

did and did not participate are important to know. Without this, attributing any of the observed associations to the wind turbines (either noise from them or the sight of them) is premature.

### **3.3.e Summary of Epidemiological Data**

There is only a limited literature of epidemiological studies on health effects of wind turbines. Furthermore, existing studies are limited by their cross sectional design, self-reported symptoms, limited ability to control for other factors, and to varying degrees of non-response rates. The study that accounted most extensively for other factors that could affect reported symptoms had a very low response rate (E. Pedersen et al., 2009; van den Berg, et al., 2008).

All four peer-reviewed papers discussed above suggested an association between increasing sound levels from wind turbines and increasing annoyance. Such an association was also suggested by two of the non-peer reviewed reports that met at least basic criteria to be considered studies. The only two papers to consider the influence of seeing a wind turbine (each one of the peer-reviewed papers) both found a strong association between seeing a turbine and annoyance. Furthermore, in the studies with available data, the influence of either sound from a turbine or seeing a turbine was reduced—if not eliminated, as was the case for sound in one study—when both of these factors were considered together. However, this precise relation cannot be disentangled from the existing literature because the published analyses do not properly account for both seeing and hearing wind turbines given the relation between these two that the data seem to suggest. Specifically, the possibility that there may be an association between either of those factors and annoyance, but possibly only for those who both see and hear sound from a turbine, and not for those who either do not hear sound from or do not see a turbine. Furthermore, in the one study to consider whether individuals benefit economically from the turbines in question, there appeared to be virtually no annoyance regardless of whether those people could see or hear a turbine. Even if one considers the data just for those who could see a wind turbine and did not benefit economically from the turbines, defining at what noise levels the percentage of those annoyed becomes more dramatic is difficult. Higher percentages of annoyance did appear to be more consistent above 40 dB(A). Roughly 27% were annoyed (at least 4 on a 1–5 point scale of annoyance; 5 being the worst), while roughly 18% were very annoyed (5 on a 1–5 scale). The equivalent levels of annoyed and very annoyed for 35–40 dB(A) were roughly 15% and 6%, respectively. These percentages, however, should be considered upper bounds for a specific relation with noise levels because, with respect to

estimating direct effects of noise, they are likely inflated as a result of both selective participation in the studies and the fact that the percentages do not take into account the effect of seeing a turbine.

Thus, in considering simply exposure to wind turbines in general, while all seem to suggest an association with annoyance, because even the peer-reviewed papers have weaknesses, including the cross sectional designs and sometimes quite low response rates, **the Panel concludes that there is limited evidence suggesting an association between exposure to wind turbines and annoyance.** However, only two of the studies considered both seeing and hearing wind turbines, and even in these the possible contributions of seeing and hearing a wind turbine were not properly disentangled. Therefore, **the Panel concludes that there is insufficient evidence to determine whether there is an association between noise from wind turbines and annoyance independent from the effects of seeing a wind turbine and vice versa.** Even these conclusions must be considered in light of the possibility suggested from one of the peer-reviewed studies that there is extremely low annoyance—regardless of seeing or hearing sound from a wind turbine—among people who benefit economically from the turbines.

There was also the suggestion that poorer sleep was related to wind turbine noise levels. While it intuitively makes sense that more noise would lead to more sleep disruption, there is limited data to inform whether this is occurring at the noise levels produced from wind turbines. An association was indicated in the New Zealand study, suggested without presenting details in one of the Swedish studies, and found in two non-peer-reviewed studies. Therefore, **the Panel concludes that there is limited evidence suggesting an association between noise from wind turbines and sleep disruption and that further study would quantify precise sound levels from wind turbines that disrupt sleep.**

The strongest epidemiological study to examine the association between noise and psychological health suggests there is not an association between noise from wind turbines and measures of psychological distress or mental health problems. There were two smaller, weaker, studies: one did note an association, one did not. Therefore, **the Panel concludes the weight of the evidence suggests no association between noise from wind turbines and measures of psychological distress or mental health problems.**

