OLLSON
Environmental Health Management

February 14, 2019

South Dakota Public Utilities Commission
Public Utilities Commission Staff
Capitol Building, 1st Floor
500 E. Capitol Ave.
Pierre, SD 57501-5070

RE: Scientific Basis for 30-Hour Shadow Flicker Standard used by Crowned Ridge Wind Farm

Public Utilities Commission Staff:

Since November 2016, Dr. Ollson of Ollson Environmental Health Management (OEHM) has been retained by NextEra Energy Resources (NEER) to aid in the proper siting of the Crowned Ridge Wind Farm in South Dakota. Over the past two years Deuel County, Codington County and Grant County have all undertaken updates to their local ordinances governing local siting of wind turbines. Throughout this time Dr. Ollson, on behalf of NEER, provided both written and oral presentations to their Planning and Zoning and County Commissions on science-based appropriate siting requirements to protect the health and welfare of county residents.

OEHM has been asked to provide a response to the South Dakota Public Utilities Commission (PUC) Staff data request:

> "*Did Applicant base its 30-hour per year shadow flicker limit on any factor other than county ordinance? If so, provide support.*"

This report summarizes the information that was provided to each county in development of local ordinances and its scientific basis.

In summary, over the past decade there has been considerable research conducted around the world evaluating health concerns of those living in proximity to wind turbines. This independent research by university professors, consultants and government medical agencies has taken place in many different countries on a variety of models of turbines that have been in communities for numerous years. Based on scientific principles, and the collective scientific findings presented in research articles, OEHM believes that:

1. Shadow flicker is not a health concern (e.g., seizure in photosensitive epileptics), rather it can be considered a nuisance by some non-participating project residents.
2. There is no scientific evidence that shadow flicker impairs quality of life or is of particular nuisance for any duration of time. Limiting shadow flicker to no more than 30-hours a year at non-participating residences is commonplace in those United States jurisdictions that have set standards. It has been effective to reduce complaints associated with those living in proximity to wind projects.

All of the scientific journal articles have been attached to this report for the benefit of PUC Staff.

1 Qualifications of Dr. Christopher Ollson of OEHM

Dr. Ollson is owner and a senior environmental health scientist with OEHM. His expertise is in the field of environmental health science. Dr. Ollson is trained, schooled and practiced in the evaluation of potential risks and health effects to people and ecosystems associated with environmental issues.

Dr. Ollson's formal education includes:

- Doctorate of Philosophy, Environmental Science, Royal Military College of Canada, Kingston, Ontario, Canada, 2003.
- Master of Science, Environmental Science, Royal Military College of Canada, Kingston, Ontario, Canada, 2000.
- Bachelor of Science (Honours), Biology, Queen's University, Kingston, Ontario, Canada, 1995.

In addition to his consulting practice he holds an appointment of Adjunct Professor in the School of the Environment at the University of Toronto. In 2013, he was appointed to the Governing Council, and was Vice-Chair of the Academic Affairs Committee, of the University of Toronto Scarborough until 2016. Dr. Ollson teaches a graduate course at the University of Toronto in Environmental Risk Analysis and co-supervises doctoral students.

Approximately one third to half of Dr. Ollson's practice on an annual basis has been devoted to better understanding the relationship between people, animals and wind energy. For almost a decade, he has been engaged by a number of private companies to review the potential health effects that may be associated with living in proximity to wind turbines as part of their preparation of planning and permitting documentation. He has published six peer-review scientific journal articles in the field. These research efforts were first published in a peer-reviewed scientific article entitled:

> *Knopper, L.D. and* ***Ollson, C.A.*** *2011. Health Effects and Wind Turbines: A Review of the Literature. Environmental Health. 10:78. Open Access. Highly Accessed.*

After its publication in September 2011 the journal quickly identified the article as "highly accessed", it has been viewed over 49,000 times and cited in more than 30 other scientific articles.

Dr. Ollson's research has been presented at numerous international scientific conferences. He has been formally qualified to provide expert opinion evidence on wind turbines and potential health effects at a number of North American hearings, tribunals and legal cases.

Dr. Ollson has appeared before numerous County Planning & Zoning and County Commissions, including in South Dakota, to provide an overview of potential health concerns during their deliberations on review of WES ordinances and granting Conditional/Special Use Permits for wind generating facilities. In addition, from 2014 to 2017, Dr. Ollson provided expert advice on wind turbines, health and proper siting requirements for the Vermont Public Services Department. He has also appeared before the Indiana State Senate Energy Committee Meeting on Wind Turbine Siting (2017) and twice before the North Dakota State Senate Energy and Natural Resources Committee (2017).

2 Crowned Ridge Wind Farm County Ordinance Requirements Limiting Shadow Flicker

Table 1 provides a list of the county ordinances that are applicable to the Crowned Ridge Wind Farm. Codington County and Grant County have identical wording and requirements limiting shadow flicker to no more than 30 hour of actual shadow flicker at any school, church, business and occupied dwelling (regardless of participating or non-participating status). However, both have a provision to waive the requirement of no more than 30 hours a year with landowner agreement.

Table 1. County Ordinances for Shadow Flicker

County	Ordinance Section	Shadow Flicker Ordinance Requirement
Codington County	Section 5.22.03.13	Flicker Analysis. A Flicker Analysis shall include the duration and location of flicker potential for all schools, churches, businesses and occupied dwellings within a one (1) mile radius of each turbine within a project. The applicant shall provide a site map identifying the locations of shadow flicker that may be caused by the project and the expected durations of the flicker at these locations from sun-rise to sun-set over the course of a year. The analysis shall account for topography but not for obstacles such as accessory structures and trees. Flicker at any receptor shall not exceed thirty (30) hours per year within the analysis area. a. Exception: The Board of Adjustment may allow for a greater amount of flicker than identified above if the participating or non-participating landowners agree to said amount of flicker. If approved, such agreement is to be recorded and filed with the Codington County Zoning Officer. Said agreement shall be binding upon the heirs, successors, and assigns of the title holder and shall pass with the land.
Grant County	Section 1211.04.9	Flicker Analysis. A Flicker Analysis shall include the duration and location of flicker potential for all schools, churches, businesses and occupied dwellings within a one (1) mile radius of each turbine within a project. The applicant shall provide a site map identifying the locations of shadow flicker that may be caused by the project and the expected durations of the flicker at these locations from sun-rise to sun-set over the course of a year. The analysis shall account for topography but not for obstacles such as accessory structures and trees. Flicker at any receptor shall not exceed thirty (30) hours per year within the analysis area. a. Exception: The Board of Adjustment may allow for a greater amount of flicker than identified above if the participating or non-participating landowners agree to said amount of flicker. If approved, such agreement is to be recorded and filed with the Grant County Register of Deeds. Said agreement shall be binding upon the heirs, successors, and assigns of the title holder and shall pass with the land.

Over the course of the past two years both Codington County and Grant County undertook a detailed and thorough review of their Wind Energy System (WES) ordinances. Their original ordinances did not include limitations on shadow flicker. On behalf of NEER, Dr. Ollson prepared numerous written submissions on proposed science-based ordinance changes, which included a recommendation of limiting shadow flicker to no more than 30-hours of actual shadow flicker a year at a non-participating residence. Dr. Ollson appeared at countless Planning & Zoning Commission hearings and a number of County Commissioner hearings to answer questions of both the public and the county officials. Ultimately, this limit was adopted by both jurisdictions.

3 <u>Shadow Flicker Phenomenon and Model Predictions</u>

Shadow flicker occurs when interruption of sunlight by the wind turbine blades. Figure 1 was taken from Smedley et al. (2010) and demonstrates the shadow flicker phenomenon from wind turbines. Shadow flicker is unavoidable for wind turbines, however, it typically only occurs for a limited number of hours a year at a home. This is due to the fact that certain factors must be present:

a. the sun must be in a precise location in the sky such that sunlight will cast a shadow from the wind turbine;

b. the wind turbine must be in operation during this period (i.e., the wind must be of sufficient speed for the wind turbine to be operational);

c. shadow will not be cast on overcast of cloud cover days; and,

d. the shadow will typically not be cast any further than 10x the rotor diameter of the turbine to any appreciable extent. For most modern turbines this would mean shadow flicker would not extend past one mile.

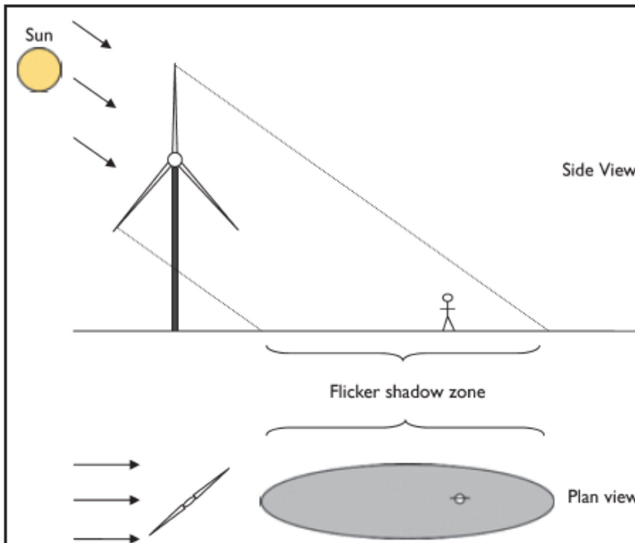

Figure 1.
Generalized geometry for turbine flicker, showing an observer in the shadow area. Note the main analysis assumes the observer and turbine blades are directly facing each other.
Epilepsia © ILAE

Shadow flicker most often occurs when the angle of the sun is lower in the horizon at sunrise and sunset. Although it can occur year round it is typically more frequent in the winter months when the sun's angle is lower in the horizon.

Although not all jurisdictions have shadow flicker regulations, conducting shadow flicker modeling has become common practice for proposed wind farm projects across the United States. There are several commercially available software packages, including WindPro that was used to model the Crowned Ridge Wind Farm (Crowned Ridge Wind Farm PUC Application – Appendix I Shadow Flicker Monitoring Report).

All models initially calculate a "Worst Case or Astronomical" number of hours that a residence may experience shadow flicker. These numbers can then be adjusted to provide a "Realistic, Actual or Expected" number of hours of shadow flicker. It is important to distinguish between these scenarios, as some jurisdictions have adopted standards based on either astronomical or realistic shadow flicker hour predictions.

> ***Worst Case / Astronomical:*** *The models consider that the sun is always shining during daytime hours, the wind turbines are always rotating, and the wind direction from each turbine is such that the wind turbine is always perpendicular to the residences so that shadows could be cast at the residences. This is a predicted extreme theoretical number hours that will not occur at any residence.*

__Realistic / Expected:__ The model is run in the astronomical mode and then the results are adjusted for percentage of monthly cloud cover (solar statistics) and operating hours of the wind project. Under these conditions shadow flicker will not be generated and it more accurately predicts the number of hours of shadow flicker at a residence.

There are other obstructions that can limit both the Worst Case and the Realistic modeled numbers of shadow flicker. These include trees, shrubs, and other ancillary non-occupied structures (e.g., barns) that could interrupt the predicted shadow flicker at a home. Neither of the two reporting scenarios takes into account these types of obstructions at residential receptors. Another layer of conservatism is that models are set-up and run in the “greenhouse mode”. This means each residence is oriented to have omni-directional windows and thus it will produce more conservative results since it assumes that there is always a window in direct line of site of each wind turbine and the sun.

The model outputs can show the exact days, the time of day, the duration and turbine of origin of shadow flicker. These values are then summed to provide the annual number of hours of shadow flicker predicted. For the Realistic scenario the percentage of cloud cover and operational downtime is used to adjust these values. The model will also provide the date, time and duration of shadow flicker caused by each turbine.

4 Shadow Flicker is Not a Health Concern but can be a Nuisance

In preparation of this report an updated search of both the primary scientific literature in PubMed and Google was conducted for wind turbine shadow potential health concerns, and report of annoyance or nuisance. Of this body of literature two of the published papers address shadow flicker.

The main health concern that has been raised with shadow flicker is the potential risk of seizures in those people with photosensitive epilepsy. Photosensitive epilepsy affects approximately 5% of people with epilepsy where their seizures can be triggered by flashing light. The Epilepsy Society first investigated this issue in the United Kingdom in the late 2000s. They polled their members and determined that no one had experienced an epileptic seizure living or being in proximity to a wind farm from shadow flicker (Epilepsy Society, 2012).

Following on from this informal polling, two of the United Kingdom’s academic experts in epilepsy published scientific research articles in the area. Harding et al. (2008) and Smedley et al. (2010) have published the seminal studies dealing with this concern. Both authors investigated the relationship between photo-induced seizures (i.e., photosensitive epilepsy) and wind turbine shadow flicker. Both studies indicate that flicker from turbines that interrupt or reflect sunlight at frequencies greater than 3 Hz pose a potential risk of inducing photosensitive seizures in 1.7 people per 100,000 of the photosensitive population. For turbines with three blades, this translates to a maximum speed of rotation of 60 revolutions per minute (rpm).

Large, modern, utility scale wind turbines spin at rates well below this threshold and are typically below 20 rpm. For example, the General Electric (GE) turbines being proposed for the Crowned Ridge Wind Farm have a maximum rotational speed of 15.6 rpm (0.78 Hz). Therefore, shadow flicker from these wind turbines is not at a flash frequency that could trigger seizures and not a concern.

The primary focus of the health-based research in proper siting of wind turbines has been focused on sound (audible, low frequency noise and infrasound). This is because exposure to shadow flicker is not commonly raised as a concern surrounding operating wind projects.

In 2011, the Department of Energy and Climate Change (United Kingdom) released a consultant's report entitled "Update of UK Shadow Flicker Evidence Base". The report concluded that

> *"On health effects and nuisance of the shadow flicker effect, it is considered that the frequency of the flickering caused by the wind turbine rotation is such that it should not cause a significant risk to health.*

Therefore, there is nothing in the scientific literature that suggests that shadow flicker should be limited to protect health.

5 Shadow Flicker Guidelines to Reduce Nuisance or Annoyance from Shadow Flicker

Two of the most comprehensive and widely cited published scientific review articles on this topic are Knopper & Ollson (2011) and McCunney et al. (2014). Both papers review the potential health impacts of shadow flicker and concluded that there are no health effects associated with this issue living in proximity to wind turbines. Knopper & Ollson (2011) concluded:

> *"Although shadow flicker from wind turbines is unlikely lead to a risk of photo-induced epilepsy there has been little if any study conducted on how it could heighten the annoyance factor of those living in proximity to turbines. It may however be included in the notion of visual cues. In Ontario it has been common practice to attempt to ensure no more than 30 hours of shadow flicker per annum at any one residence."*

Since 2011, there has only been one study conducted that examined the potential for shadow flicker to lead to increased annoyance for those living near wind turbines. Health Canada recently completed the most comprehensive study of wind turbine health and annoyance issues of its kind in the world (Health Canada, 2014). In 2016, Health Canada published a paper "*Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered*" (Voicescu et al., 2016). By using questionnaires of over 1200 people living as close as 800 feet from a turbine they attempted to determine if they could predict the percentage of people that were highly annoyed by varying levels of hours of shadow flicker (SF) a year or number of minutes on a given day. However, although annoyance did tend to increase with increasing minutes a day they could not find a statistical relationship:

> *"For reasons mentioned above, when used alone, modeled SF_m results represent an inadequate model for estimating the prevalence of HA_{WTSF} as its predictive strength is only about 10%. This research domain is still in its infancy and there are enough sources of uncertainty in the model and the current annoyance question to expect that refinements in future research would yield improved estimates of SF annoyance."*

That said OEHM does believe that limits on shadow flicker are prudent to keep nuisance levels to a minimum at non-participating residences. A number of U.S. Counties and States have adopted various ordinances and rules limiting shadow flicker on non-participating land. A no more than 30 hours of shadow flicker modeled on a residence has almost become the universally adopted standard. Erroneously this level of shadow flicker at homes has often been referred to as the

“Industry Standard”. It is not the wind turbine proponents that derived this standard, rather it is one that has been adopted in either national, state or local statute.

The origins of this standard are traced to Germany in 2002. The German Territorial Committee for Emissions control released the document “Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen, Länderausschuss für Immissionsschutz [Notes on the identification and evaluation of optical emissions from wind turbines], (in German).” The standard was based on limiting the nuisance of local residents. This level is often cited as being below one that would result in nuisance of local residents. They subsequently codified this formal shadow flicker guideline as part of the *Federal Emission Control Act* (Haugen, 2011). Similar standards to this have been adopted internationally with modifications for shadow flicker.

Each jurisdiction that has adopted a shadow flicker restriction at non-participating residence has had to weigh what would be a reasonable level of shadow flicker that they believe would be acceptable and avoid complaints. This is clear from the Koppen et al. (2017) review of international standards for shadow flicker. They state:

> *However, there are differences in the exact implementation, like the consideration of only the worst case, only the real case or both the worst and the real case shadow impact. Other common differences are the exact definition of shadow flicker sensitive receptors and the zone of influence which has to be considered. This can lead to considerable differences in energy production losses by a shadow flicker control module.*

Across the United States many jurisdictions have successfully adopted shadow flicker restrictions based on the “Realistic/Expected” scenario. The following are examples of state-wide legislation.

<u>North Dakota</u>

The North Dakota Public Service Commission requires effects from the impact upon light-sensitive land uses to be managed and maintained at an acceptable minimum (N.D. Admin. Code §69-06-08-01(5)(c)(3)). The North Dakota Public Service Commission has recognized the 30-hour per year standard and evaluates shadow flicker impacts pursuant to this standard. Justification, similar to what is contained in this report, for continued use of this standard has been provided to the ND PSC during several recent wind project applications and hearings.

<u>Connecticut</u>

Similarly the Regulations of Connecticut State Agencies Section 16-50j-95, part (c) requires:

> *Shadow flicker shall not occur more than 30 total annual hours cumulative at any off-site occupied structure location from each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites.*

<u>County Level Ordinances</u>

Counties across the Midwest have updated their wind turbine ordinances in recent years. There are numerous examples of counties that have adopted a no more than 30 hours of actual shadow flicker at non-participating homes, including Codington and Grant Counties. Similarly, on May 23, 2017 Deuel County South Dakota adopted Ordinance B2004-1-23B, which provides:

> *Limit for allowable shadow flicker at existing residences to no more than 30 hours annually.*

Eliminating shadow flicker at non-participating homes does not afford any additional protection for health. Therefore, OEHM suggests that no more than 30 hours of shadow flicker a year at non-participating residences is a reasonable limit to avoid annoyance or nuisance complaints. To put this in perspective it represents less than 0.5% of the daylight hours a year.

This standard has a long history of success in many United States jurisdictions that have seen over a decade of wind farm operation. Shadow flicker at operating wind projects is rarely a source of complaint. In the very unlikely event of shadow flicker complaints there are a number of mitigation strategies that can be resolved between the companies and landowners.

6 Conclusions

Over the past decade there has been considerable research conducted around the world on the potential for wind turbines to adversely impact health. This independent research by university professors, consultants and government medical agencies has taken place in many different countries on a variety of models of turbines that have been in the community for a number of years. Based on scientific principles, and the collective findings of scientific articles, shadow flicker does not present a potential health threat. Numerous jurisdictions have adopted a no more than 30 hours a year restriction of total number of hours of actual shadow flicker at a non-participating residence. This standard has a proven track record of reducing potential nuisance effects and should be considered by the South Dakota PUC when evaluating wind project applications.

Sincerely,

OLLSON ENVIRONMENTAL HEALTH MANAGEMENT

Christopher Ollson, PhD
Senior Environmental Health Scientist

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Regulations of Connecticut State Agencies

TITLE 16. Public Service companies

Agency

Connecticut Siting Council

Subject

Community Antenna Television and Telecommunications Towers

Inclusive Sections

§§ 16-50j-1—16-50j-91

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Community Antenna Television and Telecommunications Towers

Rules of Practice

Article 1

General Provisions

Part 1

Scope and Construction of Rules

Sec. 16-50j-1. Description of organization

(a) **General Course of Operations.**

The Connecticut Siting Council (Council), formerly known as the Power Facility Evaluation Council, was established in the executive branch of the state government by Public Act 575 of the 1971 General Assembly. The Public Utility Environmental Standards Act (PUESA), Title 16, Chapter 277a of the Connecticut General Statutes, governs the operation of the Council.

The Council is charged with:

(1) balancing the need for adequate and reliable public utility services at the lowest reasonable cost to consumers with the need to protect the environment and ecology of the state and to minimize damage to scenic, historic, and recreational values;

(2) providing environmental quality standards and criteria for the location, design, construction and operation of facilities for the furnishing of public utility services at least as stringent as the federal environmental quality standards and criteria, and technically sufficient to assure the welfare and protection of the people of the state;

(3) encouraging research to develop new and improved methods of generating, storing, and transmitting electricity and fuel and of transmitting and receiving television and telecommunications signals with minimal damage to the environment;

(4) promoting energy security;

(5) promoting the sharing of towers for fair consideration wherever technically, legally, environmentally and economically feasible to avoid the unnecessary proliferation of towers in the state;

(6) requiring annual forecasts of the demand for electric power, together with identification and advance planning of the facilities needed to supply that demand; and

(7) facilitating local, regional, state-wide and interstate planning.

