(49.5%)	
Child or Partner		36(28.8%)	22(20.6%)	
Pain		4(3.2%)	17(15.9%)	
Other		45(36.0%)	8(7.5%)	
Did Not Remember		24(19.2%)	7(6.5%)	
<i>Sleep Behaviors (% of Person-Nights)</i>		Unexposed	Exposed	
Slept with Windows Closed		96.4%	56.7%	
Awoke to Close Windows		0%	5.0%	
Used Sleep Medication		0%	0%	
Used Sleep Aid		3.6%	1.7%	
Required Masking Noise		5.5%	13.3%	

^a Student's *t*-test using unequal variance.

Table 4.5: Spearman correlation coefficients between subjective measures of sleep as measured by sleep diaries.

	Sleep Rating	Time of Sleep Start	Time Out of Bed
Time Out of Bed	0.54	0.50	
Awakenings	-0.70		
Wake After Sleep Onset	-0.46		
Pain	-0.46		-0.60
Other	-0.023		

All figures shown are significant with $p < 0.05$.

latency, wake after onset, and awakenings did not show a significant association with the same variables measured objectively, with the exception of subjective and objective measures of wake after sleep onset ($r_s = 0.24$). The correlation between subjective sleep latency and objective wake after sleep onset approached significance, however the correlation was weak ($r_s = 0.19$).

Table 4.6: Spearman correlation coefficients between objective and subjective measures of sleep used in this study.

		Objective		
		Sleep Latency	WASO	Awakenings
Subjective	Sleep Latency	0.072	0.19	0.19
	WASO	-0.054	0.24*	0.001
	Awakenings	-0.11	0.097	0.082

* $p < 0.05$

Looking at how individuals rated their sleep against measurements taken objectively, individuals in this study tended to overestimate their sleep latency by 10.62 minutes on

average. Conversely, wake after sleep onset and the number of awakenings were both underestimated by individuals in this sample. Individuals reported an average of 19 fewer minutes of wake after sleep onset and reported 4 fewer awakenings than recorded by actigraphy.

4.7 Risk of Poor Sleep Quality

The relationship between sleep quality and exposure status are seen in table 4.7. Here, each night of sleep was classified as *poor* or *good* using sleep efficiency data obtained from actigraphy. The table shows that there were more nights of poor sleep in the exposed group as compared with the unexposed group, 11 and 5 respectively. The prevalence of poor sleep in the exposed group (22 per 100 person-nights) was greater than the prevalence in the unexposed group (11 per 100 person-nights).

Using the data in table 4.7, logistic regression analysis was used to obtain odds ratios (OR) for poor sleep quality between exposed and unexposed groups. There was no observed difference in the crude odds (OR = 2.26 [0.72,7.09]) of poor sleep between exposed and unexposed groups. Adjustment for age showed that being of age 60 or older was not an independent risk factor for poor sleep (OR = 1.10 [0.33, 3.57]). There was no observed difference in the odds of poor sleep quality between groups after age adjustment (OR = 2.34 [0.68, 8.05]) and there was no evidence of confounding by age in this sample. After adjusting for gender, there was no observed difference in odds of poor sleep between groups (OR = 1.80 [0.55, 5.88]); however, the adjustment identified gender as an impor-

Table 4.7: Observed *poor* and *good* sleep efficiency, as measured by actigraphy, for each person-night of sleep stratified across study groups.

	Sleep Efficiency		Totals
	< 85%	≥ 85%	
Exposed	11	39	50(53%)
<i>Row Pct.</i>	22%	78%	
<i>Col. Pct.</i>	69%	49%	
<i>Total Pct.</i>	12%	41%	
Unexposed	5	40	45(47%)
<i>Row Pct.</i>	11%	89%	
<i>Col. Pct.</i>	31%	51%	
<i>Total Pct.</i>	5%	42%	
Totals	16(17%)	79(83%)	95

tant independent risk factor for poor sleep (OR = 3.40 [1.05, 10.99]) with males in this study 3.4 times more likely to experience a night of poor sleep compared to females.

4.8 Noise Exposure Assessment

Data obtained from sound monitoring are seen in table 4.8 below. Eight hour equivalent sound pressure levels (L_{Aeq}) for each observation night are shown. In addition, the range of one minute L_{Aeq} readings within the eight hour observation are given. Measured sound pressure levels were greater in the unexposed group compared with the exposed group for each of the nights recorded. In the exposed group, the mean sound pressure level over the five days of observation was 31.82 dBA with the highest recording on night 5 at 34 dBA and the lowest recording on night 4 at 30.7 dBA. Eight hour

equivalent sound pressure levels in the exposed group did not exceed regulatory limits (45 dBA) for any of the observation nights. However, a one minute measure of 49.9 dBA was observed during the final observation night. Note that in the unexposed group a power failure occurred during the third observation night resulting in only two complete nights of measurement.

Table 4.8: Equivalent sound pressure level measured inside the bedroom during sleep hours showing nightly one minute ranges.

Observation Night	Exposed		Unexposed	
	L _{Aeq}	Range	L _{Aeq}	Range
1	31.0	21.7–42.6	41.0	40.5–50.9
2	32.0	22.0–42.0	41.0	40.2–55.3
3	31.4	23.5–41.5	30.5*	25.1–37.9*
4	30.7	22.4–42.0	-*	-*
5	34.0	22.1–49.9	-*	-*

* Limited or no data as a result of a power failure.

Table 4.9: Melancthon wind facility nightly power output as a percent of capacity showing wind speeds during the study period.

Observation Night	Output (MW) ^b	Efficiency	Wind Speed (m/s) ^a	
			Mean	Range
1	1.00	0.50%	0.96	0–1.9
2	2.13	1.07%	0.62	0–1.1
3	8.88	4.45%	1.98	1.7–3.6
4	33.71	16.90%	1.88	1.1–2.5
5	4.13	2.07%	1.39	0.6–2.5

^a Measured at 10m height. Source: National Climate Data and Information Archive (Mount Forrest, ON), Environment Canada.

^b Source: Independent Electricity System Operator (IESO).