One Swedish study apparently collected data on headache, undue tiredness, pain and stiffness in the back, neck, or shoulders, or feeling tensed/stressed and irritable, but did not report

on analyses of these data. The Dutch study found no association between noise from wind turbines and diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and migraine, although this was not reported in the peer-reviewed literature. Therefore, **the Panel concludes that none of the limited epidemiological evidence reviewed suggests an association between noise from wind turbines and pain and stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular disease, and headache/migraine.**

These conclusions align with those presented in the peer-reviewed article by Knopper and Ollson (2011). They write “Conclusions of the peer reviewed literature differ in some ways from those in the popular literature. In peer reviewed studies, wind turbine annoyance has been statistically associated with wind turbine noise, but found to be more strongly related to visual impact, attitude to wind turbines and sensitivity to noise. ... it is acknowledged that noise from wind turbines can be annoying to some and associated with some reported health effects (e.g., sleep disturbance), especially when found at sound pressure levels greater than 40 db(A).”

### **3.4 Exposures from Wind Turbines: Noise, Vibration, Shadow Flicker, and Ice Throw**

In addition to the human epidemiologic study literature on exposure to wind turbines and health effects described in the section above, the Panel assessed literature that could shed light on specific exposures resulting from wind turbines and possible health effects. The exposures covered here include noise and vibration, shadow flicker, and ice throw. Each of these exposures is addressed separately in light of their documented and potential health effects. When health effects are described in the popular media, these claims are discussed.

#### **3.4.a Potential Health Effects Associated with Noise and Vibration**

The epidemiologic studies discussed above point to noise from wind turbines as a source of annoyance. The studies also noted that some respondents note sleep disruption due to the turbine noise. In this section, the characteristics of audible and inaudible noise from turbines are discussed in light of our understanding of their impacts on human health.

It is clear that when sound levels get too high, the sound can cause hearing loss (Concha-Barrientos et al., 2004). These sound levels, however, are outside the range of what one would experience from a wind turbine. There is evidence that levels of audible noise below levels that cause hearing loss can have a variety of health effects or indicators. Detail about the evidence for such health effects have been well summarized in a WHO report that came to several relevant conclusions (WHO, 2009). First, there is sufficient evidence for biological effects of noise

during sleep: increase in heart rate, arousals, sleep stage changes and awakening; second, there is limited evidence that noise at night causes hormone level changes and clinical conditions such as cardiovascular illness, depression, and other mental illness. What the WHO report also details is observable noise threshold levels for these potential effects. For such health effects, where data are sufficient to estimate a threshold level, that level is never below 40 dB(A)—as a yearly average—for noise outside (ambient noise) at night—and these estimates take into account sleeping with windows slightly open.

One difficulty with the WHO threshold estimate is that a yearly average can mask the particular quality of turbine noise that leads survey respondents to note annoyance or sleep disruption. For instance, the pulsatile nature of wind turbine noise has been shown to lead to respondents claiming annoyance at a lower averaged sound level than for road noise (E. Pederson, 2004). Yearly averaging of sound eliminates (or smooths) the fluctuations in the sound and ignores differences between day and night levels. Regulations may or may not take this into account.

Health conditions caused by intense vibration are documented in the literature. These are the types of exposures that result from jackhammers, vibrating hand tools, pneumatic tools, etc. In these cases, the vibration is called arm-body or whole-body vibration. Vibration can cause changes in tendons, muscles, bones and joints, and can affect the nervous system. Collectively, these effects are known as Hand-Arm Vibration Syndrome (HAVS). Guidelines and interventions are intended to protect workers from these vibration-induced effects (reviewed by European Agency for Safety and Health at Work, 2008; (NIOSH 1989). OSHA does not have standards concerning vibration exposure. The American Conference of Governmental Industrial Hygienists (ACGIH) has developed Threshold Limit Values (TLVs) for vibration exposure to hand-held tools. The exposure limits are given as frequency-weighted acceleration (NIOSH, 1989).

#### ***3.4.a.i Impact of Noise from Wind Turbines on Sleep***

The epidemiological studies indicate that noise and/or vibration from wind turbines has been noted as causing sleep disruption. In this section sleep and sleep disruption are discussed. In addition, suggestions are provided for more definitively evaluating the impact of wind turbines on sleep.