(b) **Public Participation.**

The public may participate in the Council process in one of two ways: through party or intervenor status, or through a limited appearance by submission of oral or written comments to the Council. Information describing the types of participation is discussed in depth on the Council website, available at www.ct.gov/csc. The Council's website provides information regarding pending and past proceedings, forms and instructions, and statements of policy. The public is welcome to contact Council staff and make requests for information during normal business hours from 8:30 AM to 4:30 PM each weekday except Saturdays, Sundays and holidays, either in person at the Council office located at 10 Franklin Square, New Britain, CT 06051, by phone at (860) 827-2935, by fax at (860) 827-2950 or by e-mail at siting.council@ct.gov.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-1a. Procedure governed

Sections 16-50j-1 to 16-50z-4, inclusive, of the Regulations of Connecticut State Agencies govern practice and procedure before the Connecticut Siting Council under the applicable laws of the state of Connecticut and except where by statute otherwise provided. Additional regulations pertaining to hazardous waste proceedings and pertaining to low-level radioactive waste management proceedings appear in Title 22a of the Regulations of Connecticut State Agencies.

(Effective September 7, 2012)

Sec. 16-50j-2. Repealed

Repealed March 7, 1989.

Sec. 16-50j-2a. Definitions

As used in Sections 16-50j-1 to 16-50z-4, inclusive, of the Regulations of Connecticut State Agencies, except as otherwise required by the context:

(1) "Associated equipment" includes, but is not limited to:

(A) any building, structure, fuel tank, backup generator, antenna, satellite dish, or technological equipment, including equipment intended for sending or receiving radio frequency signals that is a necessary component for the operation of a community antenna television tower or telecommunications tower; or

(B) any building, structure, fuel tank, backup generator, transformer, circuit breaker, disconnect switch, control house, cooling tower, pole, line, cable, conductor or emissions equipment that is a necessary component for the operation of an electric transmission line facility, fuel transmission facility, electric generating or storage facility, or electric substation or switchyard.

(2) "Attorney" means an attorney at law, duly admitted to practice before the Superior Court of the state of Connecticut. Any other person who appears before the Council in any contested case or petition for a declaratory ruling shall be deemed to appear as the agent or representative of a person, firm, corporation, or association upon filing with the Council a written notification of appearance and the written authorization of the person, firm, corporation, or association being represented.

(3) "Blade length" means the distance between the blade tip and the center of the hub of a wind turbine.

(4) "Certificate" means a Certificate of Environmental Compatibility and Public Need as defined under Section 16-50k of the Connecticut General Statutes or a Certificate of Public Safety and Necessity as defined under Section 22a-117 of the Connecticut General Statutes to be issued, denied, conditioned, limited, modified, or amended, in accordance with the disposition of applications authorized by law to be submitted to the Council.

(5) "Chairperson" means the public member of the Council appointed pursuant to the provisions of Section 16-50j(d) of the Connecticut General Statutes.

(6) "Collocation" means the mounting or installation of antennas and associated equipment on an existing tower or other structure for the purpose of transmitting or receiving radio frequency signals for communications purposes that is unlikely to have a significant adverse environmental effect and does not increase the tower height.

(7) "Component" means a part of a mechanical or electrical system.

(8) "Contested case" means a proceeding in the Council's disposition of matters delegated to its jurisdiction by law in which the legal rights, duties, or privileges of a party are determined by the Council after an opportunity for hearing in accordance with Section 4-166(2) of the Connecticut General Statutes.

(9) "Council" means the members of the Connecticut Siting Council appointed under section 16-50j(b) and section 16-50j(c) of the Connecticut General Statutes and referred to in Section 16-50j(d) and section 22a-115 of the Connecticut General Statutes.

(10) "Customer-side distributed resources project" means a project designed to utilize "customer-side distributed resources," as defined in Section 16-1 of the Connecticut General Statutes.

(11) "Facility" means A facility as defined in Section 16-50i(a) of the Connecticut General Statutes.

(12) "Fuel" means a fuel as defined in Section 16a-17 of the Connecticut General Statutes.

(13) "Grid-side distributed resources project" means a project designed to utilize "grid-side distributed resources," as defined in Section 16-1 of the Connecticut General Statutes.

(14) "Hazardous waste facility" means land and appurtenances thereon or structures used for the disposal, treatment, management, storage or recovery of hazardous waste as these terms are defined in Section 22a-115 of the Connecticut General Statutes.

(15) "Hearing" means a proceeding whereby witnesses may be examined, and oral or documentary evidence may be received.

(16) "Hub" means the central part of a wind turbine that supports the turbine blades on the outside and connects to the rotor shaft inside the nacelle.

(17) "Intervenor" means a person other than a party, granted status as an intervenor by the Council in accordance with Section 16-50n of the Connecticut General Statutes.

(18) "Limited appearance" means the type of participation in a contested case, and the rights prescribed therefor in accordance with the provisions of Sections 22a-120(b) and 16-50n(f) of the Connecticut General Statutes.

(19) "Modification" means a significant change or alteration in the general physical

characteristics of a facility, including, but not limited to, design, capacity, process or operation that the Council deems significant, except where a modification involves a temporary facility as determined by the Council.

(A) As defined pertaining to a hazardous waste facility "modification" means:

(i) any change or alteration in the design, capacity, process or operation of an existing hazardous waste facility requiring a new permit from the Commissioner of the Department of Energy and Environmental Protection pursuant to chapter 445, 446d, or 446k of the Connecticut General Statutes, that the Council deems significant, or

(ii) any change or alteration in the approved design, capacity, process or operation of a hazardous waste facility constructed or operating pursuant to chapter 445 of the Connecticut General Statutes that the Council deems significant. Such change or alteration may include, but is not limited to, a change or alteration in the volume or composition of hazardous waste managed at such facility. The routine maintenance, repair, or replacement of the individual components at a hazardous waste facility that is necessary for normal operation or a change or alteration at a hazardous waste facility ordered by a state official in the exercise of his or her statutory authority shall not be deemed to be a modification.

(B) As defined pertaining to a low-level radioactive waste management facility, "modification" means any change or alteration in the approved design, capacity, process or operation of a low-level radioactive management facility constructed or operating pursuant to the provisions of the Northeast Interstate Low-Level Radioactive Waste Management Compact, Sections 22a-161, et seq. of the Connecticut General Statutes.

(20) "Municipality" means a city, town or borough of the state, and "municipal" has a correlative meaning.

(21) "Nacelle" means the structure at the top of a wind turbine tower behind or in front of the wind turbine blades that houses the key operational components of the wind turbine including, but not limited to, the rotor shaft, gearbox, controller, brake and generator.

(22) "Party" means each person entitled to be a party in a contested case pursuant to the provisions of Section 16-50n(a) of the Connecticut General Statutes, or in the event of a hazardous waste facility proceeding, pursuant to the provisions of Section 22a-120(a) of the Connecticut General Statutes.

(23) "Person" means any person as defined in Section 16-50i of the Connecticut General Statutes except for proceedings under Chapter 445. For proceedings under Chapter 445, "person" means any person as defined in Section 22a-115 of the Connecticut General Statutes.

(24) "Presiding Officer" means the Chairperson of the Connecticut Siting Council, or the Chairperson's designee.

(25) "Regional Low-Level Radioactive Waste Management Facility" or "Low-Level Radioactive Waste Management Facility" means a facility to be located in Connecticut, including the land, buildings, equipment, and improvements authorized by the Northeast Interstate Low-level Radioactive Waste Commission to be used or developed for the receipt, treatment, storage, management or disposal of the low-level radioactive wastes generated

within the party states to the Northeast Interstate Low-level Radioactive Waste Management Compact as these terms are defined in Section 22a-161 of the Connecticut General Statutes.

(26) "Renewable Energy Sources" include, but are not limited to, solar photovoltaic, solar thermal, wind, ocean thermal, wave or tidal, geothermal, landfill gas, hydropower or biomass.

(27) "Rotor" means the part of a wind turbine that consists of the blades and the hub.

(28) "Shadow flicker" means the intermittent shadows created by the wind turbine blades passing through the light of the sun.

(29) "Site" means a contiguous parcel of property with specified boundaries, including, but not limited to, the leased area, right-of-way, access and easements on which a facility and associated equipment is located, shall be located, or is proposed to be located.

(30) "Tower" means a structure, whether free standing or attached to a building or another structure, that has a height greater than its diameter and that is high relative to its surroundings, or that is used to support antennas for sending or receiving radio frequency signals, or for sending or receiving signals to or from satellites, or any of these, which is or is to be:

(A) used principally to support one or more antennas for receiving or sending radio frequency signals, or for sending or receiving signals to or from satellites, or any of these, and

(B) owned or operated by the state, a public service company as defined in Section 16-1 of the Connecticut General Statutes, or a certified telecommunications provider, or used in a cellular system, as defined in Section 16-50i(a) of the Connecticut General Statutes.

(31) "Tower Base" means the top of the foundation or equivalent surface that shall bear the vertical load of a tower.

(32) "Tower Height" means the measurement from ground level to the highest point on the tower;

(33) "Tower Share" means collocation on a facility in accordance with Section 16-50aa of the Connecticut General Statutes.

(34) "Wind turbine" means a device that converts wind energy to electricity.

(35) "Wind turbine height" means the measurement from ground level to the tip of the blade of a wind turbine in the vertical position.

(36) "Wind turbine tower" means the base structure that supports a wind turbine rotor and nacelle.

(37) "Wind turbine tower base" means the top of the foundation or equivalent surface that shall bear the load of a wind turbine tower.

(38) "Wind turbine tower height" means the measurement from ground level to the top of the hub.

(Effective March 7, 1989; Amended September 7, 2012; Amended May 9, 2014)

Sec. 16-50j-3. Waiver of rules

Where good cause appears, the council may permit deviation from these rules, except where precluded by statute.

(Effective July 3, 1972)

Sec. 16-50j-4. Construction and amendment

These rules shall be so construed by the council as to secure just, speedy, and inexpensive determination of the issues presented hereunder. Amendments and additions to these rules may be adopted by the council in accordance with the authority delegated to the council by law.

(Effective March 7, 1989)

Sec. 16-50j-5. Computation of time

Computation of any period of time referred to in these rules begins with the first day following that on which the act which initiates such period of time occurs. The last day of the period so computed is to be included unless it is a day on which the office of the Council is closed, in which event the period shall run until the end of the next following business day. When such period of time, with intervening Saturdays, Sundays and legal holidays counted, is five days or less, said Saturdays, Sundays and legal holidays shall be excluded from the computation; otherwise such days shall be included in the computation. The Council shall follow the state holiday calendar for such computations of time.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-6. Extensions of time

In the discretion of the council, for good cause shown, any time limit prescribed or allowed by these rules may be extended insofar as such extension is not precluded by statute. All requests for extensions of time shall be made before the expiration of the period originally prescribed or as previously extended. All parties shall be notified of the council's action upon such motion.

(Effective August 16, 1979)

Sec. 16-50j-7. Consolidation

Proceedings involving related questions of law or fact may be consolidated at the direction of the council.

(Effective July 3, 1972)

Part 2

Filing Requirements

Sec. 16-50j-8. Office

The principal office of the Council is located at 10 Franklin Square, New Britain, Connecticut 06051. The office of the Council is open from 8:30 a.m. to 4:30 p.m. each weekday except Saturdays, Sundays, and legal holidays.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-9. Date of filing

All orders, decisions, findings of fact, correspondence, motions, petitions, applications, and any other documents governed by these rules shall be deemed to have been filed or received on the date on which they are issued or received by the council at its principal office.

(Effective August 16, 1979)

Sec. 16-50j-10. Identification of communications

Communications should embrace only one matter, and should contain the name and address of the communicator and the appropriate proceeding reference, if any there be, pertaining to the subject of the communication. When the subject matter pertains to a pending proceeding, the title of the proceeding and the docket or petition number should be given.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-11. Signatures

Every application, notice, motion, petition, complaint, brief, and memorandum shall be signed by the filing person or by one or more attorneys in their individual names on behalf of the filing person.

(Effective August 16, 1979)

Sec. 16-50j-12. Filing requirements

(a) **Copies.**

Except as may be otherwise required by these rules or by any other rules or regulations of the Council or ordered or expressly requested by the Council, at the time motions, petitions, applications, documents, or other papers are filed with the Council, there shall be furnished to the Council an original of such papers. In addition to the original, there shall also be filed 20 copies for the use of the Council and its staff, unless a greater or lesser number of such copies is expressly requested by the Council. An electronic version of the document may also be filed by e-mail if the parties and intervenors are reasonably able to do so. Electronic filing at siting.council@ct.gov is strongly encouraged.

(b) **Forms.**

Except for such forms as may from time to time be provided by the Council and used where appropriate, motions, petitions, applications, documents, or other papers filed for the purpose of any proceeding before the Council shall be printed or typewritten on paper cut or folded to letter size, 8 to 8½ inches wide. Width of margins shall be not less than one inch. The printed materials may be submitted double-sided and 1.5-line spaced. Maps, charts and other pictorial exhibits shall be submitted on only one side of the paper. All copies shall be clear and permanently legible. All such filings shall be sequentially paginated.

(c) **Filing.**

All motions, petitions, applications, documents, or other papers relating to matters requiring action by the Council shall be filed at the office of the Council, 10 Franklin Square, New Britain, Connecticut 06051.

(d) **State Agency Notification.**

Pursuant to Section 8 of Public Act 07-242, each application shall be accompanied by proof of service of a copy of the application on the Department of Emergency Management and Homeland Security, or its successor agency, and any other state or municipal body as the Council may require, in addition to proof of service of a copy of the application on the enumerated departments under Section 16-50*l*(b)(6) of the Connecticut General Statutes. The Council shall consult with and solicit comments from the Department of Emergency Management and Homeland Security, or its successor agency, and any other state agency as the Council may require, in the same manner as the Council consults with and solicits comments from the enumerated departments under Section 16-50j(h) of the Connecticut General Statutes. The Council shall request state agency comments at the time a hearing notice is published and at the conclusion of a public hearing.

(e) **Service List.**

The Council shall prepare and make available a service list for each proceeding. Persons on the service list may elect to receive documents by e-mail or by U.S. Mail. Each service list shall:

(1) contain the name of each party, intervenor and participant in the proceeding and the date upon which status was granted;

(2) contain the names and addresses of the representatives of each party, intervenor and participant in the proceeding, if applicable;

(3) indicate whether each party, intervenor and participant has elected to be served by e-mail; and

(4) provide the e-mail address of every person in the proceeding who has elected to be served by e-mail.

(f) **Service requirements.**

(1) Every person shall serve a copy of a filed document to every person on the service list of the proceeding in which the document is to be filed. This subsection shall not apply to the filing of proprietary or critical energy infrastructure information for which a protective order may be sought.

(2) Each document presented for filing shall contain the following certification: "I hereby certify that a copy of the foregoing document(s) was/were (method of service) to the following service list on (date)." Signature and printed name.

(Effective March 7, 1989; Amended September 7, 2012)

ARTICLE 2

CONTESTED CASES

Part 1

Parties, Limited Appearances, and Intervenors

Sec. 16-50j-13. Designation of parties

In issuing the notice of hearing, the Council shall name as parties those persons enumerated in and qualifying under Section 16-50n(a), subdivisions (1) to (3), inclusive, of the Connecticut General Statutes. In the event of a hazardous waste facility proceeding, the Council shall name as parties those persons enumerated in and qualifying under Section 22a-120(a) of the Connecticut General Statutes. Any person named as a party may decline or withdraw such status upon notifying the Council in writing of their intent not to participate as a party.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-14. Application to be designated a party

(a) **Filing of petition.**

Any person who proposes to be named or admitted as a party to any proceeding pursuant to Section 4-177a of the Connecticut General Statutes may file a written petition to be so designated at least five days before the hearing. The five day filing requirement may be waived upon a showing of good cause.

(b) **Contents of petition.**

The petition shall state the name and address of the petitioner. It shall state facts that demonstrate that the petitioner's legal rights, duties or privileges shall be specifically affected by the Council's decision in the proceeding pursuant to Section 4-177a of the Connecticut General Statutes. It shall state the contention of the petitioner concerning the issue of the proceeding, the relief sought by the petitioner, and the statutory or other authority therefor, and the nature of the evidence, if any, that the petitioner intends to present in the event that the petition is granted.

(c) **Designation as party.**

The Council shall consider all such petitions and shall name or admit as a party any person who is required by law to be a party and any other person whose legal rights, duties, or privileges shall be specifically affected by the Council's decision in the proceeding. Any person named or admitted as a party may decline or withdraw such status at any time upon notifying the Council in writing of his or her intent not to participate as a party.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-15. Application to be designated an intervenor

(a) **Filing of petition.**

Any person who proposes to be named or admitted as an intervenor in any proceeding pursuant to Section 4-177a of the Connecticut General Statutes may file a written petition to be so designated at least five days before the date of the hearing. The five day filing requirement may be waived upon a showing of good cause.

(b) **Contents of petition.**

The petition shall state the name and address of the petitioner. It shall state facts that demonstrate the petitioner's participation shall furnish assistance to the Council in resolving the issues in the proceeding, is in the interests of justice and will not impair the orderly conduct of the proceedings pursuant to Section 4-177a of the Connecticut General Statutes. The petition shall provide a summary of the petitioner's contentions concerning the issues in the proceeding; the relief sought by the petitioner in the proceeding and the legal authority therefor; and the nature of the evidence, if any, that the petitioner intends to present in the event that the petition is granted.

(d) **Designation as intervenor.**

The Council shall determine the proposed intervenor's participation in the proceeding, taking into account whether such participation will furnish assistance to the Council in resolving the issues of the case, is in the interests of justice, and will not impair the orderly conduct of the proceedings. Any person named or admitted as an intervenor may decline or withdraw such status at any time upon notifying the Council in writing of his or her intent not to participate as an intervenor.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-15a. Participation by intervenor

The Council may limit the intervenor's participation pursuant to Section 4-177a of the Connecticut General Statutes, to designated issues in which the intervenor has a particular interest; to defined categories of records, physical evidence, papers and documents; to introduce evidence; and to cross examine on designated issues. The presiding officer may further limit the participation of an intervenor in the proceedings so as to promote the orderly conduct of the proceedings.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-15b. Limited appearance

(a) **Status of Limited Appearance.**

Pursuant to Section 4-177 and Section 16-50n of the Connecticut General Statutes, prior to, during or not later than 30 days after the close of a hearing, any person may make a limited appearance. All oral and written limited appearance statements shall become part of the record. No person making a limited appearance shall be a party or intervenor, or shall have the right to cross-examine witnesses, parties or intervenors. No party or intervenor shall have a right to cross-examine a person making a limited appearance. The Council may require a limited appearance statement to be given under oath.

(b) **Form of Limited Appearance.**

A limited appearance may be made in the following forms:

(1) a written statement submitted to the Council prior to, during or after the close of a hearing; or

(2) an oral statement made during the public comment session of a hearing held after 6:30 PM pursuant to Section 16-50m of the Connecticut General Statutes.

(Effective May 28, 1985; Amended September 7, 2012)

Sec. 16-50j-16. Procedure concerning added parties and intervenors

(a) **During proceeding.**

In addition to the designation of parties and intervenors in the initial notice and in response to petition, the Council may add parties and intervenors at any time during the pendency of any proceeding.

(b) **Notice of designation.**

In the event that the Council shall name or admit any party or intervenor after service of the initial notice of hearing in a proceeding, the Council shall give written notice thereof to all parties or intervenors theretofore named or admitted. The form of the notice shall be a copy of the order of the Council naming or admitting such added party or intervenor and a copy of any petition filed by such added party or intervenor requesting designation as a party or intervenor. Service of such notice shall be in the manner provided in these rules.

(c) **Participation by added parties and intervenors.**

Any person granted party or intervenor status is responsible for obtaining and reviewing all materials for the proceeding, including, but not limited to, any notices, orders, filings, or other documents filed or issued in the proceeding prior to the Council's designation of the person as a party or intervenor.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-16a. Grouping of parties and intervenors

Pursuant to Section 16-50n of the Connecticut General Statutes, the Council may, in its discretion, provide for the grouping of parties and intervenors with the same interests. Any party or intervenor who has been included in a group may elect not to be a member of the group by submission of written notice to the Council.

(Effective September 7, 2012)

Sec. 16-50j-17. Status of party and of intervenor

(a) **Party as party in interest.** By its decision in a proceeding, the council shall dispose of the legal rights, duties, and privileges of each party named or admitted to the proceeding. Each such party is deemed to be a party in interest who may be aggrieved by any final decision, order, or ruling of the council.

(b) **Status of intervenor.** No grant of leave to participate as an intervenor shall be deemed to be an expression by the council that the person permitted to intervene is a party in interest who may be aggrieved by any final decision, order, or ruling of the council unless such grant of leave explicitly so states.