To estimate the contribution of WT activity to the sound pressure levels observed, energy output for the wind operation during the hours of sound measurement (23:00–07:00) was obtained along with measured wind speeds from the nearest Government of Canada weather station. An attempt was made to obtain WT performance data from the operator, however the request went unanswered. Table 4.9 shows that for the period when noise exposure was estimated, WTs in the area were operational. However, there was a low level of WT activity as a result of calm wind speeds. Mean nightly energy output was 9.97 MW, corresponding to 4.9% of the generating capacity. The highest level of WT activity was seen during the fourth night (33.71 MW) at a efficiency of 16.9% of the capacity. To determine if the conditions during which sound pressure levels were surveyed varied from previous years, a year-over-year comparison of wind speeds was performed and is shown in figure 4.3. Wind speeds experienced during the study period were not unlike those recorded over the past two years. The figure illustrates a large variation in wind speeds between nights across all years. Furthermore, average nighttime wind speeds rarely exceeded the cut-in point for WTs in the study area of 3.5 m/s for each of the past two years.

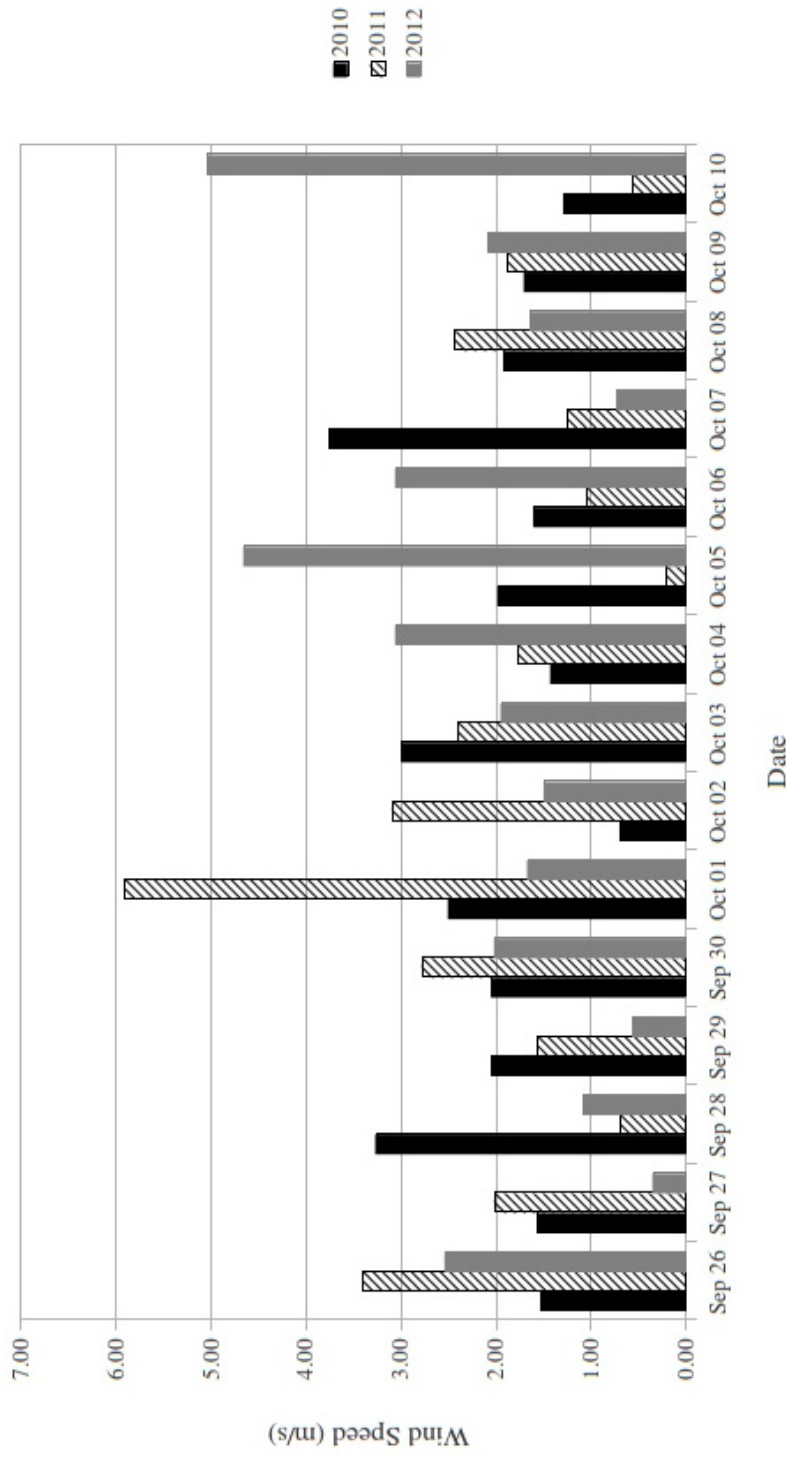


Figure 4.3: Year-Over-Year comparison of average nighttime (23:00–07:00) wind speeds measured at 10m height during the period used for noise exposure assessment. Source: National Climate Data and Information Archive (Mount Forrest, ON), Environment Canada.

Chapter 5

Discussion

5.1 General Discussion

Actigraphic methods were successful in collecting a total of 95 person-nights of sleep data. Results obtained from actigraphy show that sleep of subjects who live in the vicinity of an industrial wind operation was not significantly different than the unexposed group. Although an increased prevalence of a poor night's sleep was observed in the exposed group, 22 per 100 person-nights, compared with the unexposed group, 11 per 100 person-nights, there was no difference in the odds of a poor night of sleep between exposed and unexposed groups (OR = 2.26 [0.72,7.09]). It should be noted that measured sound pressure levels during the study period were moderate (L_{Aeq} 30.7–34 dBA) and may not have impacted sleep at a sufficient level to observe an effect. That said, no clear trend in the data towards poor sleep was observed on average, as the prevalence of poor sleep observed in this study is similar to that of a population-based sleep study by [Hublin, Kaprio, Partinen, Koskenvuo, et al. \(2001\)](#) who observed a prevalence between

19.3% and 20.6% for insufficient sleep according a sleep questionnaire.

The amount of sleep recorded by actigraphy does not appear indicative of a trend towards poor sleep on average. Total sleep time was similar between exposed and unexposed groups at 447 and 443 minutes on average, respectively, despite the fact that the exposed group was significantly older in age compared with the unexposed group. Evidence for a lack of trend towards poor sleep is seen in the consistency between observed total sleep time in the exposed group and sleep of individuals living in rural communities as measured by [Chang et al. \(2012\)](#), who found optimal sleep time (7-8 hours each night) reported by 61.7% of the study population and sleeping less than seven hours each night reported by 29.7%. In the present study, also focused on rural communities, 72.7% of subjects in the exposed group had measured sleep times between seven and eight hours, and 27.2% slept less than seven hours each night on average. In addition, sleep time as measured by actigraphy within this study group is consistent with the Canadian population ([Statistics Canada, 2008](#)) which includes individuals from major population centres who are subject greater noise at increased frequency.