All sounds have the potential to disrupt sleep. Since wind turbines produce sounds, they might cause sleep disruption. A very loud wind turbine at close distance would likely disrupt sleep, particularly in vulnerable populations (such as those with insomnia or mood disorders, aging populations, or “light sleepers”), while a relatively quiet wind turbine would not be expected to disrupt even the lightest of sleepers, particularly if it were placed at considerable distance.

There is insufficient evidence to provide very specific information about how likely particular sound-pressure thresholds of wind turbines are at disrupting sleep. Physiologic studies of noises from wind turbines introduced to sleeping people would provide these specific levels. Borrowing existing data (e.g., Basner, 2011) and guidelines (e.g., WHO) about noises at night, beyond wind turbines, might help provide reasonable judgment about noise limits at night. But it would be optimal to have specific data about the particular influence that wind turbines have on sleep.

In this section we introduce broad concepts about sleep, the interaction of sleep and noises, and the potential for wind turbines to cause that disruption.

### *Sleep*

Sleep is a naturally occurring state of altered consciousness and reduced physical activity that interacts with all aspects of our physiology and contributes daily to our health and well-being.

Measurements of sleep in people are typically performed with recordings that include electroencephalography (EEG). This can be performed in a laboratory or home, and for clinical or experimental purposes. Other physiological parameters are also commonly measured, including muscle movements, lung, and heart function.

While the precise amount of sleep that a person requires is not known, and likely varies across different people and different ages, there are numerous consequences of reduced sleep (i.e., sleep deprivation).

Deficiencies of sleep can take numerous forms, including the inability to initiate sleep; the inability to maintain sleep; abnormal composition of sleep itself, such as too little deep sleep (sometimes called slow-wave sleep, or stage N3); or frequent brief disruptions of sleep, called arousals. Sources of sleep deprivation can be voluntary (desirable or undesirable) or involuntary. Voluntary sources include staying awake late at night or awakening early. These can be for

work or school, or while engaging in some personal activities during normal sleep times. Sleep deprivation can also be caused by myriad involuntary and undesired problems (including those internal to the body such as pain, anxiety, mood disorders) and frequent need to urinate, or by numerous sleep disorders (including insomnia, sleep apnea, circadian disorders, parasomnias, sleep-related movement disorders, etc), or simply by the lightening of sleep depth in normal aging. Finally, sleep deprivation can be caused by numerous external factors, such as noises or other sensory information in the sleeper's environment.

Sleep is conventionally categorized into rapid eye movement (REM) and non-REM sleep. Within the non-REM sleep are several stages of sleep ranging from light sleep to deep sleep. Beyond these traditional sleep categories, the EEG signal can be analyzed in a more detailed and sophisticated way, including looking at the frequency composition of the signals. This is important in sleep, as we now know that certain signatures in the brain waves (i.e., EEG) disclose information about who is vulnerable to noise-induced sleep disruption, and what moments within sleep are most vulnerable (Dang-Vu et al., 2010; McKinney et al., 2011).

Insomnia can be characterized by a person having difficulty falling asleep or staying asleep that is not better explained by another condition (such as pain or another sleep disorder) (see ICSD, 2<sup>nd</sup> Edition for details of the diagnostic criteria for insomnia). Approximately 25% of the general population experience occasional sleep deprivation or insomnia. Sleep deprivation is defined by reduced quantity or quality of sleep, and it can result in excessive daytime sleepiness as well as problems including those associated with mood and cognitive function (Roth et al., 2001; Rogers, 2007; Walker, 2008). As might be expected, the severity of the sleep deprivation has an impact on the level of cognitive functioning, and real-life consequences can include driving accidents, impulsive behaviors, errors in attention, and mood problems (Rogers, 2007; Killgore, 2010). Loss of sleep appears to be cumulative, meaning it adds up night after night. This can result in subtle impairments in reaction times, decision-making ability, attentional vigilance, and integration of information that is sometimes only apparent to the sleep-deprived individual after an accident or error occurs, and sometimes not perceived by the sleep-deprived person at all (Rogers, 2007; van Dongen 2003).