(Effective March 7, 1989)

Part 2

Hearing, General Provisions

Sec. 16-50j-18. Grant of hearing

A hearing shall be held, where required by law, on all applications submitted pursuant to sections 16-50*l* to 16-50q, inclusive, of the Connecticut General Statutes, upon appeal as provided for in Section 16-50x(d) of the Connecticut General Statutes, on any petition for a declaratory ruling that the Council orders to be set for specified proceedings pursuant to Section 4-176 of the Connecticut General Statutes, and on any petition for a declaratory ruling for a wind turbine facility submitted pursuant to Section 16-50k of the Connecticut General Statutes. In the event of a hazardous waste facility proceeding, a hearing shall be held on all applications submitted pursuant to Sections 22a-117 to 22a-122, inclusive, of the Connecticut General Statutes.

(Effective March 7, 1989; Amended September 7, 2012; Amended May 9, 2014)

Sec. 16-50j-19. Calendar of hearings

A docket of all proceedings of the council shall be maintained. In addition a hearing calendar of all proceedings that are to receive a hearing shall be maintained. Proceedings shall be placed on the hearing calendar in the order in which the proceedings are listed on the docket of the council, unless otherwise directed by the council.

(Effective August 16, 1979)

Sec. 16-50j-20. Place of hearings

Hearings shall be held at times and locations specified by the Council pursuant to Sections 16-50m and 22a-119 of the Connecticut General Statutes.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-21. Notice of hearings

(a) **Persons notified.**

(1) Not later than one week after the fixing of the date, or not less than 30 days prior to a hearing date, whichever is later, the Council shall, mail written notice of a hearing in any pending matter to all parties and intervenors, to all persons or groups of parties otherwise required by statute to be notified, to such other persons as have filed with the Council their written request for notice of hearing in a particular matter, and to such additional persons as the Council directs. The Council shall give notice by newspaper publication and by such other means as it deems appropriate and advisable.

(2) The newspaper publication shall be published as specified in Section 16-50m(c) of

the Connecticut General Statutes.

(3) The applicant or petitioner shall post a sign that is visible to the public at least 10 days prior to the public hearing not less than six feet by four feet at or in the vicinity of where the proposed facility would be located informing the public of the name of the applicant or petitioner, the type of facility, the hearing date and location, and contact information for the Council.

(4) The applicant or petitioner shall provide notice of the date on or about which the application or petition will be filed with the Council to each person appearing of record as an owner of property that abuts the primary or alternative sites on which the proposed facility would be located. Pursuant to Section 16-50*l* of the Connecticut General Statutes, applicants shall publish notice of the date on or about which the application will be filed with the Council in such newspapers that will serve to substantially inform the public. The applicant or petitioner shall provide a copy of such proof of notice and publication, as applicable, in the application or petition that is submitted to the Council.

(b) **Contents of notice.** Notice of a hearing shall include, but shall not be limited to, the following:

(1) a statement of the time, place, and nature of the hearing;

(2) a statement of the legal authority and jurisdiction under which the hearing is to be held;

(3) a reference to the particular sections of the statutes and regulations involved;

(4) a short and plain statement of fact describing the nature of the hearing and the principal facts to be asserted therein; and

(5) the date, place and time for any scheduled field reviews of the proposed site by the Council.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-22. Representation of parties

Each person making an appearance before the Council as an attorney, agent, or representative of any person, firm, corporation, or association subject to the Council's regulatory jurisdiction in connection with any contested case or petition for a declaratory ruling shall promptly notify the Council in writing in order that the same may be made a part of the record of the contested case or petition for a declaratory ruling.

(Effective August 16, 1979; Amended September 7, 2012)

Sec. 16-50j-22a. Conduct of proceedings

(a) **Procedural Conferences.**

The Council may schedule a procedural conference either on its own initiative or upon written request by a party or intervenor. At such conference, the Council shall consider matters including, but not limited to:

(1) The schedule for the proceeding;

(2) The exchange of pre-hearing interrogatories and pre-filed testimony, exhibits, witness

lists and items to be administratively noticed in the proceeding;

(3) The location(s) of the sign(s) to be erected pursuant to Section 16-50j-21(a)(3) of the Regulations of Connecticut State Agencies; and

(4) Any other matters that may facilitate the proceeding.

(b) **Motions.**

Any party or intervenor may request that the Council take any action by filing a motion which clearly states the action sought and the grounds therefor. Any motions concerning jurisdictional matters shall be made in writing and shall be considered during a regular Council meeting either prior to or after a hearing, if a hearing is held, for the convenience of the public. Motions may be filed in writing not less than 10 days before a hearing or made during a hearing, if a hearing is held. A party or intervenor may file a written response not less than 7 days before a hearing or respond orally during a hearing, if a hearing is held. If a hearing is not held, written motions shall be filed and responded to in accordance with a schedule specified by Council staff. A copy of all written motions shall be served upon the service list.

(c) **Discovery.**

The purpose of discovery is to provide the Council, parties and intervenors access to all relevant information in an efficient and timely manner to ensure that a complete and accurate record is compiled. Parties and intervenors may serve written information requests only during the time specified by the Council. The Council may serve written information requests on any party or intervenor to the proceeding at any time. The presiding officer may subpoena witnesses and require the production of records, physical evidence, papers and documents to any hearing held in a contested case pursuant to Section 4-177b of the Connecticut General Statutes. Responses to information requests shall be separately and fully answered under the penalties of perjury by the witness who shall testify during the hearing as to the content of the response. Objections to information requests may be submitted in lieu of a response.

(d) **Protective Orders.**

Pursuant to Section 16-50o and Section 16-50r of the Connecticut General Statutes, any party or intervenor may file a motion for a protective order in accordance with the filing procedures of the Council for the following types of information:

(1) Trade secrets and commercial or financial information as described under Section 1-210(b) of the Connecticut General Statutes; or

(2) Critical energy infrastructure information defined as specific engineering, vulnerability or detailed design information about proposed or existing critical infrastructure that:

(A) relates to details about the production, generation, transportation, transmission or distribution of energy;

(B) could be useful to a person in planning an attack on critical infrastructure;

(C) is exempt from mandatory disclosure under Section 1-210(b) of the Connecticut General Statutes; and

(D) does not simply give the general location of critical infrastructure.

(Effective September 7, 2012)

Sec. 16-50j-23. Repealed

Repealed March 7, 1989.

Sec. 16-50j-24. Rules of conduct

Where applicable, the canons of professional ethics and the canons of judicial ethics adopted and approved by the judges of the superior court govern the conduct of the council, state employees serving the council, and all attorneys, agents, representatives, and any other persons who shall appear in any proceedings or in any contested case before the council in behalf on any public or private person, firm, corporation, or association.

(Effective August 16, 1979)

Part 3

Hearings, Procedure

Sec. 16-50j-25. General provisions

(a) **Purpose of hearing.**

The purpose of the hearing in a contested case or a petition for a declaratory ruling shall be to provide all parties an opportunity to present evidence and cross-examine all issues to be considered by the Council and to provide all intervenors an opportunity to present evidence and cross-examine such issues as the Council permits.

(b) **Uncontested disposition of case.**

Unless precluded by law, any contested case may be resolved by stipulation, agreed settlement, consent order, or default upon order of the Council. Upon such disposition, a copy of the order of the Council shall be served on each party and intervenor.

(c) **Pre-Filed Evidence and Testimony.**

At the discretion of the Council, any evidence or testimony may be required to be pre-filed by a date specified by the Council. All pre-filed evidence and testimony shall be received in evidence with the same force and effect as though it were stated orally by the witnesses, provided that each such witness shall be present at the hearing at which such prepared written testimony is offered, shall adopt such written testimony under oath, and shall be made available for cross-examination as directed by the Council.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-26. Record

(a) The record in each contested case and petition for declaratory ruling shall be maintained by the Council in the custody of the Council's designee and shall include the following:

(1) any notices, petitions, applications, orders, decisions, motions, briefs, exhibits, and any other documents that have been filed with the Council or issued by the Council in written form;

(2) all written evidence of any kind received and considered by the Council;

(3) any questions and offers of proof, together with any objections and rulings thereon during the course of the hearing;

(4) the official transcript of the hearing. The Council shall not be required to include in the transcript duplications of other portions of the record; and

(5) any proposed final decision and exceptions thereto, and the final decision.

(b) A copy of the record shall be available at all reasonable times for examination by the public without cost at the principal office of the Council.

(c) A copy of the transcript of testimony at the hearing shall be filed at an appropriate public office, as determined by the Council, in each county where the facility or any part thereof is proposed to be located.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-27. Filing of added exhibits

(a) Upon order of the council before, during, or after the hearing of a case, any party or intervenor shall prepare and file added exhibits and testimony. A copy of any such additional materials shall be given to all parties and intervenors by the party or intervenor submitting the said material.

(b) Upon a determination by the council that any filing of such additional material by a party or intervenor would be burdensome due to its form or excessive volume, the council may allow for the filing of the material at the office of the council. All parties and intervenors shall be afforded the opportunity to copy and/or inspect such material.

(Effective March 7, 1989)

Sec. 16-50j-28. Rules of evidence

In accordance with Section 4-178 of the Connecticut General Statutes, the following rules of evidence shall be followed in contested cases:

(a) **Rules of privilege.**

The Council shall give effect to the rules of privilege recognized by law in Connecticut. Subject to these requirements and subject to the right of any party or intervenor to cross examine, any testimony may be received in written form.

(b) **Relevance.**

The Council may exclude evidence that is not probative or material and that tends not to prove or disprove a matter in issue.

(c) **Testimony.**

Pursuant to Section 16-50j-25 of the Regulations of Connecticut State Agencies, in its discretion, the Council may accept any oral or written testimony.

(d) **Documentary Evidence.**

Pre-filed testimony and other documentary evidence shall be produced under oath. Such evidence shall be received by the Council in written form to expedite the public hearing.

(e) **Cross examination.**

Cross examination may be conducted by any party or intervenor if it is required by the Council for full and true disclosure of the facts. Witnesses may be cross-examined on any pre-filed testimony and documents submitted as evidence. If the Council proposes to consider a limited appearance statement as evidence, the Council shall give all parties and intervenors an opportunity to challenge or rebut the statement and to cross-examine the person who makes the statement.

(f) **Administrative Notice.**

The Council may take administrative notice of facts in accordance with Section 4-178 of the Connecticut General Statutes, including prior decisions and orders of the Council and any exhibit admitted as evidence by the Council in a prior hearing of a contested case.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-29. Order of procedure at hearings

In hearings on applications, the party that shall open and close the presentation of any part of the matter shall be the applicant. In a case where the opening portion has already been submitted in written form as provided by these rules, the hearing may open with the cross examination of persons who have given written testimony. In the event any person has given written testimony and is not available for such cross examination at the time and place directed by the council, all of such written testimony may be discarded and removed from the record at the direction of the council.

(Effective July 3, 1972)

Sec. 16-50j-30. Limited number of witnesses

To avoid unnecessary cumulative evidence, the council may limit the number of witnesses or the time for testimony upon a particular issue in the course of any hearing.

(Effective August 16, 1979)

Part 4

Hearings, Decision

Sec. 16-50j-31. Filing of proposed findings of facts and briefs

At the conclusion of the presentation of evidence in any hearing, the council shall fix a time within which any party and intervenor may file proposed findings of facts and briefs.

(Effective May 28, 1985)

Sec. 16-50j-32. Final decision

(a) **Procedure and contents.** All decisions and orders of the council concluding a contested case shall be in writing. The decision may include all findings of fact and conclusions of law relied upon by the council in arriving at the decision, the findings of fact and conclusions of law to be separately stated.

(b) **Service.**

Parties and intervenors shall be served in the manner herein provided with a copy of the findings of fact, opinion, and decision and order of the Council. A notice of the issuance of the opinion and decision and order shall be published once in each newspaper in which was printed the notice of public hearing.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-33. Repealed

Repealed March 7, 1989.

Sec. 16-50j-34. Original records

The applicant shall, upon direction of the council, furnish and make available for the use of the council the original books, papers, and documents from which any part of the application is derived. If so directed, or permitted, certified or verified copies shall be furnished in lieu of such original records. Failure to furnish original records may be ground for rejecting any component and, if appropriate, for refusing the application.

(Effective August 16, 1979)

ARTICLE 3

MISCELLANEOUS PROCEEDINGS

Part 1

Petitions Concerning Adoption of Regulations

Sec. 16-50j-35. General rule

These rules set forth the procedure to be followed by the council in the disposition of petitions concerning the promulgation, amendment, or repeal of a regulation.

(Effective July 3, 1972)

Sec. 16-50j-36. Form of petitions

Any interested person may at any time petition the council to promulgate, amend, or repeal any regulation. The petition shall set forth clearly and concisely the text of the proposed regulation, amendment, or repeal. Such petition shall also state the facts and arguments that favor the action it proposes by including such data, facts, and arguments either in the petition or in a brief annexed thereto. The petition shall be addressed to the council and sent to the principal office of the council by mail or delivered in person during normal business hours. The petition shall be signed by the petitioner and shall furnish the address of the petitioner and the name and address of petitioner's attorney, if applicable.

(Effective August 16, 1979)

Sec. 16-50j-37. Procedure after petition filed

(a) **Decision on petition.**

Not later than 30 days after receipt of a petition for regulation pursuant to Section 4-174 of the Connecticut General Statutes, the Council shall deny the petition in writing or initiate regulation-making proceedings in accordance with Section 4-168 of the Connecticut General Statutes.

(b) **Procedure on denial.** If the council denies the petition, the council shall give the petitioner notice in writing, stating the reasons for the denial based upon the data, facts, and arguments submitted with the petition by the petitioner and upon such additional data, facts, and arguments as the council shall deem appropriate.

(Effective March 7, 1989; Amended September 7, 2012)

Part 2

Petitions for Declaratory Rulings

Sec. 16-50j-38. General rule

These rules set forth the procedure to be followed by the council in initiating a proceeding or disposing of a petition for declaratory rulings as to the applicability of any statutory provision or validity or applicability of any regulation, final decision, or order of the council. Such a ruling of the council disposing of a petition for a declaratory ruling shall have the same status as any decision or order of the council in a contested case.

(Effective March 7, 1989)

Sec. 16-50j-39. Filing requirements

(a) **General.**

Any interested person may at any time request a declaratory ruling of the Council with respect to the applicability to such person of any statute, or the validity or applicability of any regulation, final decision, or order enforced, administered, or promulgated by the Council. Such request shall be addressed to the Council and sent to the principal office of the Council by mail or delivered in person during normal business hours. The request shall state clearly and concisely the substance and nature of the request; it shall identify the statute, regulation, final decision, or order concerning which the inquiry is made and shall identify the particular aspect to which the inquiry is directed. The request for a declaratory ruling shall be accompanied by a statement of any data, facts, and arguments that support the position of the person making the inquiry. Where applicable, Sections 16-50j-13 to 16-50j-17, inclusive, of the Regulations of Connecticut State Agencies govern requests for participation in the proceeding.

(b) **Form and content.**

The form to be followed in the filing of petitions may vary to the extent necessary to provide for the nature of the legal rights, duties, or privileges involved therein, and to the extent necessary to comply with statutory requirements. Nevertheless, all petitions shall include the following components:

(1) the purpose for which the petition is being made;

(2) the statutory authority for such petition;

(3) the exact legal name of each person seeking the authorization or relief and the address or principal place of business of each such person. If any petitioner is a corporation, trust association, or other organized group, it shall also give the state under the laws of which it was created or organized;

(4) the name, title, address, and telephone number of the attorney or other person to whom correspondence or communications in regard to the petition are to be addressed. Notice, orders, and other papers may be served upon the person so named, and such service shall be deemed to be service upon the petitioner;

(5) such information as may be required under the applicable provisions of the Uniform Administrative Procedure Act, chapter 54 of the Connecticut General Statutes and the Public Utilities Environmental Standards Act, chapter 277a of the Connecticut General Statutes;

(6) such information as any department or agency of the state exercising environmental controls may, by regulation require;

(7) such information as the petitioner may consider relevant; and

(8) such additional information as the Council may request.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-39a. Completeness review

(a) **Submission of Petition for Declaratory Ruling to the Council.**

No declaratory ruling shall be issued to any person until a complete petition containing all information deemed relevant by the Council has been filed. Relevant information shall at a minimum include that listed in Section 16-50j-39 of the Regulations of Connecticut State Agencies unless an explanation of irrelevancy is provided for any item omitted from a petition. The Council will reserve final judgment of an item's relevancy.

(b) **Notification of Completeness.**

No later than 30 days after receipt of a petition for declaratory ruling, the Council shall notify the petitioner in writing as to the lack of completeness of the petition. If a petitioner fails or refuses to correct any deficiencies in the manner directed and within the time prescribed by the Council, the petition may be refused for lack of proper submission.

(Effective September 7, 2012)

Sec. 16-50j-40. Procedure after petition filed

(a) **Notice to other persons.**

Prior to submitting a petition for a declaratory ruling to the Council, the petitioner shall, where applicable, provide notice to each person other than the petitioner appearing of record as an owner of property which abuts the proposed primary or alternative sites of the proposed facility, each person appearing of record as an owner of the property or properties on which the primary or alternative proposed facility is to be located, and the appropriate municipal officials and government agencies. Proof of such notice shall be submitted with the petition for declaratory ruling. These notice requirements are applicable to proposed facilities that, by statute, are required to be approved by a declaratory ruling in lieu of a certificate under Section 16-50k of the Connecticut General Statutes, and to petitions for a declaratory ruling that the subject of the petition does not constitute a facility. The term "appropriate municipal officials and government agencies" means, in the case of a facility required to be approved by declaratory ruling, the same officials and agencies to be noticed in the application for a certificate under Section 16-50*l* of the Connecticut General Statutes. Petitioners seeking a declaratory ruling where the subject of the petition is not a facility, shall serve notice to the chief elected official of the municipality where the proposed project is located in whole or in part. Within 30 days after receipt of a petition for a declaratory ruling, the Council shall give notice of the petition to all persons to whom notice is required by any provision of law and to all persons who have requested notice of declaratory ruling petitions on the subject matter of the petition. The notice provided by the Council shall provide contact information for the Council, a timeline for public involvement and the date, place and time for any scheduled field review of the proposed project. The Council may receive and consider data, facts, arguments, and opinions from persons other than the persons requesting the ruling.

(b) **Provision for hearing.**

If the Council deems a hearing necessary or helpful in determining any issue concerning the request for a declaratory ruling, the Council shall schedule such hearing and give such notice thereof as shall be appropriate. The contested case provisions of Sections 16-50j-13 to 16-50j-34, inclusive, of the Regulations of Connecticut State Agencies shall govern the practice and procedure of the Council in any hearing concerning a declaratory ruling.

(c) **Decision on petition.**

Within 60 days after receipt of a petition for a declaratory ruling, the Council in writing shall: (1) issue a ruling declaring the validity of a regulation or the applicability of the provision of the Connecticut General Statutes, the regulation, or the final decision in question to the specified proceedings; (2) order the matter set for specified proceedings; (3) agree to issue a declaratory ruling by a specified date; (4) decide not to issue a declaratory ruling and initiate regulation-making proceedings, under Section 4-168 of the Connecticut General Statutes, on the subject; or (5) decide not to issue a declaratory ruling, stating the reasons for its action.

(d) **Decision.**

A copy of all rulings issued and any actions taken under subsection (c) of this section shall be promptly delivered to the petitioner and other parties and intervenors personally or by United States mail, certified or registered, postage prepaid, return receipt requested. A declaratory ruling shall contain the names of all parties and intervenors to the proceeding, the particular facts on which it is based, and the reasons for its conclusion.

(Effective March 7, 1989; Amended September 7, 2012)

Part 3

Miscellaneous Provisions

Sec. 16-50j-41. Council investigations

The Council may at any time initiate investigations and enforcement actions pursuant to Section 16-50u of the Connecticut General Statutes. Orders initiating the investigation shall indicate the nature of the matters to be investigated and shall be served upon any person being investigated. Upon direction by the Council said person shall file with the Council such data, facts, arguments and statement of position as shall be necessary to respond to the inquiry of the Council. The presiding officer may subpoena witnesses and require the production of records, physical evidence, papers and documents to any hearing held in a contested case pursuant to Section 4-177b of the Connecticut General Statutes. A motion for a protective order may be filed with the Council if the Council requests information that may qualify as trade secrets or commercial or financial information as described under Section 1-210(b) of the Connecticut General Statutes, or critical energy infrastructure information.

(Effective July 3, 1972; Amended September 7, 2012)

Sec. 16-50j-42. Procedure

The rules of practice and procedure set forth in Sections 16-50j-13 to 16-50j-34, inclusive, of the Regulations of Connecticut State Agencies for a contested case proceeding shall govern any hearing held for the purpose of such an investigation.

(Effective July 3, 1972; Amended September 7, 2012)

Sec. 16-50j-43. Intervention under the Environmental Protection Act of 1971

Any person or other legal entity authorized by or qualifying under the provisions of Sections 22a-14 to 22a-20, inclusive, of the Connecticut General Statutes to intervene as a party in any proceeding before the Council shall do so in accordance with the provisions of these rules and regulations as they may be applicable.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-44. Transferability of certificates

(a) No certificate may be transferred without approval of the Council pursuant to Section 16-50k of the Connecticut General Statutes.