The majority of the poor sleep observed in this study was seen among the males, with males experiencing shorter sleep times and lower sleep efficiencies. Sleep measured by actigraphy identified—in line with previous research—sex to be an important independent risk factor for poor sleep quality. Males in this study population were found to be at 3 times the odds of a poor night's sleep compared with females. The finding is consistent with the work of [Knutson, Van Cauter, Rathouz, DeLeire, and Lauderdale \(2010\)](#), which showed that males are at greater odds of poor sleep compared with their female counterparts in population-level study in the United States. Comparing actigraphic sleep

measures between men and women, [van den Berg et al. \(2009\)](#) found that women slept 16 minutes longer than men and had a 1.2% greater sleep efficiency. In the present study, women slept 10.5 minutes longer than men and showed 2.8% greater sleep efficiency. Although a full explanation for the sex differences in sleep is not currently known, a partial explanation could be that women have a higher need for sleep than men ([van den Berg et al., 2009](#)). The increased need for sleep in women may have implications for the study wind turbine noise on sleep disturbance. Having an increased need for sleep, women may regard disturbances as more detrimental to sleep than men, leading women to underestimate their sleep when using subjective measures. The use of objective measures of sleep in future investigations of wind turbine noise is, therefore, encouraged to protect against the possibility of reporting bias based on sex.

Previous studies investigating the relationship between sleep and wind turbine noise have shown results that are in line with the present study. In a study conducted in the Netherlands, [Pedersen and Waye \(2004\)](#) found that 23% of survey respondents reported sleep disturbance from noises in general. Considering all noise sources in the present study, poor sleep was observed in 22% of participants in the exposed group. Given the similarities between these studies and those mentioned previously, a trend in the prevalence of poor sleep near 20% emerges as a possible baseline figure for poor sleep in healthy adults. In addition, a cross-sectional investigation in the United States by [Nissenbaum, Aramini, and Hanning \(2012\)](#) found worse sleep in participants who reside within 1.5km of a industrial wind operation compared to participants residing beyond 3km. However, this study failed to establish a dose response for distance, as there was no difference in the proportion of poor sleep between near and far groups. Distance to

the nearest wind turbine in the present study did not correlate with sleep efficiency ($r_s = -0.58$ $p = 0.06$) and there does not appear to be a trend towards distance from the nearest wind turbine being predictive of poor sleep.

Specifically to wind turbine noise, [Pedersen and Waye \(2004\)](#) found that for participants at predicted outdoor noise exposures above 35 dBA, 16% reported sleep disturbance due to wind turbine noise. In the current study, average sleep efficiency was not found to be correlated with indoor L_{Aeq} measured at up to 34 dBA. A threshold for sleep disturbance by wind turbine may, therefore, exist at 35 dBA. However, this is not likely the case, as noise exposure levels measured indoors would be upwards of 20 dB greater if measured outdoors and should have resulted in sleep disturbance, given the results of [Pedersen and Waye](#). Furthermore, analysis of sleep epochs identified that a relationship between sound pressure level and awakening was significant only at exposure levels above 45 dBA measured indoors. Increased awakenings at levels above 45 dBA is expected as this figure is in excess of regulatory limits for noise at night ([WHO, 1999](#)). Similar results are seen in a survey conducted in the Netherlands, where [Bakker et al. \(2012\)](#) found a low frequency of sleep disturbance by wind turbine noise and a significant relationship between sleep disturbance and wind turbine noise only for sound pressure levels above 45 dBA. The authors conclude that annoyance was the only factor predictive of sleep disturbance in subjects who notice sound from WTs. This finding suggests a combination of visual impact and personal sensitivity to wind turbine noise as possible risk factors for sleep disturbance through the development of annoyance. Future studies using objective measures of sleep and noise exposure along with estimates of annoyance will better capture the influence of wind turbine noise on sleep at exposures below 45

dBa.

A detailed analysis of individual sleep epochs showed that the sleep of subjects living in the vicinity of WTs was relatively unaffected by noise events. The attributable risk of awakenings scored by actigraphy during one minute epochs of noise exposure of at least 45 dBA was 0.4% (1 in 250 noise events), and a significant association between awakenings and noise events which occurred in the same epoch was only found for noise events above 55 dBA. The World Health Organization guidelines for noise at night state that events with one minute L_{Amax} of at least 45 dBA should be avoided to protect against sleep disturbance (WHO, 1999). These guidelines are not truly reflected in the present study as an increase in noise events did not result in an increase in actigraphically assessed awakenings observed across study nights. Considering a correction of 20 dB for indoor sound pressure levels, results of this study are consistent with a study of aircraft noise conducted by Horne, Pankhurst, Reyner, and Hume (1994) who found that the relationship between the probability of an awakening scored by actigraphy and aircraft noise events below 82 dBA (outdoors) was not significant, and became significant above this level. The authors conclude that study subjects may have acquired a tolerance to aircraft noise. Therefore, tolerance to noise may have accounted for the low impact of noise events on awakenings, as the majority of subjects had lived in the area for many years. However, this conclusion applies to community noise in general and should be treated with caution, because of the inability in this study to identify specific wind turbine noise events. Studies involving sleep under exposure to wind turbine noise recordings are needed to explore the hypothesis of tolerance.

Sleep measured through the use of a sleep diary was useful in providing information

on the subjective aspects of sleep not related to physiology. Time of night that subjects in the exposed group retired to bed was an hour earlier than the unexposed group, 22:00 and 23:00 respectively. The same difference was observed with the time of night subject reported going to sleep, 06:00 and 07:00, respectively. A possible reason for this difference could be that subjects in the exposed group may have gone to sleep earlier in attempt to increase the amount of time available for sleep, in the case that WTs cause a disruption. However, the difference is most likely due to differences in age between subjects, as extension of the sleep period does not correlate with an improvement in sleep efficiency (Harrison & Horne, 1996). Through a study of home-based sleep, Harrison and Horne (1996) found that extension of the sleep period to ten hours from the usual seven or eight resulted in a greater amount of inefficient sleep including increases in sleep latency, and wake after sleep onset, and decreased sleep efficiency. This finding is consistent with a significant correlation found between the amount of time spent in bed and the number awakenings assessed by actigraphy ($r_s = 0.63$). Therefore, the difference in time subjects reported going to sleep does not appear to be altered by living in the vicinity of WTs. Furthermore, those in the exposed group appeared to be content with the sleep they were getting, as measured by the lack of a significant difference in perceived sleep quality. Providing an indication that the observed sleep schedule was the norm for this group.