### ***Sleep and Wind Turbines***

Given the effects of sleep deprivation on health and well-being, including problems with mood and cognition, it is possible that cognitive and mood complaints and other medical or

psychological issues associated with sleep loss can stem from living in immediate proximity to wind turbines, if the turbines disrupt sleep. Existing data, however, on the relationship between wind turbines and sleep are inadequate. Numerous factors determine whether a sound disrupts sleep. Broadly speaking, they are derived from factors about the sleeper and factors about the sound.

Case reports of subjective complaints about sleep, particularly those not critically and objectively appraised in the normal scientific manner, are the lowest level of evidence, not simply because they lack any objective measurements, but also because they lack the level of scrutiny considered satisfactory for making even crude claims about cause and effect. For instance, consider the case of a person who sleeps poorly at home (near a wind turbine), and sleeps better when on vacation (away from a wind turbine). One might conclude from this case that wind turbines cause sleep disruption for this person, and even generalize that information to other people. But there are numerous factors that might make it more likely that a person can sleep well on vacation, having nothing to do with the wind turbine. Furthermore, given the enormous prevalence of sleep disorders, such as insomnia, and the potentially larger prevalence of disorders that impinge on sleep, such as depression, it is crucial that these factors be taken into consideration when weighing the evidence pointing to a causal effect of wind turbines on sleep disruption for the general population. It is also important to obtain objective measurements of sleep, in addition to subjective complaints.

Subjective reports of sleeping well or sleeping poorly can be misleading or even inaccurate. People can underestimate or overestimate the quality of their sleep. Future studies should examine the acoustic properties of wind turbines when assessing the elements that might disrupt sleep. There are unique properties of the noises wind turbines make, and there are some acoustic properties in common with other noises (such as trucks or trains or airplanes). It is important to make these distinctions when assessing the effects of wind turbines on noise, by using data from other noises. Without this physiologic, objective information, the effects of wind turbines on sleep might be over- or underestimated.

It should be noted that not all sounds impair the ability to fall asleep or maintain sleep. To the contrary, people commonly use sound-masking techniques by introducing sounds in the environment that hinder the perception of undesirable noises. Colloquially, this is sometimes called “white noise,” and there are certain key acoustic properties to these kinds of sounds that

make them more effective than other sounds. Different noises can affect people differently. The emotional valence that is ascribed by an individual to a particular sound can have a major influence on the ability to initiate or maintain sleep. Certain aspects of sounds are particularly alerting and therefore would be more likely to disrupt sleep at lower sound pressure levels. But among those that are not, there is a wide range of responses to these sounds, depending partly on the emotional valence ascribed to them. A noise, for instance, that is associated with a distressing object, is more likely to impede sleep onset.

Finally, characteristics of sleep physiology change across a given night of sleep—and across the life cycle of a person—and are different for different people, including the effects of noise on sleep (e.g., Dang-Vu et al., 2010; McKinney et al., 2011). And some people might initially have difficulty with noises at night, but habituate to them with repeated exposure (Basner, 2011).

In summary, **sleep is a complex biological state, important for health and well-being across a wide range of physiologic functions. To date, no study has adequately examined the influence of wind turbines on sleep.**

Future directions: The precise effects of noise-induced sleep disruption from wind turbines may benefit from further study that examines sound-pressure levels near the sleeper, while simultaneously measuring sleep physiology to determine responses of sleep to a variety of levels of noise produced by wind turbines. The purpose would be to understand the precise sound-pressure levels that are least likely to disturb sleep. It would also be helpful to examine whether sleepers might habituate to these noises, making the impact of a given sound less and less over time. Finally, it would be helpful to study these effects in susceptible populations, including those with insomnia or mood disorders or in aging populations, in addition to the general population.

#### *Summary of Sleep Data*

In summary, sleep is a complex biological state, important for health and well-being across a wide range of physiologic functions. **To date, no study has adequately examined the influence of wind turbines and their effects on sleep.**