(b) Any person desiring to transfer a certificate shall jointly submit with the proposed transferee an application to the Council. Such application shall, at a minimum, include the date on which such transfer was agreed upon by the parties to the transfer, an explanation of the reasons for the proposed transfer, and the same information about the transferee which is required of an applicant for a certificate.

(c) The proposed transferee shall agree, in writing, to comply with the terms, limitations, and conditions contained in the certificate.

(d) The Council shall not approve any transfer if it finds:

(1) That such transfer was contemplated at or prior to the time the certificate was issued and that such fact was not adequately disclosed during the certification proceeding; or

(2) That the transferor or transferee, or both, are not current with payments to the Council for their respective annual assessments and invoices under Section 16-50v of the Connecticut General Statutes.

(Effective September 7, 2012)

Sec. 16-50j-45—16-50j-55. Reserved

ARTICLE 4

ENERGY FACILITIES

Part 1

Rules of Practice

Sec. 16-50j-56. Finding

Pursuant to Section 16-50i (a) (1) to (4), inclusive, of the Connecticut General Statutes, the Council finds that each energy site and its associated equipment except as specified in Section 16-50j-57 of the Regulations of Connecticut State Agencies may have a substantial adverse environmental effect and therefore is a facility, and any modification, as defined in section 16-50j-2a(m) of the Regulations of Connecticut State Agencies, to an existing energy site, except as specified in Section 16-50j-57 of the Regulations of Connecticut State Agencies may have a substantial adverse environmental effect.

(Effective September 7, 2012)

Sec. 16-50j-57. Exemptions

(a) **Exemptions.** A facility or any modification to a facility that the Council, or its designee, has determined satisfies the criteria of this section shall be deemed not to have a substantial adverse environmental effect and shall not require a certificate pursuant to Section 16-50k of the Connecticut General Statutes. Facilities or modifications to facilities, including, but not limited to, installation or change-out of circuit breakers, disconnects, transformers, buses and appurtenant equipment, upon Council acknowledgment or acknowledgment of its designee, may qualify for such exemption.

(1) An energy component and associated equipment installed adjacent to a damaged or inoperable existing energy component and associated equipment in order to maintain

continuity of service shall not constitute a facility provided that:

(A) such energy component and associated equipment shall be removed at the earliest practicable time but in no event later than one year after installation, unless otherwise approved by the Council or unless exempt under subsection (b) of this section, in which event the existing damaged or inoperable energy component and associated equipment shall be removed no later than one year after installation of the new energy component and associated equipment;

(B) the owner or operator of such energy component and associated equipment shall give the property owner of record, if the property owner of record is different from the owner or operator of such component and associated equipment, and the chief elected official of the municipality in which the energy component and associated equipment is located, written notice of the installation or proposed installation of such energy component and associated equipment. The owner or operator of such energy component and associated equipment shall provide the Council with written proof of service of the written notice to the property owner of record, if the property owner of record is different from the owner or operator of such component and associated equipment, and the municipality in which the energy component and associated equipment is located. Notice to all parties shall include the following:

(i) the location of such energy component and associated equipment,

(ii) the reason for the installation, and

(iii) the estimated time such energy component and associated equipment will remain in place;

(C) the notice shall be given at the earliest practicable time but not later than 48 hours after the installation of such energy component and associated equipment; and

(D) the owner or operator of such energy component and associated equipment shall restore the site to its original condition as nearly as practical, subject to such other conditions as ordered by the Council, or its designee.

(b) None of the following shall constitute a modification to an existing energy facility that may have a substantial adverse environmental effect:

(1) Routine general maintenance and one-for-one replacement of facility components that are necessary for reliable operation;

(2) Changes on an existing site that do not:

(A) extend the boundaries of the site beyond the existing fenced compound;

(B) increase the height of existing associated equipment;

(C) increase noise levels at the site boundary by 6 decibels or more, or to levels that exceed state and local criteria;

(D) manage electric and magnetic field levels at the site boundary in a manner that is inconsistent with the Council's Best Management Practices for Electric and Magnetic Fields at the site boundary;

(E) cause a significant adverse change or alteration in the physical or environmental characteristics of the site; or

(F) impair the structural integrity of the facility, as determined in a certification provided by a professional engineer licensed in Connecticut, where applicable.

(c) Placement of energy components and associated equipment, owned or operated by the state or a public service company, as defined in Section 16-1 of the Connecticut General Statutes, on any existing non-facility energy site, shall not constitute a substantial adverse environmental effect when the changes on the existing non-facility energy site:

(1) Have received an acknowledgment by the Council that such placement of energy components and associated equipment would not cause a significant change or alteration to the physical and environmental characteristics of the site;

(2) Do not extend the boundaries of the site by any dimension;

(3) Do not increase the height of existing associated equipment;

(4) Do not increase noise levels at the site boundary by 6 decibels or more, or to levels that exceed state and local criteria;

(5) manage electric and magnetic field levels at the site boundary in a manner that is consistent with the Council's Best Management Practices for Electric and Magnetic Fields at the site boundary; and

(6) Have received all municipal zoning approvals and building permits, where applicable.

(d) The temporary use of energy components and associated equipment shall not constitute a facility provided that:

(1) The temporary use is necessary to provide emergency or essential energy service to areas of local disaster or events of statewide significance.

(2) Any provider of temporary energy service for an event of statewide significance shall provide the Council for its approval 30-day advance written notice of the development of such temporary service. The provider shall also provide the property owner of record, if the property owner of record is different from the provider, and the chief elected official of the affected municipality in which the temporary energy components and associated equipment are to be located 30-day advance written notice prior to the installation. Such notice shall state:

(A) the location of the temporary energy components and associated equipment;

(B) a letter from the property owner of record, if the property owner of record is different from the provider, authorizing use of the property for the temporary service;

(C) the height of the temporary energy components and associated equipment;

(D) the electric and magnetic field levels at the site boundary of the temporary energy components and associated equipment will be managed in a manner that is consistent with the Council's Best Management Practices for Electric and Magnetic Fields;

(E) the noise levels of the temporary energy components and associated equipment measured at the site boundary;

(F) the estimated time the temporary energy components and associated equipment shall be on site and the hours of operation for the temporary energy components and associated equipment; and

(G) the specific reasons for the installation, including, but not limited to, the nature of the event.

(3) Any provider of temporary energy service at an area of a local disaster shall provide to the chief elected official of the affected municipality and the Council written notice not later than 48 hours of the deployment stating:

(A) The location of the temporary energy components and associated equipment;

(B) a letter from the property owner of record, if the property owner of record is different from the provider, authorizing use of the property for the temporary service;

(C) the height of the temporary energy components and associated equipment;

(D) the electric and magnetic field levels at the site boundary of the temporary energy components and associated equipment will be managed in a manner that is consistent with the Council's Best Management Practices for Electric and Magnetic Fields;

(E) the noise levels of the temporary energy components and associated equipment measured at the site boundary;

(F) the estimated time the temporary energy components and associated equipment shall be on site, the hours of operation of the temporary energy components and associated equipment, and conditions that would render the use of the temporary energy components and associated equipment no longer necessary; and

(G) the nature of the emergency.

(4) In no event shall temporary use of energy components and associated equipment exceed 30 days unless the property owner of record, if the property owner of record is different from the provider, and the Council grant approval for an extension.

(Effective September 7, 2012)

Sec. 16-50j-58. Notice of intent to install an exempt energy component and associated equipment

Except as provided under Sections 16-50j-57(a) and 16-50j-57(d) of the Regulations of Connecticut State Agencies, the owner or operator of any energy component and associated equipment claiming such component and associated equipment are exempt pursuant to Section 16-50j-57 of the Regulations of Connecticut State Agencies shall give the Council, the property owner of record, if the property owner of record is different from the owner or operator of the energy component and associated equipment, and the chief elected official of the municipality in which the energy component and associated equipment is to be located, notice in writing prior to construction of the owner or operator's intent to install such energy component and associated equipment, detailing its reasons for claiming exemption under Section 16-50j-57 of the Regulations of Connecticut State Agencies.

(Effective September 7, 2012)

Sec. 16-50j-59. Information required

In addition to conforming to Section 16-50*l* of the Connecticut General Statutes and Section 16-50*l*-2 of the Regulations of Connecticut State Agencies, an application for a certificate of environmental compatibility and public need for the construction of a new energy facility, or a modification of an existing energy facility, as defined in Section 16-50i(a)(1) to (4), inclusive, of the Connecticut General Statutes shall include, but not be limited to:

(1) A description of the proposed facility and associated equipment, or modification of an existing facility and associated equipment, including, but not limited to, heights of facility components, special design features, and access roads;

(2) A statement of the need for the proposed facility and associated equipment, or modification of an existing facility and associated equipment with as much specific information as is practicable to demonstrate the need;

(3) A statement of the benefits expected from the proposed facility and associated equipment, or modification of an existing facility and associated equipment with as much specific information as is practicable;

(4) (A) The most recent U.S.G.S. topographic quadrangle map (scale 1 inch = 2000 feet) marked to show the approximate site of the facility and associated equipment, or modification of an existing facility and associated equipment and any significant changes within a one mile radius of the site; and

(B) a map (scale 1 inch = 200 feet or less) of the lot or tract on which the facility and associated equipment, or modification of an existing facility and associated equipment is proposed to be located showing the acreage and dimensions of such site, the name and location of adjoining public roads or the nearest public road, and the names of abutting owners and the portions of their lands abutting the site;

(5) (A) Plan and elevation drawings showing the proposed facility and associated equipment, or modification of an existing facility and associated equipment, the components and all structures on the site; and

(B) where relevant, a terrain profile showing the proposed facility and associated equipment, or modification of an existing facility and associated equipment;

(6) A description of the site, including the zoning classification of the site and surrounding areas;

(7) A description of the land uses of the site and surrounding areas;

(8) A description of the scenic, natural, historic, and recreational characteristics of the proposed site and surrounding area;

(9) A statement in narrative form of the environmental effects of the proposed facility and associated equipment, or modification of an existing facility and associated equipment;

(10) A statement containing justification for the site selected including a description of siting criteria and the narrowing process by which other possible sites were considered and eliminated;

(11) A statement of the estimated cost for site acquisition and construction of the facility and associated equipment, or modification of an existing facility and associated equipment;

(12) A schedule showing the proposed program of site acquisition, construction, completion, and operation;

(13) The names and mail addresses of the owner of the site and all abutting owners;

(14) A listing of any federal, state, regional, district, and municipal agencies with which reviews were conducted concerning the facility or modification of an existing facility, including a copy of any state and municipal agency position or decision with respect to the facility or modification of an existing facility;

(15) Where relevant, a list of all energy facilities and associated equipment within a 5-mile radius of the proposed facility or modification of an existing facility which are owned or operated by a public service company or the state;

(16) A description of technological alternatives and a statement containing justification for the proposed facility;

(17) A description of alternate sites, if applicable, for the proposed facility and associated equipment, or modification of an existing facility and associated equipment with the following information:

(A) a U.S.G.S. topographic quadrangle map (scale 1 inch = 2000 feet) marked to show the location of alternate sites;

(B) a map (scale 1 inch = 200 feet or less) of the lots or tracts of the alternate sites for the proposed facility and associated equipment, or modification of an existing facility and associated equipment showing the acreage and dimensions of such site, the name and location of adjoining public roads or the nearest public road, and the names of abutting owners and the portions of their land abutting the alternate site; and

(C) such additional information as would be necessary or useful to compare the costs and environmental impacts of the alternate sites with those of the proposed site;

(18) A statement describing hazards to human health, if any, with such supporting data or references to authoritative sources of information as will be helpful to the understanding of all aspects of the issue, including electric and magnetic field levels at the property boundaries of the proposed site and compliance with the Council's Best Management Practices for Electric and Magnetic Fields; and

(19) Additional information as may be requested by the Council.

(Effective September 7, 2012)

Part 2

Development and Management Plan

Sec. 16-50j-60. Requirements for a Development and Management Plan (D&M Plan)

(a) **Purpose.**

The Council may require the preparation of full or partial Development and Management Plans (D&M Plans) for proposed energy facilities, modifications to existing facilities, or where the preparation of such a plan would help significantly in balancing the need for adequate and reliable utility services at the lowest reasonable cost to consumers with the need to protect the environment and ecology of the state.

(b) **When required.**

A partial or full D&M plan shall be prepared in accordance with this regulation and shall include the information described in Sections 16-50j-61 to 16-50j-62, inclusive, of the Regulations of Connecticut State Agencies, for any proposed energy facility for which the Council issues a certificate of environmental compatibility and public need, except where the Council provides otherwise at the time it issues the certificate. Relevant information in the Council's record may be referenced.

(c) **Procedure for preparation.**

The D&M plan shall be prepared by the certificate holder or the owner or operator of the proposed facility or modification to an existing facility. The preparer may consult with the staff of the Council to prepare the D&M plan.

(d) **Timing of plan.**

The D&M plan shall be submitted to the Council in one or more sections, and the Council shall approve, modify, or disapprove each section of the plan not later than 60 days after receipt of it. If the Council does not act to approve, modify or disapprove the plan or a section thereof within 60 days after receipt of it, the plan shall be deemed approved. Except as otherwise authorized by the Council, no clearing or construction shall begin prior to approval of applicable sections of the D&M plan by the Council.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-61. Elements of a D&M plan

(a) **Key map.**

The D&M plan shall include a key map for the site, including the entire electric transmission line or fuel transmission line, as applicable, that is a reproduction at scale of 1inch = 2,000 feet of the most recent USGS topographic maps for its location and route.

(b) **Plan drawings.**

The D&M plan shall consist of maps at a scale of 1 inch = 100 feet or larger (called "plan drawings") and supporting documents, which shall contain the following information:

(1) The edges of the proposed site and of any existing site contiguous to or crossing it, the portions of those sites owned by the company in fee and the identity of the property owners of record of the portions of those sites not owned by the company in fee;

(2) Public roads and public lands crossing or adjoining the site;

(3) The approximate location along the site of each 50-foot contour line shown on the key map;

(4) The probable location, type, and height of the proposed facility, energy components and associated equipment supporting the facility operation, including, but not limited to, each new transmission structure, position of guys, generalized description of foundations, trench grading plans, depth and width of trenches, trench back-filling plans, and the location of any utility or other structures to remain on the site or to be removed;

(5) The probable points of access to the site, and the route and likely nature of the access ways, including alternatives or options to the probable points of access and access ways;

(6) The edges of existing and proposed clearing areas, the type of proposed clearing

along each part of the site, and the location and species identification of vegetation that would remain for aesthetic and wildlife value;

(7) Sensitive areas and conditions within and adjoining the site, including, but not limited to:

(A) Wetland and watercourse areas regulated under Chapter 440 of the Connecticut General Statutes, and any locations where construction may create drainage problems;

(B) Areas of high erosion potential;

(C) Any known critical habitats or areas identified as having rare, endangered, threatened or special concern plant or animal species listed by federal and state governmental agencies;

(D) The location of any known underground utilities or resources including, but not limited to, electric lines, fuel lines, drainage systems and natural or artificial, public or private water resources, to be crossed;

(E) Residences or businesses within or adjoining the site that may be disrupted during the construction process; and

(F) Significant environmental, historic and ecological features, including, but not limited to, significantly large or old trees, buildings, monuments, stone walls or features of local interest.

(c) **Supplemental information.**

(1) Plans, if any, to salvage marketable timber, restore habitat and to maintain snag trees within or adjoining the site;

(2) All construction and rehabilitation procedures with reasonable mitigation measures that shall be taken to protect the areas and conditions identified in section 16-50j-61(b)(7) of the Regulations of Connecticut State Agencies, including, but not limited to:

(A) Construction techniques at wetland and watercourse crossings;

(B) Sedimentation and erosion control and rehabilitation procedures, consistent with the Connecticut Guidelines for Soil Erosion and Sediment Control, as updated and amended, for areas of high erosion potential;

(C) Precautions and all reasonable mitigation measures to be taken in areas within or adjoining the site to minimize any adverse impacts of such actions or modifications on endangered, threatened or special concern plant or animal species listed by federal and state governmental agencies and critical habitats that are in compliance with federal and state recommended standards and guidelines, as amended;

(D) Plans for modification and rehabilitation of surface, drainage, and other hydrologic features;

(E) Plans for watercourse bank restoration in accordance with the provisions of Chapter 440 of the Connecticut General Statutes; and

(F) Plans for the protection of historical and archaeological resources with review and comment from a state historic preservation officer of the Department of Economic and Community Development, or its successor agency.

(3) Plans for the method and type of vegetative clearing and maintenance to be used within or adjacent to the site;

(4) The location of public recreation areas or activities known to exist or being proposed in or adjacent to the site, together with copies of any agreements between the company and public agencies authorizing public recreation use of the site to the extent of the company's property rights thereto;

(5) Plans for the ultimate disposal of excess excavated material, stump removal, and periodic maintenance of the site;

(6) Locations of areas where blasting is anticipated;

(7) Rehabilitation plans, including, but not limited to, reseeding and topsoil restoration;

(8) Contact information for the personnel of the contractor assigned to the project; and

(9) Such site-specific information as the Council may require.

(d) **Notice.**

A copy, or notice of the filing, of the D&M plan, or a copy, or notice of the filing of any changes to the D&M plan, or any section thereof, shall be provided to the service list and the property owner of record, if applicable, at the same time the plan, or any section thereof, or at the same time any changes to the D&M plan, or any section thereof, is submitted to the Council.

(e) **Changes to plan.**

The Council may order changes to a D&M plan, including, but not limited to, vegetative screening, paint color, or fence design at any time during or after preparation of the plan.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-62. Reporting requirements

(a) **Site Testing and Staging areas.**

The certificate holder, or facility owner or operator, shall provide the Council with written notice of the location and size of all areas to be accessed or used for site testing or staging areas. If such an area is to be used prior to approval of the D&M plan, the Council may approve such use on terms as it deems appropriate.

(b) **Notice**

(1) The certificate holder, or facility owner or operator, shall provide the Council, in writing, with a minimum of two weeks advance notice of the beginning of:

(A) clearing and access work in each successive portion of the site and

(B) facility construction in that same portion.

(2) The certificate holder, or facility owner or operator, shall provide the Council with advance written notice whenever a significant change of the approved D&M plan is necessary. If advance written notice is impractical, verbal notice shall be provided to the Council immediately and shall be followed by written notice not later than 48 hours after the verbal notice. Significant changes to the approved D& M plan shall include, but are not limited to, the following:

(A) the location of a wetland or watercourse crossing;

(B) the location of an access way or a structure in a regulated wetland or watercourse area;

(C) the construction or placement of any temporary structures or equipment;

(D) a change in structure type or location including, but not limited to, towers, guy wires, associated equipment or other facility structures; and

(E) utilization of additional mitigation measures, or elimination of mitigation measures.

The Council, or its designee, shall promptly review the changes and shall approve, modify, or disapprove the changes in accordance with subsection (d) of section 16-50j-60 of the Regulations of Connecticut State Agencies.

(3) The certificate holder, or facility owner or operator, shall provide the Council with a monthly construction progress report, or a construction progress report at time intervals determined by the Council or its designee, indicating changes and deviations from the approved D&M plan. The Council may approve changes and deviations, request corrections or require mitigation measures.

(4) The certificate holder, or facility owner or operator, shall provide the Council with written notice of completion of con(struction and site rehabilitation.

(c) **Final report.**

The certificate holder, or facility owner or operator, shall provide the Council with a final report for the facility not later than 180 days after completion of all site construction and site rehabilitation This final report shall identify:

(1) all agreements with abutters or other property owners regarding special maintenance precautions;

(2) significant changes of the D&M plan that were required because of the property rights of underlying and adjoining owners or for other reasons;

(3) the location of construction materials which have been left in place including, but not limited to, culverts, erosion control structures along watercourses and steep slopes, and corduroy roads in regulated wetlands;

(4) the location of areas where special planting and reseeding have been done; and

(5) the actual construction cost of the facility, including, but not limited to, the following costs:

(A) clearing and access;

(B) construction of the facility and associated equipment;

(C) rehabilitation; and

(D) property acquisition for the site or access to the site.

(d) **Protective Order.**

The certificate holder, or facility owner or operator, may file a motion for a protective order pertaining to commercial or financial information related to the site or access to the site.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-63—16-50j-69. Reserved

ARTICLE 5

Community Antenna Television and Telecommunications Towers

Part 1

Rules of Practice

Sec. 16-50j-70. Repealed

Repealed March 7, 1989.