Sleep diaries used in this study asked participants to identify the sources which caused them to wake up under the headings: *use of bathroom, child or partner, pain, other*, and *I don't remember*. For sources listed as *other*, participants were asked to specify the source in attempt to examine whether WTs were a source of awakening, without prompt-

ing the participants with a heading labeled specifically for WTs. None of the subjects in the exposed group cited wind turbine noise specifically, or WTs in general as a source of awakening. Similar results are seen in a study by [Horne et al. \(1994\)](#) who found that individual factors including using the bathroom, children, telephone, etc. had a greater influence on sleep than aircraft noise events measured at up to 60 dBA outdoors. The lack of reported awakenings related to WTs supports the hypothesis of tolerance to community noise, described above. However, it is possible that the subjects under investigation were not sensitive to noise and, therefore, did not notice noise during sleep. Looking at awakenings identified as *'I don't remember'*, these accounted for a small amount of the total in the exposed group (6.5%) and may have contained some less obvious wind turbine noise events among others. While the actual cause of *'I don't remember'* awakenings cannot be determined, it is unlikely that it contains a disproportionate amount of wind turbine events, due to the low frequency of noise events observed in general (24% of total sleep epochs), as mentioned above.

One objective of this study was to compare the methods used to evaluate sleep in those who reside near WTs—those being actigraphy and sleep diaries—to determine if a relationship exists between sleep measured subjectively and objectively. Experimental methods were not used explicitly for this purpose; however, the similarities between the study groups with respect to sleep in rural communities allows this comparison to be permissible. Large variation in sleep between subjects was observed and is known to exist as a result of personal characteristics like age and gender ([Vitiello, Larsen, & Moe, 2004](#)), but may also be due to differences in lifestyle such as work-life balance ([Williams, Franche, Ibrahim, Mustard, & Layton, 2006](#)). It should be stated that observed varia-

tion, in combination with the small sample size used, may limit the ability to properly compare the measurement tools.

Sleep measures which showed a correlation ($p < 0.05$) in this study include wake after sleep onset measured by actigraphy and sleep diary ($r_s = 0.24$). Measures which did not show a correlation ($p > 0.05$) include measured sleep latency versus all subjective measures, and measured awakenings versus all subjective measures. This lack of correlation between measurement tools was not unexpected and is consistent with previous work using actigraphy and a sleep diary to measure sleep. In a study of insomnia patients, [Wilson, Watson, and Currie \(1998\)](#) assessed the concordance between actigraphy and sleep diary and found correlations between sleep latency and wake after sleep onset for only one of two study nights. In a study of road traffic noise on sleep, [Öhrström and Skånberg \(2004\)](#) found only a single significant correlation between objective and subjective sleep variables, that being subjective sleep latency and objective wake episodes; however, the correlation was low in magnitude ($r = 0.49$). Overestimation of sleep by actigraphy and the difficulty in remembering awakenings less than four minutes ([Öhrström & Skånberg, 2004](#)) are possible reasons for the discrepancy between measurement tools and point out that actigraphy and sleep diaries should be used concurrently to obtain a triangulated view of sleep.

Actigraphic measures in this study which were correlated ($p < 0.05$) include sleep efficiency with sleep onset latency ($r_s = -0.71$), wake after sleep onset ($r_s = -0.96$), and awakenings ($r_s = -0.63$). In addition, sleep onset latency and wake after sleep onset, both of which are variables which influence sleep efficiency, were found to be correlated in this study ($r_s = 0.57$). This correlation has also been reported by [Öhrström and Skån-](#)

berg (2004) who found several significant correlations between variables assessed by actigraphy including sleep latency and wake after sleep onset ($r_s = 0.46$) in a study of road traffic noise. This similarity indicates that sleep assessed by actigraphy in the current study population shares a trend with regard to sleep inefficiency with a population exposed to a different source of community noise. In addition, the similarity suggests that actigraphy can be a valid tool in the measurement of sleep under community noise exposure. Future studies of wind turbine noise on sleep in the field can make use of actigraphy, as this tool allows for investigations of large populations within the environment of interest without supervision.

Subjective measures in correspondence ($p < 0.05$) included judged sleep rating with awakenings ($r_s = -0.70$), wake after sleep onset ($r_s = -0.46$), and awakening events caused by pain ($r_s = -0.46$). Awakenings caused by pain was also negatively correlated with time identified as 'getting up' ($r_s = -0.60$) which may partly explain a portion of the poor sleep observed. The correlation between awakenings and reported sleep quality is not unexpected, as an increased frequency of awakenings that can be recalled should negatively impact an individual's subjective view of their sleep. There appears to be a threshold for remembering an awakening, as Öhrström and Skånberg (2004) found that individuals have difficulty remembering awakenings of length shorter than four minutes. This suggests that awakenings which occurred in this study were either of long enough length to be remembered, or awakenings had an identified cause (i.e. use of bathroom, pain, child or partner, etc.), or some combination of the two. This may also partly explain the absence of awakenings deemed to be caused by WTs, as these events may have occurred in too short a duration and were, therefore, not easily identifiable. Unfortunately, the

methods used in this study were not able to detect short term changes in sleep, as the focus of this study was aimed towards the macro-structure of sleep to generate hypotheses moving forward. Studies of the micro-structure of sleep are, therefore, needed as short term noise events from wind turbine noise presents the possibility of arousals during sleep.

Short term noise events are known in the literature as 'arousals'. These events are described by [Bonnet and Carley \(1992\)](#) as, "transient and do not result in behavioral awakening"; however, arousals are known to cause fragmentation of sleep through abrupt activation of the nervous system ([Bonnet & Carley, 1992](#)) and are considered as a factor of interest in sleep research. Studies of community noise have placed a focus on arousals under low noise exposure levels. A laboratory study of aircraft noise conducted by [Basner, Glatz, Griefahn, Penzel, and Samel \(2008\)](#) illustrated that arousals predominate sleep changes at sound pressure levels below 45 dBA. Applied to this study, the possibility exists that a proportion of wind turbine noise events observed in this study led to arousal, given the low frequency of wind turbine noise events observed above 45 dBA in this study. These arousals would have gone undetected by actigraphy and would not have been recalled subjectively, however, wind turbine noise arousals may have stimulated participants and led to awakenings of another cause some time after. To better explore the effect of arousals, the use of PSG is required in future studies to evaluate changes in the micro-structure of sleep under wind turbine noise exposure, in relation to other sources of community noise.