#### **3.4.b Shadow Flicker Considerations and Potential Health Effects**

Shadow flicker is caused when changes in light intensity occur from rotating wind turbine blades that cast shadows (see Appendix B for more details on the physics of the

phenomenon.) These shadows move on the ground and on buildings and structures and vary in terms of frequency rate and intensity. Shadow flicker is reported to be less of a problem in the United States than in Northern Europe due to higher latitudes and lower sun angles in Europe. Nonetheless, it can still be a considerable nuisance to individuals exposed to shadow flicker for considerable amounts of time per day or year in the United States as well. Shadow flicker can vary significantly by wind speed and duration, geographic location of the sunlight, and the distance from the turbine blades to any relevant structures or buildings. In general, shadow flicker branches out from the wind turbine in a declining butterfly wing characteristic geographic area with higher amounts of flicker being closer to the turbine and less flicker in the outer parts of the geographic area (New England Wind Energy Education Project (NEWEEP), 2011; Smedley et al., 2010). Shadow flicker is present up until approximately 1400 m, but the strongest flicker is up to 400 m from the turbine when it occurs (NEWEEP, 2011). In addition, shadow flicker usually occurs in the morning and evening close to sunrise and sunset when shadows are the longest. Furthermore, shadow flicker can fluctuate in different seasons of the year depending on the geographic location of the turbine such that some sites will only report flicker during the winter months while others will report it during summer months. Other factors that determine shadow flicker rates and intensity include objects in the landscape (i.e., trees and other existing shadows) and weather patterns. For instance, there is no shadow flicker on cloudy days without sun as compared with sunny days. Also, shadow flicker speed (shadows passing per second) increases with the rotor speed (NRC, 2007). In addition, when several turbines are located relatively close to one another there can be combined flicker from the different blades of the different turbines and conversely, if situated on different geographic areas around structures, shadow flicker can occur at different times of the day at the same site from the different turbines so pre-planning of siting location is very important (Harding et al., 2008). General consensus in Germany resulted in the guidance of 30 hours per year and 30 minutes per day (based on astronomical, clear sky calculations) as acceptable limits for shadow flicker from wind turbines (NRC, 2007). This is similar to the Denmark guidance of 10 hours per year based on actual conditions.

#### **3.4.b.i Potential Health Effects of Flicker**

Because some individuals are predisposed to have seizures when exposed to certain types of flashing lights, there has been concern that wind turbines had the potential to cause seizures in

these vulnerable individuals. In fact, seizures caused by visual or photic stimuli are typically observed in people with certain types of epilepsy (Guerrini & Genton, 2004), particularly generalized epilepsy. While it is not precisely known how many people have photosensitivity that causes seizures, it appears to be approximately 5% of people with epilepsy, amounting to about 100,000 people in the United States. And many of these people will already be treated with antiepileptic medications thus reducing this risk further.

Fortunately, not all flashing light will elicit a seizure, even in untreated people with known photosensitivity. There are several key factors that likely need to simultaneously occur in order for the stimulus to induce a seizure, even among the fraction of people with photosensitive seizures. The frequency of the stimulus is important as is the stimulus area and pattern (See below) (<http://www.epilepsyfoundation.org/aboutepilepsy/seizures/photosensitivity/gerba.cfm>).

Frequencies above 10 Hz are more likely to cause epileptic seizures in vulnerable individuals, and seizures caused by photic stimulation are generally produced at frequencies ranging from greater than 5 Hz. However, shadow flicker frequencies from wind turbines are related to the rotor frequency and this usually results in 0.3–1.0 Hz, which is outside of the range of seizure thresholds according to the National Resource Council and the Epilepsy Foundation (NRC, 2007). In fact, studies performed by Harding et al. (2008) initially concluded that because light flicker can affect the entire retina, and even if the eyes are closed that intermittent light can get in the retina, suggested that 4 km would be a safe distance to avoid seizure risk based on shadow flicker (Harding et al., 2008). However, a follow-up analysis considering different meteorological conditions and shadow flicker rates concluded that there appeared to be no risk for seizures unless a vulnerable individual was closer than 1.2 times the total turbine height on land and 2.8 times the total turbine height in the water, which could potentially result in frequencies of greater than 5 Hz (Smedley et al., 2010).

Although some individuals have complained of additional health complaints including migraines, nausea, dizziness, or disorientation from shadow flicker, only one government-sponsored study from Germany (Pohl et al., 1999) was identified for review. This German study was performed by the Institute of Psychology, Christian-Albrechts-University Kiel on behalf of the Federal Ministry of Economics and Technology (BMW) and supported by the Office of Biology, Energy, and Environment of the Federal Ministry for Education and Research (BMBF), and on behalf of the State Environmental Agency of Schleswig. The purpose of this

government-sponsored study was to determine whether periodic shadow with a duration of more than 30 minutes created significant stress-related health effects. The shadows were created by a projection system, which simulated the flicker from actual wind turbines.