Sec. 16-50j-71. Finding

Pursuant to Section 16-50i (a) (5) and (6) of the Connecticut General Statutes, the Council finds that each community antenna television tower or telecommunications tower and its associated equipment except as specified in Sections 16-50j-72 and 16-50j-88 of the Regulations of Connecticut State Agencies may have a substantial adverse environmental effect and therefore is a facility; and any modification, as defined in Section 16-50j-2a of the Regulations of Connecticut State Agencies, to an existing tower site, except as specified in Sections 16-50j-72 and 16-50j-88 of the Regulations of Connecticut State Agencies, may have a substantial adverse environmental effect.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-72. Exceptions

(1) **Exemptions.**

A facility or any modification to a facility that the Council, or its designee, has determined satisfies the criteria of this section shall be deemed not to have a substantial adverse environmental effect and shall not require a certificate pursuant to Section 16-50k of the Connecticut General Statutes. Facilities or modifications to facilities, including, but not limited to, change-outs and installations of antennas on existing telecommunications towers, existing radio towers, functioning smokestacks, functioning water tanks and on or in existing buildings, upon Council acknowledgment or acknowledgment of its designee, may qualify for such exemption.

(2) A community antenna television tower or telecommunications tower and associated equipment installed adjacent to a damaged or inoperable existing tower and associated equipment in order to maintain continuity of community antenna television service or telecommunications shall not constitute a facility provided that:

(A) such tower and associated equipment shall be removed at the earliest practicable time but in no event later than one year after installation, unless otherwise approved by the Council or unless exempt under subsection (b) of this section in which event the existing damaged or inoperable tower and associated equipment shall be removed no later than one year after installation of the new tower and associated equipment;

(B) the owner or operator of such tower and associated equipment shall give the Council, the property owner of record, if the property owner of record is different from the owner or operator of such tower and associated equipment, and the chief elected official of the municipality in which the tower and associated equipment is located, written notice of the installation or proposed installation of such tower and associated equipment. The owner or operator of such tower and associated equipment shall provide the Council with proof of service of the written notice to the property owner of record, if the property owner of record is different from the owner or operator of such tower and associated equipment, and the municipality in which the tower or associated equipment is located. Notice to all parties shall include the following:

(i) the location of such tower and associated equipment;

(ii) the reason for its installation; and (iii) the estimated time such tower and associated equipment shall remain in place.

(C) the notice shall be given at the earliest practicable time but not later than 48 hours after the installation of such tower and associated equipment; and

(D) the owner or operator of such tower or associated equipment shall restore the site to its original condition as nearly as practical, subject to such other conditions as ordered by the Council, or its designee.

(b) None of the following shall constitute a modification to an existing community antenna television or telecommunications tower that may have a substantial adverse environmental effect:

(1) Routine general maintenance and one-for-one replacement of facility components that is necessary for reliable operation;

(2) Changes on an existing site that do not:

(A) increase the tower height;

(B) extend the boundaries of the site by any dimension;

(C) increase noise levels at the site boundary by 6 decibels or more, or to levels that exceed state and local criteria;

(D) add radio frequency sending or receiving capability which increases the total radio frequency electromagnetic radiation power density measured at the site boundary to or above the standards adopted by the Federal Communications Commission pursuant to Section 704 of the Telecommunications Act of 1996, as amended, and the State Department of Energy and Environmental Protection, pursuant to Section 22a-162 of the Connecticut General Statutes;

(E) cause a significant adverse change or alteration in the physical or environmental characteristics of the site; and

(F) impair the structural integrity of the facility, as determined in a certification provided by a professional engineer licensed in Connecticut, or

(3) Replacement of an existing CATV tower or telecommunications tower and associated equipment with a tower that is no taller than the tower to be replaced and that does not

support public service company or state antennas, or antennas to be used for public cellular radio communications emitting total radio frequency electromagnetic radiation power density measured at the site boundary to or above the standard adopted by the Federal Communications Commission pursuant to Section 704 of the Telecommunications Act of 1996, as amended, and the State Department of Energy and Environmental Protection pursuant to Section 22a-162 of the Connecticut General Statutes.

(c) Placement of community antenna television towers and head-end structures, telecommunications towers, and associated telecommunications equipment, owned or operated by the state or a public service company, as defined in Section 16-1 of the Connecticut General Statutes, or used in a cellular system, as defined in the code of Federal Regulations Title 47, Part 22, as amended, on any existing non-facility tower, shall not constitute a substantial adverse environmental effect when the changes on the existing non-facility tower:

(1) Have received an acknowledgment from the Council that such a facility would not cause a significant change or alteration in the physical and environmental characteristics of the site;

(2) Do not extend the boundaries of the site by any dimension;

(3) Do not increase noise levels at the site boundary by 6 decibels or more, or to levels that exceed state and local criteria;

(4) Do not increase the total radio frequency electromagnetic radiation power density measured at the site boundary to or above the standard adopted by the Federal Communications Commission pursuant to Section 704 of the Telecommunications Act of 1996, as amended, and the State Department of Energy and Environmental Protection pursuant to Section 22a-162 of the Connecticut General Statutes; and

(5) Have received all municipal zoning approvals and building permits, where applicable.

(d) The temporary use of telecommunications equipment shall not constitute a facility provided that:

(1) The temporary use is necessary to provide emergency or essential telecommunications service to areas of local disaster or events of statewide significance.

(2) Any provider of temporary telecommunications service for an event of statewide significance shall provide to the Council for its approval 30 day advance written notice of the development of such temporary service. The provider shall also provide the property owner of record, if the property owner of record is different from the provider, and the chief elected official of the municipality in which the temporary facility is to be located, advance written notice not less than 30 days prior to the installation. Such notice shall include:

(A) The location of the temporary telecommunications equipment;

(B) A letter from the property owner of record, if the property owner of record is different from the provider, authorizing use of the property for the temporary telecommunications service;

(C) The height and power density of the temporary telecommunications equipment;

(D) The noise levels of the temporary telecommunications equipment measured at the property lines;

(E) The estimated time the temporary telecommunications equipment shall be in use, including the approximate start and end dates; and

(F) The specific reasons for the installation, including, but not limited to, the nature of the event.

(3) Any provider of temporary telecommunications service at an area of a local disaster shall provide to the Council written notice not later than 48 hours after the deployment including:

(A) The location of the temporary telecommunications equipment;

(B) A letter from the property owner of record, if the property owner of record is different from the provider, authorizing use of the property for the temporary telecommunications service;

(C) The height and power density of the temporary telecommunications equipment;

(D) The noise levels of the temporary telecommunications equipment measured at the property lines;

(E) The estimated time the temporary telecommunications equipment shall be in use, including, but not limited to, the hours of operation of the temporary telecommunications equipment and conditions that would render the use of the temporary telecommunications equipment no longer necessary; and

(F) The nature of the emergency.

(4) In no event shall temporary use of telecommunications equipment exceed 30 days unless the Council and the property owner of record, if the property owner of record is different from the provider, grant approval for an extension.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-73. Notice of intent to erect an exempt tower and associated equipment

Except as otherwise provided under sections 16-50j-72(a) and sections 16-50j-72(d), the owner or operator of any tower and associated equipment claiming such tower and associated equipment is exempt pursuant to section 16-50j-72 of the Regulations of Connecticut State Agencies shall give the Council, the property owner of record, if the property owner of record is different from the owner or operator of the tower and associated equipment, and the chief elected official of the municipality in which the facility is to be located, notice in writing prior to construction of its intent to construct such tower and associated equipment, detailing its reasons for claiming exemption under these regulations.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-74. Information required

In addition to conforming to Section 16-50*l* of the Connecticut General Statutes and to Section 16-50*l*-2 of the Regulations of Connecticut State Agencies, an application for a certificate of environmental compatibility and public need for the construction of a new community antenna television tower and head-end structure or telecommunications tower and associated equipment, or modification to an existing community antenna television tower and head-end structure or telecommunications tower and associated equipment, as defined in Sections 16-50i (a) (5) and (6) of the Connecticut General Statutes, shall include, but not be limited to, the following:

(1) A description of the proposed tower and associated equipment, or modification and associated equipment including height and special design features, access roads and power lines, if any;

(2) A statement of the need for the proposed tower and associated equipment, or modification and associated equipment with as much specific information as is practicable to demonstrate the need;

(3) A statement of the benefits expected from the proposed tower and associated equipment, or modification and associated equipment with as much specific information as is practicable;

(4) (A) The most recent U.S.G.S. topographic quadrangle map (scale 1 inch = 2000 feet) marked to show the approximate site of the tower and associated equipment, or modification and associated equipment and any significant changes within a one mile radius of the site; and

(B) a map (scale 1 inch = 200 feet or less) of the lot or tract on which the tower and associated equipment, or modification and associated equipment is proposed to be located showing the acreage and dimensions of such site, the name and location of adjoining public roads or the nearest public road, and the names of abutting owners and the portions of their lands abutting the site;

(5) (A) Plan and elevation drawings showing the proposed tower and associated equipment, or modification and associated equipment, the antennas and other components to be supported, and all structures on the site; and

(B) where relevant, a terrain profile showing the proposed tower and associated equipment, or modification and associated equipment;

(6) A description of the site, including the zoning classification of the site and surrounding areas;

(7) A description of the land uses of the site and surrounding areas;

(8) A description of the scenic, natural, historic, and recreational characteristics of the proposed site and surrounding area;

(9) A statement in narrative form of the environmental effects of the proposed tower and associated equipment, or modification and associated equipment;

(10) A statement containing justification for the site selected including a description of siting criteria and the narrowing process by which other possible sites were considered and eliminated;

(11) A statement of the estimated cost for site acquisition and construction of the tower and associated equipment, or modification and associated equipment;

(12) A schedule showing the proposed program of site acquisition, construction, completion, and operation;

(13) The names and mail addresses of the owner of the site and all abutting owners;

(14) A listing of any federal, state, regional, district, and municipal agencies with which reviews were conducted concerning the tower and associated equipment or modification and associated equipment, including a copy of any state and municipal agency position or decision with respect to the tower or modification and associated equipment;

(15) Where relevant, a list of all towers and associated equipment within a 5-mile radius of the proposed tower and associated equipment or modification and associated equipment;

(16) A description of technological alternatives and a statement containing justification for the proposed facility;

(17) A description of alternate sites for the proposed tower, if applicable, and associated equipment, or modification and associated equipment with the following information:

(A) a U.S.G.S. topographic quadrangle map (scale 1 inch = 2000 feet) marked to show the location of alternate sites;

(B) a map (scale 1 inch = 200 feet or less) of the lots or tracts of the alternate sites for the proposed tower and associated equipment, or modification and associated equipment showing the acreage and dimensions of such site, the name and location of adjoining public roads or the nearest public road, and the names of abutting owners and the portions of their land abutting the alternate site; and

(C) such additional information as would be necessary or useful to compare the costs and environmental impacts of the alternate sites with those of the proposed site;

(18) A statement describing hazards to human health, if any, with such supporting data or references to authoritative sources of information as will be helpful to the understanding of all aspects of the issue, including signal frequency and power density at the proposed site to be transmitted or received by the proposed facility; and

(19) Additional information as may be requested by the Council.

(Effective March 7, 1989; Amended September 7, 2012)

Part 2

Development and Management Plan

Sec. 16-50j-75. Requirement for a Development and Management Plan (D&M plan)

(a) **Purpose.**

The Council may require the preparation of full or partial D&M plans for proposed community antenna television towers or head-end structures and associated equipment or telecommunications towers and associated equipment or a modification to an existing site, where the preparation of such a plan would help significantly in balancing the need for adequate and reliable utility services at the lowest reasonable cost to consumers with the need to protect the environment and ecology of the state.

(b) **When required.**

A partial or full D&M plan shall be prepared in accordance with this Section and shall include the information described in Sections 16-50j-76 to 16-50j-77, inclusive, of the

Regulations of Connecticut State Agencies for any proposed facility for which the Council issues a certificate or for a modification to an existing site, except where the Council provides otherwise at the time it issues the certificate. Relevant information in the Council's record may be referenced.

(c) **Procedure for preparation.**

The D&M plan shall be prepared by the certificate holder of the tower and associated equipment, or modification to an existing facility. The preparer may consult with the staff of the Council to prepare the D&M plan.

(d) **Timing of plan.**

The D&M plan shall be submitted to the Council in one or more sections, and the Council shall approve, modify or disapprove each section of the plan not later than 60 days after receipt of it. If the Council does not act to approve, modify or disapprove the plan or any section thereof within 60 days after receipt of it, the plan shall be deemed approved. Except as otherwise authorized by the Council, no clearing or construction shall begin prior to approval of applicable sections of the D&M plan by the Council.

(e) **Notice.**

A copy, or notice of the filing, of the D&M plan, or any section thereof, or a copy, or notice of the filing of any changes to the D&M plan, or any section thereof, shall be provided to the service list and the property owner of record, if applicable, at the same time the plan, or any section thereof, or at the same time any changes to the D&M plan, or any section thereof, is submitted to the Council.

(f) **Changes to plan.**

The Council may order changes to the D&M Plan including, but not limited to, vegetative screening, paint color, or fence design at any time during or after preparation of the plan.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-76. Elements of a D&M plan

(a) **Key map.**

The D&M Plan shall include a key map for the site that is a reproduction at a scale of 1 inch = 2,000 feet of the most recent USGS topographic maps marked to show the site locations of the tower and associated equipment.

(b) **Plan drawings.**

The D&M plan shall consist of a map or blueprint at a scale of 1 inch = 100 feet or less (called "plan drawings") and supporting documents, which shall contain the following information:

(1) The edges of the proposed site and of any existing tower and associated equipment sites contiguous to or crossing it, and the identity of the property owner(s) of record of such site(s);

(2) Public roads and public lands crossing or adjoining the site;

(3) The approximate location on the site of each 10-foot contour line;

(4) The approximate location, type, and height of the proposed tower and associated

equipment, position of guys, generalized description of foundations, and the location of any utility or other structures to remain on the site or to be removed;

(5) The probable points of access to the site including alternatives or options to the probable points of access;

(6) The edges of existing and proposed clearing areas, the type of proposed clearing at the site, and the location and species identification of vegetation to be cleared;

(7) Sensitive areas and conditions within and adjoining the tower site, including, but not limited to:

(A) Wetland and watercourse areas regulated under Chapter 440 of the Connecticut General Statutes, and any locations where construction may create drainage problems;

(B) Areas of high erosion potential;

(C) Any known critical habitats or areas identified as having rare, threatened, endangered, or special concern plant or animal species listed by federal and state governmental agencies;

(D) The location of any known underground utilities or resources including, but not limited to, electric lines, fuel lines, drainage systems, and natural or artificial, public or private water resources;

(E) Residences or businesses within or adjoining the site that may be disrupted during the construction process; and

(F) Significant environmental, historic and ecological features, including, but not limited to, significantly large or old trees, buildings, monuments, stone walls or areas of local interest.

(c) **Supplemental information.**

(1) Special environmental considerations arising from peculiar or unusual characteristics of the site;

(2) Special design features required by peculiar or unusual characteristics of the site; and

(3) All construction and rehabilitation procedures with reasonable mitigation measures that shall be taken to protect the areas and conditions identified in Subsection (b)(7) of this Section of the Regulations of Connecticut State Agencies, including, but not limited to:

(A) Construction techniques at wetland and watercourse crossings;

(B) Sedimentation and erosion control and rehabilitation procedures, consistent with the Connecticut Guidelines for Soil Erosion and Sediment Control, as updated and amended, for areas of high erosion potential;

(C) Precautions and all reasonable mitigation measures that shall be taken in areas within or adjoining the site to minimize any adverse impacts of such actions or modifications on endangered, threatened or special concern plant or animal species listed by federal and state governmental agencies and critical habitats that are in compliance with federal and state recommended standards and guidelines, as amended;

(D) Plans for modification and rehabilitation of surface, drainage and other hydro-logic features;

(E) Plans for watercourse bank restoration in accordance with the provisions of Chapter 440 of the Connecticut General Statutes; and

(F) Plans for the protection of historical and archaeological resources with review and comment from a state historic preservation officer of the Department of Economic and Community Development, or its successor agency.

(4) The location of public recreation areas or activities known to exist or being proposed in or adjacent to the proposed site;

(5) Plans for the method and type of vegetative clearing and maintenance to be used for the proposed site;

(6) Plans for the ultimate disposal of excess excavated material, stump removal and for the periodic maintenance of the site;

(7) Locations of areas where blasting is anticipated;

(8) Rehabilitation plans, including, but not limited to, reseeding and topsoil restoration; and

(9) Such site-specific information as the Council may require.

(Effective March 7, 1989; Amended September 7, 2012)

Sec. 16-50j-77. Reporting requirements

(a) **Supervisory Personnel.**

The certificate holder, or facility owner or operator, shall submit to the Council contact information for the personnel of the contractor assigned to the project.

(b) **Notice.**

(1) The certificate holder, or facility owner or operator, shall provide the Council, in writing, with a minimum of two weeks advance notice of the beginning of:

(A) clearing and access work, and

(B) construction of the tower and associated equipment.

(2) The certificate holder, or facility owner or operator, shall provide the Council with advance written notice whenever a significant modification of the approved D&M plan is necessary including, but not limited to, a change in the location of the tower, associated equipment, guy wires, or access road. The Council, or its designee shall promptly review the changes, and the Council shall approve, modify, or disapprove the changes in accordance with subsection (d) of Section 16-50j-75 of the Regulations of Connecticut State Agencies.

(3) The certificate holder, or facility owner or operator, shall provide the Council with a monthly construction progress report, or a construction progress report at time intervals determined by the Council, indicating changes and deviations from the approved D&M plan. The Council may approve the changes and deviations or request corrections or mitigating measures.

(4) The certificate holder, or facility owner or operator, shall provide the Council with written notice of completion of construction and site rehabilitation.

(c) **Final report.**

The certificate holder, or facility owner or operator, shall provide the Council with a final report not later than 180 days after completion of all site construction and site rehabilitation. This final report shall identify:

(1) all agreements with abutters or other property owners regarding special maintenance precautions;

(2) significant modifications of the D&M plan that were required because of the property rights of underlying and adjoining owners or for other reasons;

(3) the location of construction materials which have been left in place in the form of culverts, erosion control structures along watercourses and steep slopes, and corduroy roads in regulated wetlands;

(4) the location of special areas where special planting and reseeding have been done; and

(5) agreements between the certificate holder and public agencies authorizing public recreational use of the site to the extent of the certificate holder's property rights thereto.

(d) The final report shall include the actual construction cost of the tower and associated equipment, including, but not limited to, the following costs:

(1) construction of the tower and associated equipment;

(2) site rehabilitation; and

(3) property acquisition for site or access to site.

(e) **Protective Order.**

The certificate holder, or facility owner or operator, may file a motion for a protective order pertaining to commercial or financial information related to the site or access to the site.

(Effective May 28, 1985; Amended September 7, 2012)

Sec. 16-50j-78—16-50j-79. Reserved

Rules of Practice

Telecommunication Tower

Sec. 16-50j-80—16-50j-84. Repealed

Repealed May 28, 1985.

Telecommunication Tower Development and Management Plan

Sec. 16-50j-85—16-50j-87. Repealed

Repealed May 28, 1985.

Part 3

Tower Sharing

Sec. 16-50j-88. Procedure governed

A facility or any modification to a facility that the Council has determined satisfies the criteria of this section shall be deemed not to have a substantial adverse environmental effect and shall not require a certificate pursuant to Section 16-50k of the Connecticut General Statutes. Applications for proposed collocations or shared use of facilities, upon Council order approving the collocation or shared use, shall qualify for such exemption. The person requesting the collocation or shared use of a facility shall provide the Council with information in accordance with Section 16-50aa of the Connecticut General Statutes.

(Effective September 7, 2012)

Sec. 16-50j-89. Requirements for tower sharing

(a) **Application for tower sharing.**

A person requesting collocation or shared use of a facility under Section 16-50aa of the Connecticut General Statutes shall file with the Council an application for tower sharing, which shall include, but not be limited to, the following information:

(1) A description of the facility with a site plan detailing existing and proposed antenna installations and associated equipment;

(2) A description of the proposed antenna installation and associated equipment, including, but not limited to, types, number, height and configuration of antennas, location of associated equipment and utility connections;

(3) A structural analysis of the tower performed by an engineer licensed in the State of Connecticut with a certification that the proposed shared use is technically feasible;

(4) A letter from the owner of the facility that the owner agrees to the proposed shared use of the facility;

(5) A description of any potential environmental impact associated with the proposed shared use, including, but not limited to, on visibility, wetlands and water resources, air quality and noise;

(6) A calculation based on an approved methodology prescribed by the Federal Communications Commission of the power density of the radio frequency emissions to be generated by the existing antennas and the antennas to be installed;

(7) Such information as the applicant may consider relevant; and

(8) Such additional information as the Council may request.

(b) **Feasibility Proceeding.**

Upon request of the person seeking shared use of a facility, the Council shall initiate a feasibility proceeding under Section 16-50aa of the Connecticut General Statutes to determine whether the proposed shared use of a facility is technically, legally, environmentally and economically feasible and meets public safety concerns. The contested case provisions of Sections 16-50j-13 to 16-50j-34, inclusive, of the Regulations of

Connecticut State Agencies shall govern the practice and procedure of the Council in any feasibility proceeding concerning the proposed shared use of a facility.

(Effective September 7, 2012)

Sec. 16-50j-90. Completeness review

(a) **Submission of Tower Share application to the Council.**

No tower share application shall be approved until a complete application containing all information deemed relevant by the Council has been filed. Relevant information shall at a minimum include that listed in Section 16-50j-89 of the Regulations of Connecticut State Agencies unless an explanation of irrelevancy is provided for any item omitted from an application. The Council will reserve final judgment of an item's relevancy.