Sleep diary measures which did not show a correlation ($p > 0.05$) include reported sleep latency with sleep quality. The lack of correlation is counter-intuitive, especially

given the strong correlation between the sleep latency and sleep efficiency as measured by actigraphy, mentioned above. In terms of subjective sleep, the finding suggests that sleep attainment was less of a disruption than sleep continuity among this sample. However, a cross-sectional study conducted by [Middelkoop, den Doel, Neven, Kamphuisen, and Springer \(1996\)](#) found that longer sleep latencies were predictive of poor subjective sleep quality, suggesting that more weight is placed on sleep latency in the evaluation of sleep the following morning. Considering that participants in this study overestimated their sleep latency using the sleep diary compared with actigraphy, the poor conformity with sleep quality indicates that participants were able to overlook problems in falling asleep and considered other criteria when performing an appraisal of their sleep the following morning. Replication of this result with greater ability to manipulate wind turbine noise exposure will provide insight surrounding which area of sleep (sleep attainment or sleep continuity) is most important in the subjective review of sleep.

5.2 Methodological Considerations

The present study was, to the author's knowledge, the first epidemiological study conducted on a Canadian population to incorporate objective measures in the investigation of the impact of wind turbine noise on sleep. Actigraphy was employed to obtain physiological measures—which has been lacking in previous studies—to improve the precision with which sleep is measured. In a recent review of sleep research tools, [Basner, Brink, Elmenhorst, et al. \(2012\)](#) concluded that actigraphy provides a cost-effective

method for estimating sleep that is robust and non-intrusive. Actigraphy, as applied in this study, was well received by study participants and there was very little negative feedback in regards to comfort or intrusion of sleep. Also, actigraphy required little instruction and allowed for sleep to be measured unsupervised. However, in general there are some inconsistencies when evaluating sleep with actigraphy. There is a tendency for actigraphy to overestimate sleep during periods of static wakefulness, which may lead to misclassification. Also, several subjects reported a failure in the strap holding the device on the wrist, which led to a minor loss of sleep data. These shortcomings are specific to the manufacturer of the device and vary across different models of actigraphs. Therefore, functional and logistical requirements should be taken into consideration when using actigraphy in future studies to provide the appropriate level of data quality.

Sleep diaries or questionnaires are the easiest and most inexpensive method to evaluate sleep (Basner et al., 2012). Because sleep diaries are typically used to gather information about resentment, sleep quality, and waking episodes, sleep diaries can provide important information about how sleep is perceived. Sleep diaries are also versatile, as the contents can be adapted to explore a particular environment or disturbance. Applied to this study, sleep diaries were used to observe the differences in sleep behaviour related to sleeping in the vicinity of WTs. Response rate for the sleep diaries used in this study was high (100%) and participants did not mention problems with understanding the questions. Parallel with other studies using survey data, the validity of sleep diaries in the measurement of sleep is considered questionable. This criticism applies, as sleep diaries used in this study did not make use of validated items to measure sleep and contain a limited comparability with other studies. However, sleep diaries used in this

study were employed to enrich the data obtained by actigraphy, using the evaluation of subject's sleep-related experiences and were not intended as a stand alone measure of sleep. Additional items that would be useful to future investigations include a measure of noise sensitivity, length of residency, visual impact, and annoyance from WTs.

The strength of actigraphy combined with the insight recorded by sleep diaries permits an effective and triangulated view of sleep. Therefore, actigraphy and sleep diaries can be seen as complementary measurement tools and should be used together. Actigraphy provides objective information about the physiologic aspects of sleep which subjects are unable to provide through a sleep diary. Likewise, sleep-related experiences and subjective perceptions of sleep can only be obtained through the use of a sleep diary. Furthermore, sleep diaries can be essential to data quality of sleep measured with actigraphy, because artifacts can be investigated and removal of the actigraph can be checked.

The assessment of noise exposure presents two important methodological issues, the first being the issue of background noise. Background noise, or ambient noise, is considered as the threshold below which the sound level seldom drops. Estimating the background noise level is essential to estimate the additional contribution of noise attributable to WTs. Typically, percentile levels are used to represent the background noise level, as these show the sound level that is exceeded a certain percentage of the time (e.g. 95%, 90%, etc.). Use of percentile levels can be difficult in practice, as was the case in this study, because measurement of background noise with percentile levels requires that the intruding sound be absent during the measurement. Fortunately, prediction methods exist for estimating background noise based on the premise that human activity is

the cause of everyday noise. The following model has been validated for use (Stewart, Russell, & Luz, 1999) and is recommended for predicting background noise in areas of Europe (Gjestland, 2008):

$$L_{50} = 13 + 10 \log p \quad (5.1)$$

where L_{50} is the sound level exceeded 50% of the time, and p is the population density of the area in square kilometers. This model may be applied to estimate background levels in situations where isolation or separation of wind turbine noise from the background is complex, or where a formal measure of background noise is unnecessary. Obtaining background levels has implications for future research by increasing the resolution with which the exposure is measured. The increased resolution will allow for identification of specific wind turbine noise events and a direct investigation with the impacts on sleep.

Another methodological consideration is the time of year during which the survey of wind turbine noise takes place. Caution should be taken when attempting to survey wind turbine noise inside the home during the colder months of the year in Canada (November to March), because noise emissions from home heating systems may mask other noises, especially those outdoors. Evidence of this was seen in the noise assessment for the unexposed group, as the baseline sound pressure levels were well above that of the exposed group and variation in sound pressure level throughout the night was small. Secondly, orientation of bedroom windows at night is another seasonal consideration. Sleep diaries indicated that participants in the unexposed group were more likely to sleep with the windows closed. This finding was likely due to the cold conditions experienced during data collection within this group. However, orientation of

the windows during sleep can alter the amount of noise exposure, as shown by Finegold, Harris, and von Gierke (1994) who found a difference of 10 dB for closed window conditions versus opened windows for general transportation noise. Therefore, noise exposure assessment should take into account seasonal differences which may mediate behaviours within the study area.

5.3 Limitations

The limitations of this study include a small sample size (21 participants and a total of 95 person-nights of observation) and a resulting low statistical power. However, limited estimates of the effect size presented a challenge in calculating the required sample size during the study design. Moreover, the focus of this study was placed towards an exploratory analysis rather than performing hypothesis tests, as this study was among the first to incorporate an objective measure of sleep. Sampling bias may have affected the results of this study, as exposed and unexposed groups were not balanced in terms of age. Given that age was not statistically associated with sleep quality, there is a low probability that bias alone influenced the association. As mentioned previously, actigraphy tends to overestimate sleep. Overestimation of sleep by actigraphy may have led to misclassification towards better sleep. However, these events would have occurred randomly, leading to a misclassification which did not vary between the study groups. Missing data may have introduced an information bias, however the overall proportion of missing data was low (4.7%).