Two groups of different aged individuals were studied. The first group consisted of 32 students (average age 23 years). The second group included 25 professionals (average age 47 years). Both men and women were included. The subjects were each randomly assigned to one of two experimental groups, so there was a control group and an experimental group. The experimental group was exposed to 60 minutes of simulated flicker. For the control group lighting conditions were the same as in the experimental group, but without periodic shadow. The main part of the study consisted of a series of six test and measurement phases, two before the light was turned on, three each at intervals of 20 minutes while the simulated shadow flickering was taking place, and one more after the flicker light was turned off. Among the variables measured were general performance indicators of stress (arithmetic, visual search tasks) and those of mental and physical well-being, cognitive processing, and stress in the autonomic nervous system (heart rate, blood pressure, skin conductance, and finger temperature). Systematic effects due to the simulated flicker could be detected in comparable ways in both exposure groups studied. Both physical and cognitive effects were found in this exposure scenario for shadow flicker.

It appears clear that shadow flicker can be a significant annoyance or nuisance to some individuals, particularly if they are wind project non-participants (people who do not benefit economically or receive electricity from the turbine) whose land abuts the property where the turbine is located. In addition, flashing (a phenomenon closely related to shadow flicker, but due to the reflection of sunlight – see Appendix B) can be a problem if turbines are sited too close to highways or other roadways. This could cause dangerous conditions for drivers. Accordingly, turbine siting near highways should be planned so as to reduce flashing as much as possible to protect drivers. However, use of low reflective turbine blades is commonly employed to reduce this potential flashing problem. Provisions to avoid many of these potential health and annoyance problems appear to be employed as current practice in many pre-planning sites with the use of computer programs such as WindPro. These programs can accurately determine shadow flicker rates based on input of accurate analysis area, planned turbine location, the turbine design (height, length, hub height, rotor diameter, and blade width), and residence or

roadway locations. Many of these computer programs can then create maps indicating the location and incidence of shadow flicker. Such programs may also provide estimates of daily minutes and hours per year of expected shadow flicker that can then be used for wind turbine planning and siting or for mitigation efforts. Several states require these analyses to be performed before any new turbine projects can be implemented.

#### **3.4.b.ii Summary of Impacts of Flicker**

Collectively, although shadow flicker can be a considerable nuisance particularly to wind turbine project non-participants, the evidence suggests that there is no risk of seizure from shadow flicker caused by wind turbines. In addition, there is limited evidence primarily from a German government-sponsored study (Pohl et al., 1999) that prolonged shadow flicker (more than 30 minutes) can result in transient stress-related effects on cognition (concentration, attention) and autonomic nervous system functioning (heart rate, blood pressure). There was insufficient documentation to evaluate other than anecdotal reports of additional health effects including migraines or nausea, dizziness or disorientation. There are documented mitigation methods for addressing shadow flicker from wind turbines and these methods are presented in Appendix B.

#### **3.4.c Ice Throw and its Potential Health Effects**

Under certain weather conditions ice may form on the surface of wind turbine blades. Normally, wind turbines intended for use in locations where ice may form are designed to shut down when there is a significant amount of ice on the blades. The means to prevent operation when ice is present may include ice sensor and vibration sensors. Ice sensors are used on most wind turbines in cold climates. Vibration sensors are used on nearly all wind turbines. They would cause the turbine to shut down, for example, if ice buildup on the blades resulted in an imbalance of the rotor and hence detectable vibrations in the structure.

Ice built up on blades normally falls off while the turbine is stationary. If that occurs during high winds, the ice could be blown by the wind some distance from the tower. In addition, it is conceivable that ice could be thrown from a moving wind turbine blade under some circumstances, although that would most likely occur only during startup (while the rotational speed is still relatively low) or as a result of the failure of the control system. It is therefore worth considering the maximum plausible distance that a piece of ice could land from the turbine under two “worst case” circumstances: 1) ice falls from a stopped turbine during very