(b) **Notification of completeness.**

No later than 30 days after receipt of a tower share application, the Council shall notify the applicant in writing as to the lack of completeness of the application. If an applicant fails or refuses to correct any deficiencies in the manner directed and within the time prescribed by the Council, the application may be refused for lack of proper submission.

(Effective September 7, 2012)

ARTICLE 6

HAZARDOUS WASTE FACILITIES

Sec. 16-50j-91. Procedure governed

The rules contained in Sections 22a-116-1 to 22a-116-B-11, inclusive, of the Regulations of Connecticut State Agencies govern the practice and procedure for hazardous waste facilities siting before the Connecticut Siting Council under the applicable laws of the state of Connecticut and except where by statute otherwise provided.

(Effective September 7, 2012)

Sec. 16-50j-92. Application for a certificate of environmental compatibility and public need

Pursuant to Section 16-50k of the Connecticut General Statutes, any person seeking to construct, operate and maintain a wind turbine facility with a generating capacity of more than 65 megawatts shall file an application for a certificate. The application shall be filed with the Council in accordance with the filing requirements of Section 16-50j-59 of the Regulations of Connecticut State Agencies and Sections 16-50*l*-1 to 16-50*l*-5, inclusive, of the Regulations of Connecticut State Agencies. The application filed with the Council shall also include additional information required to be submitted to the Council as part of the application under Section 16-50j-94 of the Regulations of Connecticut State Agencies. A motion for protective order may be filed with the Council for any information that may qualify as proprietary or critical energy infrastructure information pursuant to Subsection

(d) of Section 16-50j-22a of the Regulations of Connecticut State Agencies.

(Effective May 9, 2014)

Sec. 16-50j-93. Petition for a declaratory ruling

Pursuant to Subsection (a) of Section 16-50k of the Connecticut General Statutes, any person seeking to construct, operate and maintain a customer-side distributed resources project or a grid-side distributed resources project with a capacity of not more than 65 megawatts or a wind turbine facility with a capacity of less than one megawatt provided the facility fails to meet the criteria for exemption under Section 16-50i (a)(3) of the Connecticut General Statutes, shall file a petition for a declaratory ruling. The petition for a declaratory ruling shall be filed with the Council in accordance with the filing requirements of Sections 16-50j-38 to 16-50j-40, inclusive, of the Regulations of Connecticut State Agencies. The petition for a declaratory ruling filed with the Council shall also include additional information required to be submitted to the Council as part of the petition under Section 16-50j-94 of the Regulations of Connecticut State Agencies. A motion for protective order may be filed with the Council for any information that may qualify as proprietary or critical energy infrastructure information pursuant to Subsection (d) of Section 16-50j-22a of the Regulations of Connecticut State Agencies.

(Effective May 9, 2014)

Sec. 16-50j-94. Additional information required

(a) **Notification.**

In addition to the notification requirements under Subsection (d) of Section 16-50j-12 of the Regulations of Connecticut State Agencies, as applicable, each application for a certificate or petition for a declaratory ruling for a wind turbine facility shall be accompanied by proof of service of a copy of the application or petition for a declaratory ruling on the following entities:

(1) Department of Defense. The applicant or petitioner shall notify and consult with the Executive Director of the Department of Defense Siting Clearinghouse and the Department of Defense Regional Environmental Coordinator at Commander, Navy Region Mid-Atlantic. Any comments and recommendations received from the Department of Defense shall be submitted to the Council.

(2) Federal Aviation Administration. The applicant or petitioner shall notify and consult with the Federal Aviation Administration. Any comments and recommendations received from the Federal Aviation Administration shall be submitted to the Council.

(3) State Historic Preservation Office. The applicant or petitioner shall notify and consult with the State Historic Preservation Office, or its successor agency. Any comments and recommendations received from the State Historic Preservation Office, or its successor agency, shall be submitted to the Council.

(4) Telecommunications Infrastructure Owners and Operators. The applicant or petitioner shall notify and consult with public and private owners and operators of telecommunications

infrastructure within a two-mile radius of the proposed site and any alternative sites for wind turbine facilities. Any comments or recommendations received from the owners and operators of telecommunications infrastructure shall be submitted to the Council.

(b) **Abutting properties map.**

The applicant or petitioner shall submit a map that depicts the dimensions of the proposed site and any alternative sites, the names and addresses of abutting property owners and the dimensions of the abutting properties that clearly delineates the setback distance in feet from each of the proposed wind turbine locations and any alternative wind turbine locations for the proposed site and any alternative sites to each abutting property line.

(c) **Visual Impact Evaluation Report.**

The applicant or petitioner shall submit a visual impact evaluation report that analyzes the potential visibility of each of the proposed wind turbine locations and any alternative wind turbine locations for the proposed site and any alternative sites that includes:

(1) A detailed description of the potential visibility of each of the proposed wind turbine locations and any alternative wind turbine locations for the proposed site and any alternative sites, including a description of the potential visibility of the wind turbine heights, wind turbine tower heights and blade lengths, the sites, surrounding land uses, average tree canopy height and methodology used to evaluate visibility.

(2) A study area map for the proposed site and any alternative sites depicting the view-shed analyses study area radius used in accordance with Subdivision (3) of this section that delineates the view-shed radius, site boundaries of the proposed and any alternative sites, and locations of the photographic simulations submitted in accordance with Subdivision (4) of this section.

(3) View-shed analyses for the proposed site and any alternative sites depicting areas of potential year-round and seasonal visibility of each wind turbine, specifying the wind turbine heights, wind turbine tower heights and blade lengths, using a study area radius that is based on the wind turbine height of each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites as follows:

(A) less than 200 feet - 2 mile radius

(B) between 200 feet and 400 feet – 4 mile radius

(C) between 400 feet and 600 feet – 6 mile radius

(D) greater than 600 feet – 8 mile radius

If the study area radius truncates any area of potential year-round and seasonal visibility, the applicant or petitioner shall expand the study area radius to include the entire area of potential visibility. The view-shed analyses shall depict the site boundaries of the proposed site and any alternative sites, the proposed wind turbine locations and any alternative wind turbine locations, town boundaries, and, as applicable, historic sites, historic districts, state and locally designated scenic roads, recreational areas, open space and conservation areas, schools, trails, forests, parks, and water resources.

(4) Photographic simulations from locations that may have potential seasonal and year-round visibility of each of the proposed wind turbines and any alternative wind turbines at

the proposed site and any alternative sites, specifying the visibility of the wind turbine heights, wind turbine tower heights and blade lengths.

(5) Identification of any potential mitigation measures to minimize visual impact, including paint color of the facility, vegetative screening and landscaping.

(6) For wind turbine facilities with a capacity of more than 65 megawatts, the applicant shall submit, as part of the Visual Impact Evaluation Report, a separate view-shed analysis for the proposed site and any alternative sites using a study area radius of 10 miles that depicts the site boundaries, the proposed wind turbine locations and any alternative wind turbine locations, town boundaries, and, as applicable, historic sites, historic districts, state and locally designated scenic roads, recreational areas, open space and conservation areas, schools, trails, forests, parks, water resources, military bases, airports and weather stations. Each such application for a certificate shall be accompanied by proof of service of a copy of the application on all of the municipalities within the 10 mile study area radius.

(d) **Noise Evaluation Report.**

The applicant or petitioner shall submit a noise evaluation report for each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites in accordance with the noise control regulations established by the Department of Energy and Environmental Protection under Sections 22a-69-1 to 22a-69-7, inclusive, of the Regulations of Connecticut State Agencies. The report shall include the following:

(1) A detailed description of the potential noise levels that would be generated by the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites including existing sound levels at the proposed site and any alternative sites, projected sound levels to be generated by the operation of the proposed wind turbines and any alternative wind turbines, the methodology used to monitor and evaluate sound levels, the wind turbine manufacturer's technical documentation of the noise emission characteristics of the proposed wind turbines and any alternative wind turbines, and an analysis of compliance with the noise control regulations established by the Department of Energy and Environmental Protection.

(2) Calculations in accordance with the noise control regulations established by the Department of Energy and Environmental Protection, of projected maximum cumulative sound levels generated when the proposed wind turbines and any alternative wind turbines are in operation at the proposed site and any alternative sites measured at the property lines, projected maximum day-time and night-time sound levels generated when the proposed wind turbines and any alternative wind turbines are in operation measured at the nearest receptors, and projected maximum levels of infrasonic sound, ultrasonic sound, impulsive noise and prominent discrete tones generated when the proposed wind turbines and any alternative wind turbines are in operation at the proposed site and any alternative sites measured at the nearest receptors.

(3) A study area map for the proposed site and any alternative sites depicting the noise analysis study area radius, site boundaries, sound level monitoring locations and nearest

receptor locations.

(4) Identification of any potential mitigation measures to minimize sound levels at the nearest receptor locations, including utilization of best practical noise control measures in accordance with Section 22a-69-1 to 22a-69-7, inclusive, of the Regulations of Connecticut State Agencies.

(e) **Ice Drop and Ice Throw Evaluation Report.**

The applicant or petitioner shall submit an ice drop and ice throw evaluation report for each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites that shall include:

(1) A detailed description of the conditions at the proposed site and any alternative sites that may cause ice to be dropped or ice to be thrown, or both, from the wind turbine blades of the proposed wind turbines and any alternative wind turbines, the methodology used to evaluate and assess the risk of ice drop or ice throw, or both, and the wind turbine manufacturer's technical documentation relating to recommended ice drop and ice throw setback distances and installed ice monitoring devices and sensors.

(2) Calculations in feet of the maximum distance that ice could be dropped from the wind turbine blades of each proposed wind turbine and any alternative wind turbines at the proposed site and any alternative sites when the wind turbines are stationary and calculations in feet of the maximum distance that ice could be thrown from the wind turbine blades for each proposed wind turbine and any alternative wind turbines at the proposed site and any alternative sites when the wind turbines are in operation.

(3) A study area map for the proposed site and any alternative sites depicting the ice throw study area radius, site boundaries and locations where ice could be dropped or locations where ice could be thrown from the wind turbine blades, or both, of each proposed wind turbine and any alternative wind turbines at the proposed site and any alternative sites when the wind turbines are stationary and in operation.

(4) Identification of any potential mitigation measures to minimize the risk, occurrence and impact of ice drop or ice throw, or both, from the wind turbine blades of each of the proposed wind turbines and any alternative wind turbines, including automatic and remote manual shutdown of the wind turbines.

(f) **Blade Shear Evaluation Report.**

The applicant or petitioner shall submit a blade shear evaluation report for each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites that shall include:

(1) A detailed description of the conditions at the proposed site and any alternative sites that may cause blade shear from each of the proposed wind turbines and any alternative wind turbines, the methodology used to evaluate and assess the risk of blade shear, and the manufacturer's technical documentation relating to recommended blade shear setback distances and installed blade monitoring devices and sensors.

(2) Calculations in feet of the maximum distance that a blade could be sheared from each of the proposed wind turbines and any alternative wind turbines at the proposed site

and any alternative sites when the wind turbines are stationary and calculations in feet of the maximum distance that a blade could be sheared from each of the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites when the wind turbines are in operation.

(3) A study area map for the proposed site and any alternative sites depicting the blade shear study area radius, site boundaries and locations where a blade could be sheared from each of the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites when the wind turbines are stationary and when the wind turbines are in operation.

(4) Identification of any potential mitigation measures to minimize the risk, occurrence and impact of blade shear from each of the proposed wind turbines and any alternative wind turbines, including automatic and remote manual shutdown of the wind turbines.

(g) **Shadow Flicker Evaluation Report.**

The applicant or petitioner shall submit a shadow flicker evaluation report for each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites that shall include:

(1) A detailed description of the potential shadow-flicker producing features of each of the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites, including, an analysis of conditions that may cause shadow flicker, the methodology used to evaluate shadow flicker and the manufacturer's technical documentation relating to shadow flicker.

(2) Calculations from each proposed wind turbine and any alternative wind turbines at the proposed site and any alternative sites to each off-site occupied structure location within a one-and-a-quarter mile radius, including, the following:

(A) distance in feet;

(B) shadow length and intensity;

(C) shadow flicker frequency;

(D) specific times shadow flicker is predicted to occur; and

(E) duration of shadow flicker measured in total annual hours.

(3) A study area map of the proposed site and any alternative sites depicting the shadow flicker analysis study area radius, site boundaries, locations of the proposed wind turbines and locations of any alternative wind turbines, locations of off-site occupied structures, and areas of shadow flicker occurrence identified according to total annual hours.

(4) Identification of potential mitigation measures to minimize the impact of shadow flicker, including, vegetation, screening and fence construction.

(h) **Natural Resource Impact Evaluation Report.**

The applicant or petitioner shall submit a natural resource impact evaluation report for the proposed site and any alternative sites that includes bird studies, bat studies, wetland studies, and terrestrial and marine wildlife habitat studies, as applicable. The report shall also include:

(1) A detailed description of the potential natural resource impacts as a result of the

construction, operation and maintenance of the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites including an analysis of:

(A) the topography, geology, vegetation, soil types, water resources, and avian, terrestrial and marine wildlife habitat areas, as applicable; and

(B) compliance with air and water quality standards of the Department of Energy and Environmental Protection;

(C) compliance with the United States Fish and Wildlife Service Land-Based Wind Energy Guidelines, as applicable; and

(D) compliance with site-specific recommendations provided by the Department of Energy and Environmental Protection Natural Resources Division.

(2) Calculations based on the studies submitted in accordance with this subsection for the proposed site and any alternative sites that include, but are not limited to:

(A) estimated number of bird fatalities;

(B) estimated number of bat fatalities;

(C) total square feet of permanent wetland impacts;

(D) total square feet of temporary wetland impacts;

(E) total square feet of permanent terrestrial and marine wildlife habitat impacts, as applicable;

(F) total square feet of temporary terrestrial and marine wildlife habitat impacts, as applicable;

(G) total acreage of site disturbance;

(H) total acreage of site restoration;

(I) total volume in cubic yards of cut required; and

(J) total volume in cubic yards of fill required.

(3) A study area map for the proposed site and any alternative sites depicting the natural resource impact analysis study area radius, site boundaries and locations of, as applicable, important bird areas, bat hibernacula, terrestrial and marine wildlife habitat, as applicable, flood zones, wetlands and watercourses, forests, recreational areas, open space and conservation areas.

(4) Identification of potential mitigation measures to minimize natural resource impacts including, recommended protocols for protection of wetlands and wildlife, proposed open space or conservation areas, minimization of tree clearing, erosion and sedimentation controls, soil stabilization, re-vegetation and post-construction monitoring plans for avian, terrestrial and marine wildlife, as applicable.

(5) For wind turbine facilities with a capacity of more than 65 megawatts, the applicant shall submit, as part of the Natural Resource Impact Evaluation Report, a Terrestrial Habitat Conservation plan for land-based wind turbine facilities or a Marine Habitat Conservation Plan for off-shore wind turbine facilities, for the proposed site and any alternative sites. The applicant shall consult with the United States Fish and Wildlife Service and the Department of Energy and Environmental Protection in the development of the Terrestrial or Marine Habitat Conservation Plan.

(i) **Decommissioning Plan.**

Any application for a certificate for a wind turbine facility or petition for a declaratory ruling for a wind turbine facility shall contain a decommissioning plan for the proposed site and any alternative sites that shall include:

(1) the projected useful life of the wind turbines;

(2) identification of any circumstances that would trigger decommissioning of the facility in advance of the projected useful life of the wind turbines;

(3) a description of the method by which foundations, wind turbines, associated equipment and components will be dismantled and removed;

(4) a description of the method by which the site will be restored as near as possible to its original condition, including, stabilization, re-grading and re-vegetation;

(5) an estimate of the total cost of implementing the decommissioning plan calculated by a certified professional engineer based on the projected useful life and the projected salvage value of the facility; and

(6) financial assurance to ensure that sufficient funds are available for decommissioning the facility.

For purposes of this section, financial assurance may include a performance bond, surety bond, letter of credit, corporate guarantee, escrow, deposit, insurance, certificate of deposit, domestic security, trust, any combination of such financial devices, or any other form of financial device that is acceptable to the Council to ensure sufficient funds are available for decommissioning the facility.

(j) **Waivers.**

(1) **Agreements**. Pursuant to Section 16-50o of the Connecticut General Statutes, the applicant or petitioner shall submit any agreements entered into with any abutting property owner of record to waive the requirements under subsections (a) and (c) of section 16-50j-95 of the Regulations of Connecticut State Agencies.

(2) **Requests.** The applicant or petitioner shall submit to the Council any request for a waiver of the requirements under subsections (a) and (c) of section 16-50j-95 of the Regulations of Connecticut State Agencies at the time an application or petition is filed with the Council. If the Council finds good cause for a waiver of the requirements under subsections (a) and (c) of section 16-50j-95 of the Regulations of Connecticut State Agencies during a public hearing, the applicant or petitioner shall provide notice by certified mail to the abutting property owner of record that includes, the following:

(A) notice of the requirements under subsections (a) and (c) of section 16-50j-95 of the Regulations of Connecticut State Agencies;

(B) notice of the criteria considered for a good cause determination to waive the requirements under subsections (a) and (c) of section 16-50j-95 of the Regulations of Connecticut State Agencies;

(C) notice of the wind turbine manufacturer's recommended setback distances; and

(D) notice that the abutting property owner of record is granted a 30-day period of time from the date notice by certified mail is sent to an abutting property owner of record to provide written comments on the proposed waiver of the requirements under subsections (a) and (c) of section 16-50j-95 of the Regulations of Connecticut State Agencies to the Council or to file a request for party or intervenor status with the Council pursuant to Sections 16-50j-13 to 16-50j-17, inclusive, of the Regulations of Connecticut State Agencies.

(Effective May 9, 2014)

Sec. 16-50j-95. Considerations for decision

In making its decision to grant or deny an application for a certificate or to issue or not to issue a petition for a declaratory ruling, the Council shall, consistent with the Uniform Administrative Procedure Act, Chapter 54 of the Connecticut General Statutes, and the Public Utility Environmental Standards Act, Chapter 277a of the Connecticut General Statutes, consider, among other relevant facts and circumstances, the following factors:

(a) **Setback Distances.**

(1) **Requirements.**

(A) Any application for a certificate for a proposed wind turbine facility with a capacity of more than 65 megawatts shall include setback distances from each of the proposed wind turbine locations and any alternative wind turbine locations of not less than 2.5 times the wind turbine height from all property lines at the proposed site and any alternative sites or shall comply with the wind turbine manufacturer's recommended setback distances, whichever is greater. A copy of the wind turbine manufacturer's recommended setback distances shall be included in the application or petition. In its discretion, the Council may require greater setback distances based on the results of any evaluation report submitted under Section 16-50j-94 of the Regulations of Connecticut State Agencies.

(B) Any petition for a declaratory ruling for a proposed wind turbine facility with a capacity of less than 65 megawatts shall include setback distances from each of the proposed wind turbine locations and any alternative wind turbine locations of not less than 1.5 times the wind turbine height from all property lines at the proposed site and any alternative sites or shall comply with the wind turbine manufacturer's recommended setback distances, whichever is greater. A copy of the wind turbine manufacturer's recommended setback distances shall be included in the application or petition. In its discretion, the Council may require greater setback distances based on the results of any evaluation report submitted under Section 16-50j-94 of the Regulations of Connecticut State Agencies.

(2) **Waiver of requirements.** The minimum required setback distances for each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites may be waived, but in no case shall the setback distance from the proposed wind turbines and any alternative wind turbines be less than the manufacturer's recommended setback distances from any occupied residential structure or less than 1.5 times the wind turbine height from any occupied residential structure, whichever is greater:

(A) by submission to the Council of a written agreement between the applicant or petitioner and abutting property owners of record stating that consent is granted to allow reduced setback distances; or

(B) by a vote of two-thirds of the Council members present and voting to waive the minimum required setback distances upon a showing of good cause, which includes consideration of:

(i) land uses and land use restrictions on abutting parcels;

(ii) public health and safety;

(iii) public benefit and reliability;

(iv) environmental impacts;

(v) policies of the state; and

(vi) wind turbine design and technology.

(b) **Noise.**

Noise levels generated by the operation of each of the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites shall comply with the Department of Energy and Environmental Protection Noise Control Regulations under Sections 22a-69-1 to 22a-69-7, inclusive, of the Regulations of Connecticut State Agencies.

(c) **Shadow Flicker.**

(1) **Requirements.** Shadow flicker shall not occur more than 30 total annual hours cumulative at any off-site occupied structure location from each of the proposed wind turbine locations and any alternative wind turbine locations at the proposed site and any alternative sites.

(2) **Waiver of Requirements.** The maximum total annual hours of shadow flicker generated by the operation of each of the proposed wind turbines and any alternative wind turbines at the proposed site and any alternative sites may be waived:

(A) by submission to the Council of a written agreement between the applicant or petitioner and property owners of record stating that consent is granted to allow excess total annual hours of shadow flicker; or

(B) by a vote of two-thirds of the Council members present and voting to waive the total annual hours of shadow flicker requirements upon a showing of good cause, which includes consideration of:

(i) land uses and land use restrictions on abutting parcels;

(ii) public health and safety;

(iii) public benefit and reliability;

(iv) environmental impacts;

(v) policies of the state; and

(vi) wind turbine design and technology.