As mentioned above, ventilation noise during assessment of noise exposure in the unexposed group was a source of bias; however, this was not observed in the exposed group and did not effect the analysis of sleep. Misdiagnoses of noise exposure may have been present, as a measurement taken at a single residence was used to estimate the noise exposure for all other subjects in the exposed group. While the method of estimation is considered reliable, exact noise conditions may have varied, due to differences in building materials between houses. Exposed and unexposed groups were not surveyed under the same weather conditions which may have impacted sleep behaviours; however, this did not have an impact on sleep measured with actigraphy.

Chapter 6

Conclusion

Using a representative sample of rural Ontario residents, this study was successful in exploring the sleep of residents who live in the vicinity of an industrial wind operation. Results from actigraphy and a sleep diary were not indicative of a trend towards poorer sleep in individuals who reside within fifteen hundred metres of a WT, compared to those who do not reside near a WT. Sleep of subjects residing near WTs showed limited responsiveness to noise during the night. Tolerance to noise may exist suggesting annoyance, as a function of visual impact and personal sensitivity could exist, as a contributing factor to sleep disturbance. Identifying the role of arousals during sleep in the association is required, using more sophisticated sleep measurement to show the effect of sleep state changes in the presence of WT noise. Although WT noise is classified as a source of community noise, the behaviour of WT noise is not similar to that of the other sources. Therefore, assessment of WT noise emissions cannot be accurately assessed with the methods used for road, rail, and aircraft noises. To confidently estimate noise exposure, WT noise measurement requires a combination of indoor and outdoor sound

pressure level, along with wind speeds and direction. Successful studies in the future will benefit from the hypotheses generated by the use of actigraphy in the present study.

Applied for over thirty years in sleep research, actigraphy was employed to increase the precision with which sleep is measured. To date, measurement of sleep has been a limitation among studies investigating sleep disturbance from WTs. The use of actigraphy in this study captured over 216 hours of sleep data on subjects living near WTs and accomplished the goal of estimating the prevalence of poor sleep. As actigraphic results showed consistency with other sleep studies using this device, the validity of actigraphy to measure sleep under community noise conditions is, therefore, shown. While research into the impact of WTs on sleep is ongoing, much of the current literature lacks the compatibility needed to draw confident associations. Continued use of actigraphy in future studies will build upon and allow for comparisons with the results of the present study, allowing for conclusions surrounding the mechanisms of sleep, and straightening out of the associations between WT noise, sleep, and health. This way, research can shift the focus to where it is needed most—solutions for those currently facing hardship.

For the majority of subjects living with WTs, noise at night did not correlate with an increased frequency of awakening. The lack of response to noise raises the question as to whether subjects were able to acquire adaptation to changes in the soundscape. Drawing from the results of this study, work in the area of sound measurement to identify specific WT noise will allow for investigations of ‘worst case’ noise scenarios. Through this work, the hypothesis of tolerance can be reviewed and the characteristics of WT noise, and their effects on sleep can be evaluated. However, identification of WT noise is not an easy task and application of noise assessment methods used for other sources of

community noise may not be suitable. Future studies should incorporate simultaneous indoor and outdoor noise recordings to coordinate noise exposures from the outdoors into the bedroom, and to identify specific WT noise events. Maximizing the resolution of noise exposure will provide researchers the opportunity to firmly assess the extent to which tolerance is acquired, as a part of the overall impact of WT noise on sleep.

Industrial wind developments in Canada do not appear to be slowing down, as the changing environmental landscape requires new approaches to harnessing energy that are sustainable. The same can be said for the opposition against them, which does not appear to be backing down. While the results observed in the present study were mild, a baseline built on objective measures—which have been absent from the investigation to date—has been established. Furthermore, considerations for improved sleep and noise measurement have been illustrated to address the research questions that have emerged from this study. Issues of arousal, visual impact, habituation, and personal sensitivity described previously require further study to understand the mechanisms through which WTs act on sleep, as noise may only contribute a minor role in the mechanism.

Given the reality of the shift in the global climate, there is little doubt towards the promise that renewable energies hold for future prosperity. Taking full advantage of the available natural sources of energy represents a strategy to lessen the haste towards this change. That said, our obligation to protect the environment cannot overshadow the need to prevent health hazards. As the science evolves from this study, the challenge lies in finding ways to use WTs in a safe and responsible manner. Striking a balance to maintain the health of the environment and the community.

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Appendix A

Participant Information Letter

Title: Renewable Energy Impact on Sleep

September 17, 2012

Dear Resident,

The Ontario Research Chair program in Renewable Energy Technologies and Health (ORC-RETH) at the University of Waterloo is exploring if there is a relationship between quality of sleep and living within close proximity of renewable energy technologies such as wind operations, and biogas production facilities. This study will use different methods like surveys and sleep assessments in hopes of understanding the potential quality of sleep impacts that may result from renewable energy technologies in Ontario communities.

Your community has been selected by our research team as one of two communities to be included in this project. Your experience and perspective is very important to understanding the role renewable energy technologies play in quality of sleep across Ontario. This research will require that you fill out a sleep diary and wear a sleep actigraph for five days in your own home. The sleep diary should take approximately 5 minutes to complete each morning. The questions are intended to provide general information about your sleep times, quality and behaviour. The sleep actigraphs are small devices, similar to a wrist-watch, which monitor your body movements while you sleep. These devices

are intended to provide detailed information about your sleep times, and sleep quality. In addition, you will be asked to have a sound level meter placed in your bedroom to monitor the noise levels while you sleep.

You may change your mind about participation and not return the sleep diary; however, if you change your mind about participation, we ask that you return the sleep actigraphs. Please contact James Lane (Project Manager) using the contact information at the bottom of this letter to schedule the collection of the sleep actigraphs. Any information recorded by the sleep actigraphs will be destroyed. All questions on the sleep diary are voluntary and you do not have to complete all questions to participate. All information you provide will be considered confidential.

To ensure the confidentiality of individuals' data, each participant will be identified by a participant identification code known only to the University of Waterloo researchers. Any publications or reports that result from this study will primarily report average responses of groups of participants. In the case where individual data may be presented, the individual will not be identified. Your information will be stored safely and securely at the University of Waterloo at the School of Public Health and Health Systems. Any identifying information will be retained for seven years, after which it will be destroyed by confidential shredding. While de-identified data will be retained indefinitely, after this point, no identifiers will exist linking you to the data collected during this study. All information you provide will be kept confidential, except as required under law. There are no known or anticipated risks to participation in this study.