(Effective May 9, 2014)

Sec. 16-50j-96. Requirement for a Development and Management (D&M) Plan

The Council shall require the preparation of a full or partial D&M Plan for a proposed wind turbine facility or modification of an existing wind turbine facility. The full or partial D&M Plan shall be prepared in accordance with the final decision rendered by the Council and in accordance with Sections 16-50j-60 to 16-50j-62, inclusive, of the Regulations of Connecticut State Agencies.

(Effective May 9, 2014)

epilepsy society

Wind Turbines And Photosensitive Epilepsy

Some people worry about the possibility of wind turbines triggering epileptic seizures in people with photosensitive epilepsy. Photosensitive epilepsy affects up to 3% of people with epilepsy and is triggered by flashing lights or certain patterns.

Under certain conditions a wind turbine's rotating blades cast a shadow from the sun, having the effect of 'shadow flicker'. Studies show that for this to be a potential problem for people with photosensitive epilepsy, a number of factors need to happen at the same time:

- The turbine blades would need to rotate at speeds faster than 3 hertz (flashes per second). Turbines on commercial wind farms rotate at speeds under 2 hertz. Smaller, private turbines can rotate faster as they are not subject to the same regulations on rotation speed.
- The sun would need to be bright enough, and in just the right position and angle from the horizon in relation to the turbine, to cast shadows of enough intensity and length. The weather and atmospheric conditions in the UK for most of the year reduce this possibility down greatly.
- The person with photosensitive epilepsy would need to be within a certain distance from the turbine. Regulations for commercial wind farms include placing wind farms at enough distance from private dwellings for it not to affect people in their houses.
- The person would need to be looking at the turbine, with the sun behind the turbine. As most people will avoid looking directly at the sun, this further reduces the risk.

Reducing the risk of photosensitive triggers

If someone with photosensitive epilepsy finds themselves facing any photosensitive trigger, covering one eye with their hand immediately reduces the risk, as the photosensitive effect relies on both eyes receiving the same trigger. Closing their eyes would not stop a photosensitive effect and may even worsen the effect.   If you have had a seizure directly triggered by shadow flicker from wind turbines, and you'd like to tell us about it, we would like to hear from you. Please contact us via our online form or call our helpline.

Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen

Länderausschuss für Immissionsschutz

Stand: 13.03.2002

Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen
(WEA-Schattenwurf-Hinweise)

0. Vorbemerkung

Im Rahmen der zur Verfügung stehenden erschöpflichen Ressourcen hat die alternative/regenerative Energieerzeugung einen hohen Stellenwert, hier insbesondere die Nutzung der Windenergie. Moderne Windenergieanlagen (WEA) haben kaum noch etwas mit den "Windmühlen" früherer Generationen gemeinsam, werfen aber durch ihre Anzahl, Größe und Erscheinungsbilder bisher nicht gekannte Probleme aufgrund der Belästigungen durch Lärm und optische Effekte auf.
Hinsichtlich der Lärmeinwirkungen bestehen Regelungen, die insoweit betroffenen Nachbarn entsprechenden Schutz bieten. Für die Beurteilung der Einwirkung durch Lichtblitze und bewegten, periodischen Schattenwurf durch den Rotor einer WEA hat der Gesetzgeber bisher keine rechtsverbindlichen Vorschriften mit Grenz- oder Richtwerten erlassen oder in Aussicht gestellt.

Wissenschaftliche Untersuchungen belegen die Erfahrung, dass optische Immissionen insbesondere in Form periodischen Schattenwurfs zu erheblichen Belästigungswirkungen (Stressor) führen können. Unter Berücksichtigung dieser Untersuchungen und Anhörungen von Gutachtern sollen diese Hinweise eine einheitliche und praxisnahe Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen ermöglichen.

1. Allgemeines

1.1 Anwendungsbereich und immissionsschutzrechtliche Grundsätze

Die Hinweise finden Anwendung bei der Beurteilung der optischen Wirkungen von WEA auf den Menschen. Sie umfassen sowohl den durch den WEA-Rotor verursachten periodischen Schattenwurf als auch die Lichtreflexe („Disco-Effekt“) und sind Immissionen im Sinne des Bundes-Immissionsschutzgesetzes (BImSchG) [1]. Nicht als Immission gilt jedoch die sonstige Wirkung einer WEA aufgrund der Eigenart der Rotorbewegung, die ein zwanghaftes Anziehen der Aufmerksamkeit mit entsprechenden Irritationen bewirken kann.

Die Hinweise enthalten Beurteilungsmaßstäbe zur Konkretisierung der Anforderungen aus § 5 Abs. 1 Nrn. 1 und 2 und § 22 Abs. 1 des Bundes-Immissionsschutzgesetzes (BImSchG).

Als Gegenstand von Anordnungen kommen technische Maßnahmen sowie zeitliche Beschränkungen des Betriebes der WEA in Betracht. Eine Stilllegung kommt nur in Betracht, wenn ihr Betrieb zu Gefahren für Leben, Gesundheit oder bedeutende Sachwerte führt. Für optische Immissionen bei WEA dürfte dieses in der Regel nicht gegeben sein.

1.2 Begriffsbestimmungen

Lichtblitze (Disco-Effekte) sind periodische Reflexionen des Sonnenlichtes an den Rotorblättern.
Sie sind abhängig vom Glanzgrad der Rotoroberfläche und vom Reflexionsvermögen der gewählten Farbe.

Kernschatten ist vom Immissionsort aus betrachtet die vollständige Verdeckung der Sonne durch das Rotorblatt.

Halbschatten ist vom Immissionsort aus betrachtet die nicht vollständige Verdekkung der Sonne durch das Rotorblatt.

Periodischer Schattenwurf ist die wiederkehrende Verschattung des direkten Sonnenlichtes durch die Rotorblätter einer Windenergieanlage. Der Schattenwurf ist dabei abhängig von den Wetterbedingungen, der Windrichtung, dem Sonnenstand und den Betriebszeiten der Anlage. Vom menschlichen Auge werden Helligkeitsunterschiede größer als 2,5 % wahrgenommen [3].

Beschattungsbereich ist die Fläche, in der periodischer Schattenwurf auftritt.

Astronomisch maximal mögliche Beschattungsdauer (worst case) ist die Zeit, bei der die Sonne theoretisch während der gesamten Zeit zwischen Sonnenauf- und Sonnenuntergang durchgehend bei wolkenlosem Himmel scheint, die Rotorfläche senkrecht zur Sonneneinstrahlung steht und die Windenergieanlage in Betrieb ist.

Tatsächliche Beschattungsdauer ist die vor Ort real ermittelte und aufsummierte Einwirkzeit an periodischem Schattenwurf. Beträgt die Bestrahlungsstärke der direkten Sonneneinstrahlung auf der zur Einfallsrichtung normalen Ebene mehr als 120 W/m^2, so ist Sonnenschein mit Schattenwurf anzunehmen. Die Umrechnung in die Beleuchtungsstärke ist im Anhang aufgeführt.

Meteorologisch wahrscheinliche Beschattungsdauer ist die Zeit, für die der Schattenwurf unter Berücksichtigung der üblichen Witterungsbedingungen berechnet wird. Als Grundlage dienen die langfristigen Messreihen des Deutschen Wetterdienstes (DWD).

Maßgebliche Immissionsorte sind
a) schutzwürdige Räume, die als
   - Wohnräume, einschließlich Wohndielen
   - Schlafräume, einschließlich Übernachtungsräume in Beherbergungsstätten und Bettenräume in Krankenhäusern und Sanatorien
   - Unterrichtsräume in Schulen, Hochschulen und ähnlichen Einrichtungen
   - Büroräume, Praxisräume, Arbeitsräume, Schulungsräume und ähnliche Arbeitsräume genutzt werden.

   Direkt an Gebäuden beginnende Außenflächen (z. B. Terrassen und Balkone) sind schutzwürdigen Räumen tagsüber zwischen 6:00 - 22:00 Uhr gleichgestellt.

b) unbebaute Flächen in einer Bezugshöhe von 2 m über Grund an dem am stärksten betroffenen Rand der Flächen, auf denen nach Bau- oder Planungsrecht Gebäude mit schutzwürdigen Räumen zulässig sind.

1.3 Grundlagen der Ermittlung und Bewertung von Immissionen durch periodischen Schattenwurf

Ziel ist die sichere Vermeidung erheblicher Belästigungen, die durch periodische Lichteinwirkungen (optische Immissionen) durch WEA entstehen können. Die Erheblichkeit einer Belästigung hängt nicht nur von deren Intensität ab, sondern auch wesentlich von der Nutzung des Gebietes, auf das sie einwirkt, von der Art der Einwirkungen sowie der Zeitdauer der Einwirkungen. Bei der Beurteilung sind **alle WEA im Umkreis** einzubeziehen, die auf den jeweiligen Immissionspunkt einwirken. Einwirkungen durch periodischen Schattenwurf können dann sicher ausgeschlossen werden, wenn alle in Frage kommenden Immissionsorte in der Anlagenumgebung außerhalb des möglichen Beschattungsbereiches der jeweiligen WEA liegen.
Der zu prüfende Bereich ergibt sich aus dem Abstand zur WEA, in welchem die Sonnenfläche gerade zu 20 % durch ein Rotorblatt verdeckt wird. Da die Blatttiefe nicht über den gesamten Flügel konstant ist, sondern zur Rotorblattspitze hin abnimmt, ist ersatzweise ein rechteckiges Rotorblatt mit einer mittleren Blatttiefe zu ermitteln und zugrunde zu legen:
(Mittlere Blatttiefe = 1/2 (max. Blatttiefe + min. Blatttiefe bei 0,9 * Rotorradius)) [7].
Der Beschattungsbereich kann für eine einzelne Anlage konservativ der Abbildung im Anhang entnommen werden oder ansonsten im konkreten Einzelfall nachgewiesen werden. Darüber hinaus kann der Beschattungsbereich nach Freund [3] bestimmt werden.
Soweit mehrere WEA zu Immissionsbeiträgen führen können, gelten die Ausführungen für jede Einzelanlage. Höhendifferenzen im Gelände zwischen Standort der WEA und dem Immissionsort (z. B. bei Aufstellung einer WEA auf einem Hügel) sind zu berücksichtigen.
Eine Differenzierung in Kern- oder Halbschatten ist für die Belästigung **nicht bedeutsam.**

Soweit sich zu berücksichtigende Immissionsorte innerhalb des Beschattungsbereiches von WEA befinden, muss mit zeitweilig auftretenden wiederkehrenden Belästigungswirkungen gerechnet werden.

Von Relevanz sind die an einem Immissionsort tatsächlich auftretenden bzw. wahrnehmbaren Immissionen, die nur bei bestimmten Wetterbedingungen auftreten können. Eine Einwirkung durch zu erwartenden periodischen Schattenwurf wird als nicht erheblich belästigend angesehen, wenn die **astronomisch maximal mögliche Beschattungsdauer** [8] [9] unter kumulativer Berücksichtigung aller WEA-Beiträge am jeweiligen Immissionsort in einer Bezugshöhe von 2 m über Erdboden nicht mehr als **30 Stunden pro Kalenderjahr und darüber hinaus nicht mehr als 30 Minuten pro Kalendertag** beträgt. Bei der Beurteilung des Belästigungsgrades wurde eine durchschnittlich empfindliche Person als Maßstab zugrunde gelegt.

Bei Überschreitung der Werte für die **astronomisch maximal mögliche Beschattungsdauer** kommen unter anderem technische Maßnahmen zur zeitlichen Beschränkung des Betriebes der WEA in Betracht. Eine wichtige technische Maßnahme stellt als Gegenstand von Auflagen und Anordnungen die Installierung einer Abschaltautomatik dar, die mittels Strahlungs- oder Beleuchtungsstärkesensoren die konkrete meteorologische Beschattungssituation erfasst und somit die vor Ort konkret vorhandene Beschattungsdauer begrenzt. Da der Wert von 30 Stunden pro Kalenderjahr auf Grundlage der astronomisch möglichen Beschattung entwickelt wurde, wird für Abschaltautomatiken ein entsprechender Wert für die tatsächliche, reale Schattendauer, die **meteorologische Beschattungsdauer** festgelegt. Dieser Wert liegt auf Grundlage von [2] bei 8 Stunden pro Kalenderjahr.

2. Vorhersage des periodischen Schattenwurfs

Aus Gründen der Vergleichbarkeit und Nachvollziehbarkeit ist bei der Erstellung von Immissionsprognosen von folgenden Vereinfachungen und Annahmen auszugehen: Die Sonne ist als punktförmige Quelle anzunehmen und scheint tagsüber an allen Tagen des Jahres. Es herrscht wolkenloser Himmel und für die Bewegung des Rotors ausreichender Wind (100 % Verfügbarkeit). Die Windrichtung entspricht dem Azimutwinkel der Sonne, die Rotorkreisfläche steht dann senkrecht zur Einfallsrichtung der direkten Sonneneinstrahlung. Den Berechnungen wird geographisch Nord zugrunde gelegt. Abstände zwischen Rotorebene und Turmachse sind zu vernachlässigen. Die Lichtbrechung in der Atmosphäre (Refraktion) wird nicht berücksichtigt.

Der Schattenwurf für Sonnenstände unter 3° Erhöhung über Horizont kann wegen Bewuchs, Bebauung und der zu durchdringenden Atmosphärenschichten in ebenem Gelände vernachlässigt werden. Zur genaueren Ermittlung der astronomisch maximal möglichen Beschattungsdauer sollte von der effektiven Schatten werfenden Zone einer WEA ausgegangen werden. Diese Größe ergibt sich unter Einbeziehung der Strahlungsdiffusion in der Atmosphäre [12].
Für das Summieren der Jahresstunden ist das Kalenderjahr mit 365 Tagen und für das Summieren der täglichen Schattenzeiten der 24-Stunden-Tag zugrunde zu legen.

Dauerhafte natürliche und künstliche lichtundurchlässige Hindernisse, die den periodischen Schattenwurf von WEA begrenzen, können berücksichtigt werden.

In der abschließenden Zusammenfassung ist die astronomisch maximal mögliche Beschattungsdauer anzugeben.

3. Beurteilung

Eine erhebliche Belästigung durch periodischen Schattenwurf liegt dann nicht vor, wenn sowohl die Immissionsrichtwerte für die tägliche als auch die jährliche Beschattungsdauer durch alle auf den maßgeblichen Immissionsort einwirkenden Windenergieanlagen unterschritten werden.

3.1 Immissionsrichtwerte für die jährliche Beschattungsdauer

Bei der Genehmigung von Windenergieanlagen ist sicherzustellen, dass der Immissionsrichtwert für die astronomisch maximal mögliche Beschattungsdauer von **30 Stunden pro Kalenderjahr** nicht überschritten wird. Bei Beschwerden hinsichtlich

des Schattenwurfs durch bereits bestehende Anlagen ist die Einhaltung dieses Immissionsrichtwertes zu überprüfen.
Bei Überschreitungen ist durch geeignete Maßnahmen (siehe 4.1) die Einhaltung der Immissionsschutzanforderungen dieser Hinweise zu gewährleisten. Bei Einsatz einer Abschaltautomatik, die keine meteorologischen Parameter berücksichtigt, ist durch diese auf die astronomisch maximal mögliche Beschattungsdauer von 30 Stunden pro Kalenderjahr zu begrenzen. Wird eine Abschaltautomatik eingesetzt, die meteorologische Parameter berücksichtigt (z. B. Intensität des Sonnenlichtes), ist auf die tatsächliche Beschattungsdauer von 8 Stunden zu begrenzen.

3.2 Immissionsrichtwert für die tägliche Beschattungsdauer

Der Immissionsrichtwert für die tägliche Beschattungsdauer beträgt **30 Minuten**.

In der Laborstudie der Universität Kiel [9] wurde festgestellt, dass bereits eine einmalige Einwirkung des Schattenwurfs von 60 Minuten zu Stressreaktionen führen kann. Aus Vorsorgegründen wird daher die tägliche Beschattungsdauer auf **30 Minuten** begrenzt.

Dieser Wert gilt bei geplanten Anlagen für die **astronomisch maximal mögliche Beschattungsdauer**, bei bestehenden Anlagen für die tatsächliche Schattendauer. Bei Überschreitung dieses Richtwertes an mindestens drei Tagen ist durch geeignete Maßnahmen die Begrenzung der täglichen Beschattungsdauer auf 30 Minuten zu gewährleisten.

4. Auflagen und Minderungsmaßnahmen

4.1 Schattenwurf

Bei der Wahl von WEA-Standorten bestimmt sich das Maß der Vorsorgepflicht hinsichtlich der erreichbaren Immissionsminderung gegen Beschattung an maßgeblichen Immissionsorten einzelfallbezogen unter Berücksichtigung der Verhältnismäßigkeit und den Anforderungen der Landes-/Bauleitplanung.
Überschreitet eine WEA die zulässigen Immissionsrichtwerte gemäß 3, so ist eine Immissionsminderung durchzuführen, die die überprüfbare Einhaltung der Immissionsrichtwerte zum Ziel hat. Diese Minderung erfolgt durch die gezielte Anlagenabschaltung für Zeiten real auftretenden oder astronomisch möglichen Schattenwurfs an den betreffenden Immissionsorten. Bei der Festlegung der genauen Abschaltzeiten ist die räumliche Ausdehnung am Immissionsort (z. B. Fenster- oder Balkonfläche) zu berücksichtigen. Bei Innenräumen ist die Bezugshöhe die Fenstermitte. Bei Außenflächen beträgt die Bezugshöhe 2 m über Boden.
Die ermittelten Daten zur Sonnenscheindauer und Abschaltzeit sollen von der Steuereinheit über mindestens ein Jahr dokumentiert werden; entsprechende Protokolle sollen auf Verlangen von der zuständigen Behörde einsehbar sein. Im Falle mehrerer beitragender WEA ist eine Aufteilung der Immissionsbeiträge für den jeweiligen Immissionsort möglich.

4.2 Lichtblitze

Störenden Lichtblitzen soll durch Verwendung mittelreflektierender Farben, z. B. RAL 7035-HR [6], und matter Glanzgrade gemäß DIN 67530/ISO 2813-1978 [5] bei der Rotorbeschichtung vorgebeugt werden. Hierdurch werden die Intensität möglicher Lichtreflexe und verursachte Belästigungswirkungen (Disco-Effekt) minimiert. Lichtblitze aufgrund von Nässe oder Vereisung werden nicht berücksichtigt.

Anhang

Berechnungsverfahren

Der Nachweis, dass eine bestimmte WEA keine schädlichen Umwelteinwirkungen durch periodischen Schattenwurf verursacht, stützt sich im Rahmen von Planungsvorhaben und Anlagenüberwachung auf eine Schattenwurfprognose. Dies gilt ebenso für die Ermittlung ggf. erforderlicher Abschaltzeiten von WEA.
Eine Schattenwurfprognose gründet sich auf einem Algorithmus zur Berechnung des standort-, tages- und uhrzeitabhängigen Sonnenstandes. Zur Gewährleistung einer einheitlichen Durchführung und vereinfachter Überprüfbarkeit wird der Bezug auf die normierten und allgemein zugänglichen Berechnungsmodelle [10] bzw. [11] empfohlen.
Die Grundgenauigkeit der in eine Prognose eingehenden geometrischen Parameter sollte ± 3 ..... 10 m.... betragen. Die Bestimmung der Schattenwurfzeiten soll an einer Genauigkeit von 1 min pro Tag orientiert sein. Absolute Zeitangaben sollen in MEZ bzw. MESZ erfolgen.
Die möglichen Beschattungszeiten an allen relevanten Immissionsorten sollen in der Schattenwurfprognose tageweise mit Anfangs-, Endzeitpunkt und Beschattungsdauer ausgewiesen sein; im Falle mehrerer WEA sollen die Beiträge der Anlagen einzeln und tageweise aufsummiert entnehmbar sein. Pro Immissionsort ist die aufsummierte Jahresbeschattungsdauer anzugeben.
Bestandteil einer Schattenwurfprognose sind weiterhin Auszüge aus topografischen Karten, die Anlagenstandorte und Immissionsorte unter Angabe ihrer Gauß-Krüger-Koordinaten mit Höhenangaben wiedergeben. Als Ergebnis können auch berechnete Iso-Schattenlinien (Kurven gleicher Jahresbeschattungsdauer - insbesondere 30 h Iso-Schattenlinie - in der Anlagenumgebung) ausgewiesen werden.

Software

Aufgrund des relativ großen Berechnungsaufwandes und der guten Berechnungsmöglichkeiten mit Hilfe von Computerprogrammen empfiehlt sich der Einsatz geeigneter Software. Hierzu kann auf kommerzielle Programme zurückgegriffen werden.
Eine Prognose mit Hilfe geeigneter Tabellendaten ist ebenfalls möglich.
Verwendete Arbeitshilfen sollen die Anforderungen dieser Hinweise, z. B. bzgl. der Berechnungsverfahren, berücksichtigen.