In appreciation of your time, participants will receive a \$50 gift certificate redeemable at Tim Horton's. The amount received is taxable. It is your responsibility to report the amount received for income tax purposes.

If you have any questions about this study please contact James Lane (Project Manager) at the University of Waterloo at 519-888-4567 ext. 32818 or jlane@uwaterloo.ca.

This study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. Should you have any comments or concerns resulting from your participation in this study, please contact Dr. Maureen Nummelin, the Director, Office of Research Ethics, at 1-519-888-4567, Ext. 36005 or mau-

reen.nummelin@uwaterloo.ca. Thank you in advance for your interest in this project.

CONSENT FORM

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

I agree to take part in a research study being conducted by Dr. Philip Bigelow, PhD and James Lane, MSc. Candidate of the School of Public Health and Health Systems, University of Waterloo.

I have made this decision based on the information I have read in the *Information letter*. All the procedures, any risks and benefits have been explained to me. I have had the opportunity to ask any questions and to receive any additional details I wanted about the study. If I have questions later about the study, I can ask one of the researchers:

Philip Bigelow, School of Public Health and Health Systems, 519-888-4567 x38491

James Lane, School of Public Health and Health Systems, 519-888-4567 x32818

Shannon Majowicz, School of Public Health and Health Systems, 519-888-4567 x31790

Stephen McColl, School of Public Health and Health Systems, 519-888-4567 x32720

I was informed that I may withdraw my consent at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact Dr. Maureen Nummelin, Director, Office of Research Ethics, at 519-888-4567 ext. 36005 or maureen.nummelin@uwaterloo.ca.

Participant Name:	Signature:
Participant Address (for remuneration):	
Participant Phone Number (for remuneration):	
Witnessed:	Date:

Appendix B

Recruitment Script

P = Potential Participant; I = Interviewer

Introduction

I – Good day, my name is *[insert researcher name]* and I am a research assistant in the School of Public Health and Health Systems at the University of Waterloo with the University of Waterloo Renewable Energy Technologies and Health Research Group. We currently conducting a study on the relationship between renewable energy technologies and sleep. You may recall receiving advanced notice about this study in your mail about a week ago.

If you are willing or interested, I would like to speak with you about our study. Is this a convenient time for you? Would you be interested in participating in the study?

...if participant asks for background information

I – Background Information:

- The purpose of the study is to see whether environmental noise impacts an individual's sleep. The study will require a recording of movements during your sleep by having you wear a small device called an actigraph. This is a small device, which resembles and feels like a wrist-watch. You will be required to wear the device for five days at home.
- In addition, you will be asked to keep track of your sleep by filling out a daily sleep journal. The sleep diary will ask you about the time you when to bed, the time you woke up, and your rating of your sleep.

- If you choose to participate you will receive a \$50 gift certificate for taking part in this research.
- Involvement in this study is entirely voluntary and there are no known or anticipated risks to participation in this study.
- You may decline to answer any of the sleep diary questions for any reason and may stop participating at any time.
- All information you provide will be considered confidential. We ask for your address so we can send you the Tim Horton's gift card.
- All data collected will be kept in a secure location and destroyed of in seven years time.
- If you have any questions regarding this study, or would like additional information to assist you in reaching a decision about participation, please feel free to contact James Lane—the contact information is posted on the bottom of the information sheet that I've given you.
- I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo and the office's contact information is also provided on the information sheet that I've given you. However, the final decision about participation is yours.

Would you be interested in participating in the study?

...if participant is unsure about participating or busy

I – That's fine. Thank you very much for your time. Once again, if you have any questions or concerns please do not hesitate to contact our research office. You can keep this information letter which has our contact information on it. Thank you and good-bye.

...if participant is not interested in participating

I – Thank you very much for your time. Once again, if you have any questions or concerns please do not hesitate to contact our research office. You can keep this information letter which has our contact information on it. Thank you and good-bye.

...if participant is interested in participating

I – Thank you very much for your time. Let me inform you about the requirements

for participating, as there are some medical conditions which would prevent you from participating in the study. May I ask you some yes-or-no questions about your health?

- If yes, continue with **Health Status Form**
- If no, see "...if participant is not interested in participating"

...if participant answers "YES" to any of the above questions

I – Thank you very much for your time. Unfortunately, you are not able to participate in the study. Once again, if you have any questions or concerns please do not hesitate to contact our research office. You can keep this information letter which has our contact information on it. Thank you and good-bye.

...if participant answers "NO" to the above questions

I – You are able to participate in the study. We will need to schedule our next meeting where we will review and sign the consent form together and provide you with the training you need to participate.

- Interviewer to schedule follow-up with participant
- Interviewer to collect contact information

I – Thank you very much for your time. Once again, if you have any questions or concerns please do not hesitate to contact our research office. You can keep this information letter which has our contact information on it. Thank you and good-bye.

Appendix C

Health Status Form

This questionnaire asks some questions about your health status. This information is used to guide us with your participation into the study.

Reasons which prevent participation in this study include any diagnosis of a sleep disorder or a medical condition which interferes with your sleep. Also, a serious medical condition which affects your activity would be grounds for exclusion. This includes any kidney problems, or any cardiovascular diseases including bleeding disorders, or any respiratory diseases.

STUDY: *RETH Sleep Assessment*

Participant ID:

Exclusion Code:

Self Report Checklist

- Do you have any of the following conditions which interfere with your sleep:
Sleep Aponea Urinary/Bladder Issues
Insomnia Severe Back Pain
Restless Leg Syndrome Other (*specify*):
Epilepsy
- Do you take any prescribed sleep medication? *YES / NO*
- Have you been treated for a mental disorder in the last year? *YES / NO*

- Do you have serious medical illness?

Stroke	Deafness	Schizophrenia
Cancer	Blindness	Dementia
Chronic Renal Disease	Heart Disease	Amnesia
Hepatitis	Asthma	Depression
Bipolar Disorder		
- Are you or your partner currently pregnant, nursing or bottle feeding a child? *YES /NO*
- Do you drink more than 5 cups or glasses of caffeinated beverages per day? *YES /NO*
- Do you plan on moving from your current residence in the next month? *YES /NO*
- Are you participating in any other sleep studies? *YES /NO*

Appendix D

Sleep Diary

Daily Sleep Diary

Complete this diary each morning (“Day 1” is the morning after the first night). Don’t worry about giving exact responses, an estimate will do.

Participant ID: Day: Date:

I got into bed last night at:	PM/AM
I began trying to sleep last night at:	PM/AM
I got out of bed this morning at:	PM/AM
Last night, I fell asleep in:	minutes
I woke up during the night:	times
In total, I was awake last night for:	minutes

How many times did the following events wake you up last night? (*circle # of times*)

Awoken to use the bathroom	0	1	2	3	4	5	or more
Awoken by child/bed partner	0	1	2	3	4	5	or more
Awoken by discomfort/pain	0	1	2	3	4	5	or more
Other	0	1	2	3	4	5	or more

Please describe:

I don't remember	0	1	2	3	4	5	or more
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How would you rate last night's sleep?		<i>terrible</i>					<i>excellent</i>
	0	1	2	3	4	5	

Last night, did you sleep with the windows closed?							Yes	No
--	--	--	--	--	--	--	-----	----

Last night, did you wake up to close the windows?							Yes	No
---	--	--	--	--	--	--	-----	----

Last night, did you use any over the counter sleep medication?							Yes	No
--	--	--	--	--	--	--	-----	----

Please describe:

Last night, did you use any sleep aids? (mask, ear plugs, music, herbal remedy)							Yes	No
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Appendix E

Feedback Letter

Title: Renewable Energy Impact on Sleep

January 30, 2013

Dear Resident,

I would like to thank you for your participation in the Renewable Energy Impact on Sleep Study. As a reminder, the purpose of this study is to explore if there is a relationship between quality of sleep and living within close proximity of renewable energy technologies such as wind operations, and biofuel production facilities. Enclosed is remuneration for participating in the study – a \$50 gift card to Tim Horton's.

Please remember that results from this study will primarily report average responses of groups of participants. In the case where individual data may be presented, the individual will not be identified. Your information will be stored safely and securely at the University of Waterloo at the School of Public Health and Health Systems. Once all the data are collected and analyzed for this project, this information will be shared with the research community through seminars, conferences, presentations, and journal articles. Any publications or reports that result from this study will be presented as group data. This information will also be shared with your local media and will be mailed to you, anticipated to be sent by December 2014.

If you have any questions about the study at any time, please contact James Lane (Project Manager) at 519-888-4567 ext. 32818 or jlane@uwaterloo.ca. This study has been reviewed and received ethics clearance through the Office of Research Ethics at the Uni-

versity of Waterloo. Should you have any comments or concerns resulting from your participation in the study, please contact Dr. Maureen Nummelin, the Director, Office of Research Ethics, at 519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Regards,

University of Waterloo Renewable Energy Technologies and Health Research Group

<http://www.orc-reth.uwaterloo.ca/>

Phil Bigelow, PhD

Shannon Majowicz, PhD

Steve McColl, PhD

James Lane, MSc Candidate

Appendix F

Map of Study Areas

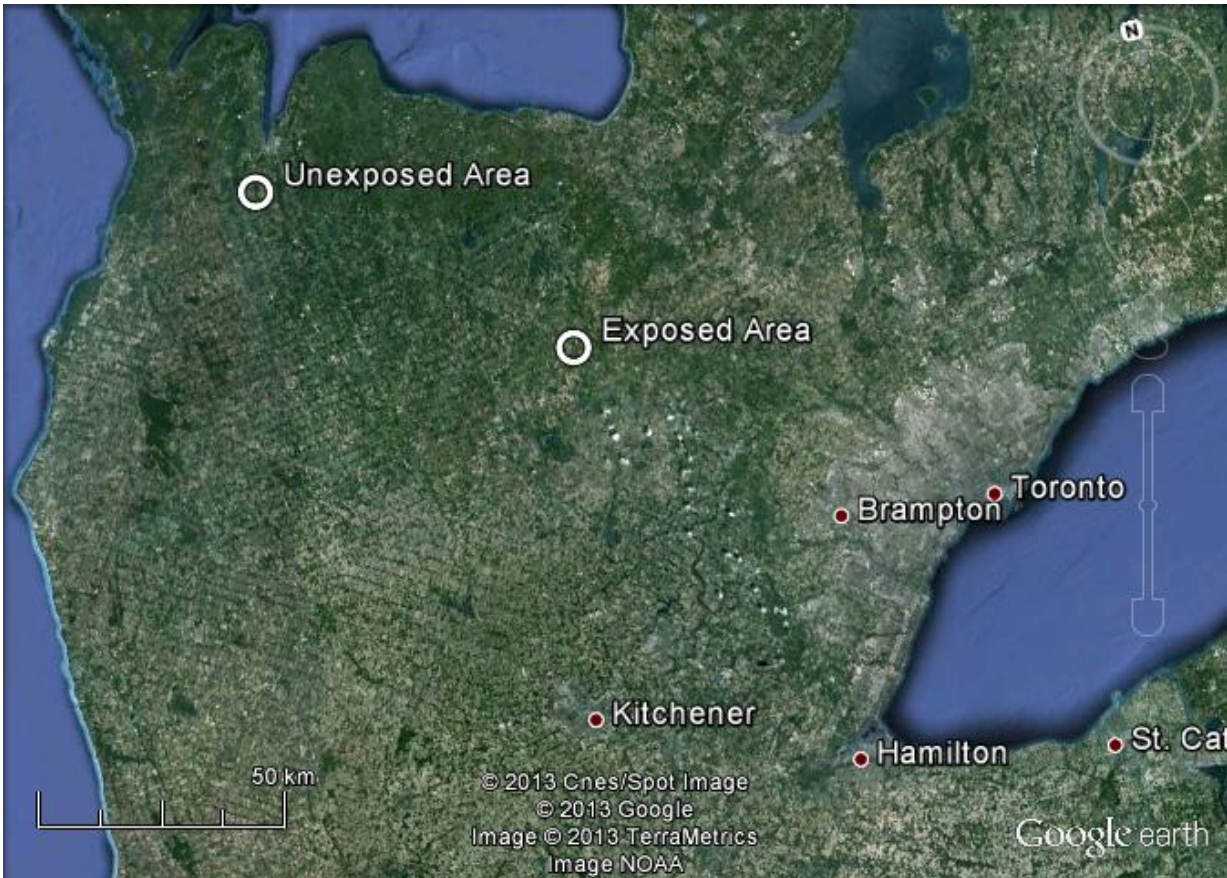


Figure F.1: Satellite image of southern Ontario depicting location of study areas relative to the major population centres.