Arbeitshilfen

Tatsächliche Beschattungsdauer: Sonnenstand und Beleuchtungsstärke

Die resultierende Beleuchtungsstärke E [lx] in einer horizontalen Messfläche hängt vom Einfallswinkel (Sonnenstand) [°] sowie dem fotometrischen Strahlungsäquivalent [lx/Wm^{-2}] ab, das von der Lichtbrechung (Refraktion) und der Lufttrübung bestimmt wird und ebenfalls vom Sonnenstand abhängt.
Vom deutschen Wetterdienst werden folgende Eckdaten für die Beleuchtungsstärke angenommen:

Sonnenstand [°]	Beleuchtungsstärke [lx]	Strahlungsäquivalent [lx/Wm^{-2}]
3	389	62
60	10.912	105

In erster Näherung ergeben sich daraus folgende Beleuchtungsstärken in Abhängigkeit vom Sonnenstand:

Sonnenstand [°]	Beleuchtungsstärke [lx]
3	389
5	664
10	1402
15	2207
20	3071
25	3986
30	4942
35	5929
40	6935
45	7949
50	8959
55	9951
60	10912

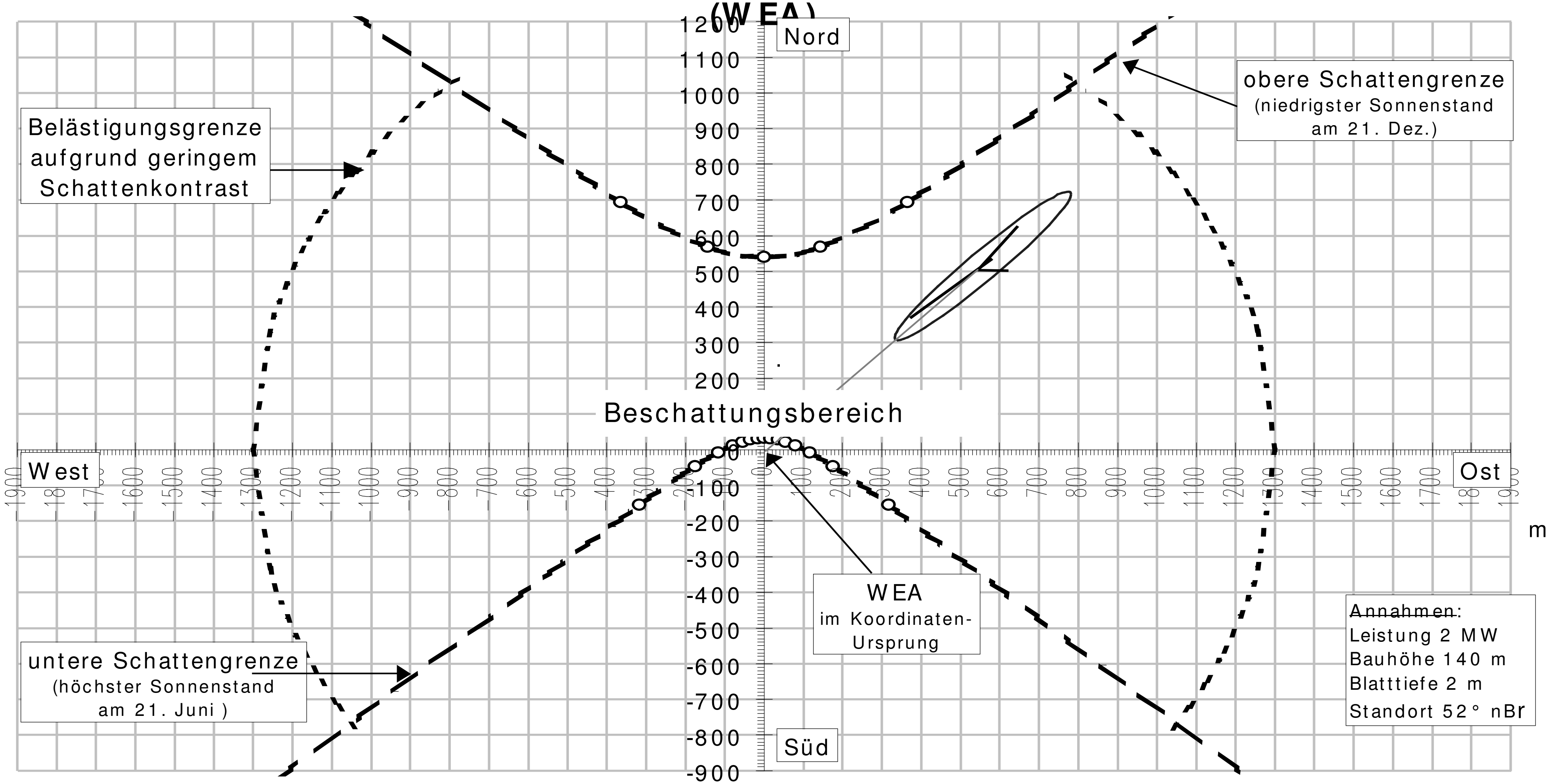
Für das Addieren der Jahresstunden ist das Kalenderjahr mit 365 Tagen und für das Addieren der täglichen Schattenzeiten der 24-Stunden-Tag zugrunde zu legen.

Sonnenauf- und –untergangszeiten [h:min; h:min]

	Berlin	Essen	Hannover	Karlsruhe	München	Schleswig	Schwerin
1. Jan	8:17;16:03	8:37;16:34	8:32;16:18	8:21;16:40	8:04;16:31	8:44;16:07	8:32;16:05
1. Apr	5:41;18:41	6:08;19:07	5:56;18:56	6:04;18:59	5:52;18:44	5:54;18:58	5:48;18:50
1. Jul	3:48;20:32	4:20;20:52	4:03;20:47	4:26;20:34	4:18;20:17	3:51;21:00	3:49;20:47
1. Okt	6:07;17:44	6:33;18:10	6:22;17:59	6:26;18:06	6:13;17:53	6:24;17:58	6:16;17:51

Quelle: DWD/BSH2001

Abb.: Möglicher Beschattungsbereich einer großen Windenergieanlage (WEA)



Beschattungsdauer im Umfeld einer Windenergieanlage – Musterdaten

Koordinaten des Bezugsstandortes der WEA in ebenem Gelände:
Geographisch: 52° 00´ 00´´N 10° 00´ 00´´E (Mitte Deutschlands)
Gauß-Krüger (Bessel): 2 637 333 | 5 764 640
Bezugshöhe 2 m über Grund; horizontaler Rezeptor 0,1 x 0,1 m^2

Lfd Nr.	Nabenhöhe [m]	Rotordurchmesser [m]	Azimut von Nord über Ost [°]	Entfernung WEA-Immissionsort [m]	Stunden/Jahr	Tage/ Jahr	Minuten/Tag
1	60	40	0°	150	90	124	60
2			40°	300	25	62	32
3			120°	450	15	49	22
4	90	60	0°	250	83	111	56
5			40°	400	28	61	36
6			120°	650	14	46	22
7	100	80	0°	300	98	108	62
8			40°	500	37	76	38
9			120°	750	20	54	26

Aufgrund der Symmetrie des Beschattungsbereiches, korrespondierend mit dem tagesbezogenen (scheinbaren) Sonnenlauf, sind für spiegelbildlich zur Nord-Süd-Achse gelegene Immissionspunkte gleichartige Immissionen zu erwarten. Bei Überlagerung der Immissionen durch mehrere WEA beträgt die Gesamt-Beschattungsdauer an einem Immissionsort maximal gleich die Summe der Beschattungsdauern durch die einzelnen immissionsbeitragenden WEA.

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Exhibit A7-6

Epilepsia, 49(6):1095–1098, 2008
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BRIEF COMMUNICATION

Wind turbines, flicker, and photosensitive epilepsy: Characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them

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Summary
Wind turbines are known to produce shadow flicker by interruption of sunlight by the turbine blades. Known parameters of the seizure provoking effect of flicker, i.e., contrast, frequency, mark-space ratio, retinal area stimulated and percentage of visual cortex involved were applied to wind turbine features. The proportion of patients affected by viewing wind turbines expressed as distance in multiples of the hub height of the turbine showed that seizure risk does not decrease significantly until the distance exceeds 100 times the hub height. Since risk does not diminish with viewing distance, flash frequency is therefore the critical factor and should be kept to a maximum of three per second, i.e., sixty revolutions per minute for a three-bladed turbine. On wind farms the shadows cast by one turbine on another should not be viewable by the public if the cumulative flash rate exceeds three per second. Turbine blades should not be reflective.
KEY WORDS: Photosensitive epilepsy, Flicker, Rotors, Visual discomfort, Wind farms, Wind turbines, Green power.

The provision of energy from renewable sources has produced a proliferation of wind turbines. Environmental impacts include safety, visual acceptability, electromagnetic interference, noise nuisance and visual interference or flicker. Wind turbines are large structures and can cast long shadows. Rotating blades interrupt the sunlight producing unavoidable flicker bright enough to pass through closed eyelids, and moving shadows cast by the blades on windows can affect illumination inside buildings.

Planning permission for wind farms often consider flicker, but guidelines relate to annoyance and are based on physical or engineering considerations rather than the danger to people who may be photosensitive.

Photosensitive Epilepsy

Photosensitive epilepsy (PSE) occurs in one in 4,000 of the population (Harding & Jeavons, 1994). The incidence is 1:1 per 100,000 per annum. Among 7–19 year-olds the incidence is more than five times greater (Fish et al., 1993). Photosensitivity persists in 75% of patients (Harding et al., 1997).

Precipitants

Sunlight is a precipitant of photosensitive seizures, whether reflected from waves, or interrupted as the subject travels past an avenue of trees or railings. In 454 patients Harding & Jeavons (1994) found 33 cases where seizures had been precipitated by flickering sunlight.

Television is a common precipitant of seizures and guidelines now prevent the broadcast of programs with flicker at rates exceeding 3 flashes per second, the frequency above which the chance of seizures is unacceptably high.

Flicker from Rotating Blades

The interruption of light by helicopter blades has caused seizures (Johnson, 1963; Gastaut & Tassinari, 1966; Cushman & Floccare, 2007) but to our knowledge there are no reports of seizures induced by rotating ceiling fans.

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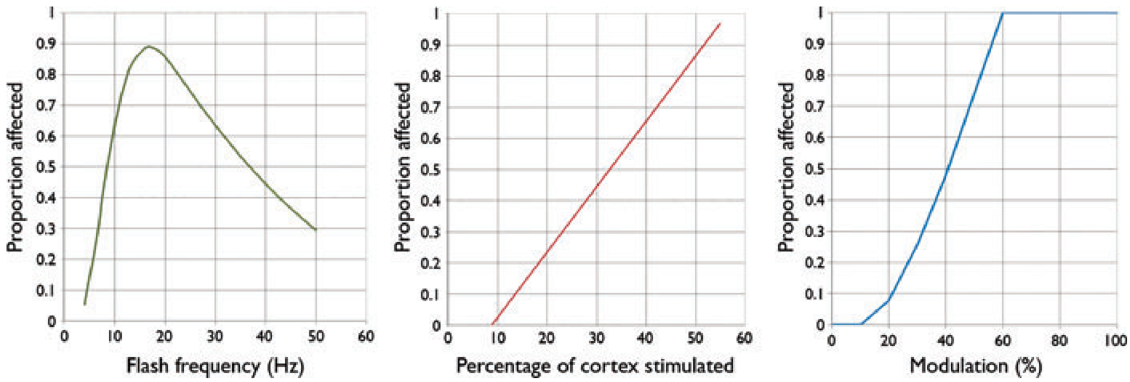

Figure 1.
Proportion of patients with photosensitive epilepsy sensitive to flicker, shown as a function of the frequency, the proportion of the cortex to which the flicker projects (estimated from the response to striped patterns, and the modulation depth of the flicker (expressed as a Michelson fraction). The data are taken from Binnie et al. (2002). *Epilepsia* © ILAE

Large wind turbines usually rotate at between 30 and 60 revolutions per minute (rpm). Many are three-bladed and operate at a constant speed, and at 60 rpm produce flicker at a rate of 3 Hz; some two bladed wind turbines also exist. Turbines that rotate faster or have more blades will produce flicker at frequencies for which the chances of seizures are unacceptably high. Smaller variable-speed turbines range between 30 and 300 rpm (Verkuijlen & Westra, 1984) and some have more than three blades, so their flicker is within the range for which seizures are likely.

When several turbines are in line with the sun's shadow there is flicker from a combination of blades from different turbines, which can have a higher frequency than from a single turbine.

If the blades of a turbine are reflective then there is the possibility of flicker from reflected light at viewing positions that are unaffected by shadows.

Exposure to flicker from a turbine is determined by the hub height and the diameter of the blades, the height of the sun and the direction of the blades relative to the observer. These variables are affected by the time of day, time of year, wind direction, and geographical location (Verkuijlen & Westra, 1984). Shadows can be cast on the windows of nearby buildings, affecting the internal illumination giving rise to flicker that cannot be avoided by occupants. Verkuijlen & Westra determined the shadow tracks of wind turbines and their effect relative to the hub height of the rotor. They assumed that the rotor diameter was 75% of the hub height, but many wind turbines deviate from this ratio.

To avoid the problems of shadow flicker Verkuijlen and Westra proposed that wind turbines should only be installed if flicker frequency remains below 2.5 Hz under all conditions, and that wind turbines should be sited where buildings were not in East-NE or WNW directions from the turbine (northern hemisphere recommendations).

Two examples of seizures induced by wind turbines on small wind turbine farms in the UK have been reported to the authors in 2007.

The seizure-provoking effects of flicker depend on the time-averaged luminance of the flicker, its contrast, frequency and mark-space fraction and the area of retina stimulated, and are well described (Fig. 1).

The area of retina stimulated by flicker from a wind turbine might be expected to depend on the area that the rotors subtend at the eye. However, if the rotors interrupt direct sunlight casting a shadow upon the observer then the luminance of the flicker is likely to be such as to scatter sufficient light within the eye as to stimulate the entire retina with intermittent light. If the eyes are closed, the light is diffused by the eyelids, and intermittent light reaches the entire retina.

The luminance contrast ratio of the flicker depends on the extent to which the blades occlude the sun. Given that the sun subtends about 0.5 degrees, it is only completely occluded when the blades subtend more than 0.5 degrees at the eye, ignoring flare. When the observer is at a distance at which the blades subtend less than 0.5 degrees, the contrast of the flicker is reduced. Flicker ceases to be provocative at luminance contrasts less than about 10%, see Fig. 1. Assuming that contrasts of less than 10% occur when the width of the turbine blade subtends at the eye an angle that is 10% of the sun's diameter (0.05 degrees), it is possible to set a limit for the distance at which shadow flicker is likely to be seizure provoking. For a turbine blade 1 m in width, this distance is 1.14 km. Most shadows are likely to be of contrast sufficient to be provocative. It may be insufficient to restrict the siting of turbines to a distance 10 diameters from habitation (Clarke).

In EEG laboratories, epileptiform EEG activity is induced in photosensitive individuals by a xenon gas discharge lamp providing a series of very brief flashes, i.e., laboratory studies have not investigated the effect of very brief dark periods in an otherwise bright stimulus (such as might be provided by a wind turbine rotor). However, in the case of a seizure induced by helicopter blades reported by Cushman and Floccare (2007) the dark period of the shadow flicker was between 24 and 27 times per second. Helicopter blades are usually narrower than those on wind turbines and would provide for a shorter dark interval that might be expected to be less provocative than for a wind turbine blade.

Flashing can occur by the reflection of sunlight from the gloss surface of blades (Clarke). The blades are likely to cause flicker only if the amount of sun reflected toward an observer varies with the rotation of the blades. Given the shape of the blades, such variation is likely. These considerations introduce the possibility of a danger zone different from that provided by the shadow cast by the blades.

In the case of reflected sunlight, the flicker may be less bright than that cast by a shadow, and the light scattered within the eye may be insufficient to cause a problem. If so, the effectiveness of the stimulus will depend on the visual angle subtended by the rotor at the observer's eye. This visual angle will be directly proportional to the rotor length (radius) and the distance from which the observer is viewing the rotor.

The visual angle subtended by the flickering light determines the likelihood of seizures. From the studies of Binnie et al. (2002) or Wilkins et al. (2005) it is clear that the risk of seizures is in direct proportion to the area of visual cortex stimulated, see Fig. 1. For this reason, flicker that is directed at the center of the visual field is more provocative than flicker in the visual periphery. (The central 10 degrees of vision provide for 90%of the neural output from the retina to the brain.)

Suppose a turbine with blades 75% of hub height is viewed from a distance (Fig. 2). The sunlight is not simultaneously reflected from more than one blade given that the angle of the blades relative to the sun will rarely be similar. We will assume that the blades are of uniform width equal to 10% of their (radial) length. The angle at the eye of an observer subtended by any blade is maximum when the blade is at the bottom of its path. Assuming gaze is centered half way up the blade, the proportionate area of the visual cortex stimulated can be calculated (Drasdo, 1977). The proportion of visual cortex (P) to which a circular centrally fixated stimulus, angular radius A, projects is $P = 1 - e^{-0.0574A}$.

Applying this formula to angular segments of the rotor surface centrally fixated, the area of cortex to which the rotor projects can be calculated and the proportion of patients

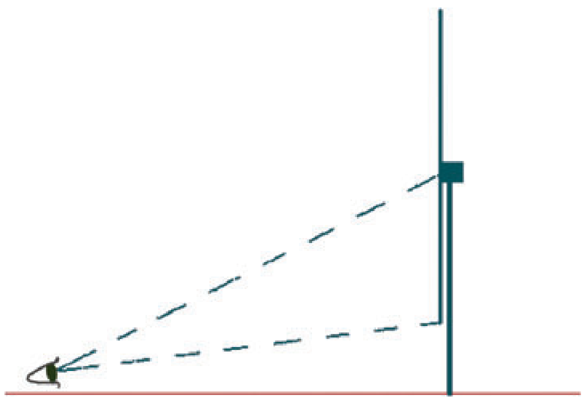

Figure 2.
Maximum visual angle is subtended by blades when at the bottom of their path.
Epilepsia © ILAE

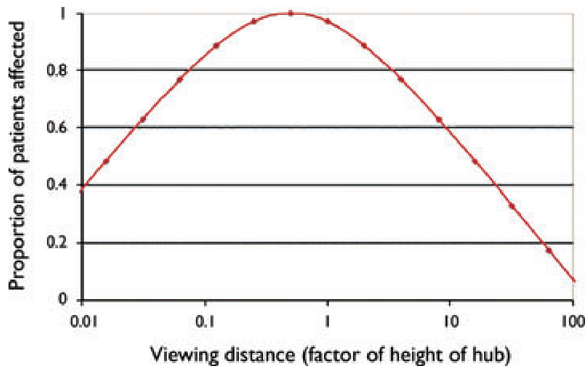

Figure 3.
Proportion of photosensitive patients liable to seizures from light reflected from a turbine blade shown as a function of viewing distance. The viewing distance is given as a factor of the height of the hub.
Epilepsia © ILAE

liable to seizures can be estimated, using the relationship between proportion affected and stimulated area of the cortex (Fig. 1). The proportion of patients affected is shown as a function of viewing distance (expressed as a factor of the height of the hub) (Fig. 3). Note that the risk of seizures does not decrease appreciably until the viewing distance exceeds 100 times the height of the hub, a distance typically more than 4 km.

The above analyses indicate that flicker from wind turbines is potentially a problem at considerable observation distances. Over 1 km, 25% of the light should be attenuated by the atmosphere (Curcio et al., 1953). Such attenuation should reduce the risk by a similar proportion (Binnie et al., 2003).

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Discussion

Flicker from turbines that interrupt or reflect sunlight at frequencies greater than 3 Hz poses a potential risk of inducing photosensitive seizures. At 3 Hz and below the cumulative risk of inducing a seizure should be 1.7 per 100,000 of the photosensitive population. The risk is maintained over considerable distances from the turbine. It is therefore important to keep rotation speeds to a minimum, and in the case of turbines with three blades ensure that the maximum speed of rotation does not exceed 60 rpm, which is normal practice for large wind farms. The layout of wind farms should ensure that shadows cast by one turbine upon another should not be readily visible to the general public. The shadows should not fall upon the windows of nearby buildings. The specular reflection from turbine blades should be minimized.

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Conflicts of interest: We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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Exhibit A7-6

Wind turbines and human health

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The association between wind turbines and health effects is highly debated. Some argue that reported health effects are related to wind turbine operation [electromagnetic fields (EMF), shadow flicker, audible noise, low-frequency noise, infrasound]. Others suggest that when turbines are sited correctly, effects are more likely attributable to a number of subjective variables that result in an annoyed/stressed state. In this review, we provide a bibliographic-like summary and analysis of the science around this issue specifically in terms of noise (including audible, low-frequency noise, and infrasound), EMF, and shadow flicker. Now there are roughly 60 scientific peer-reviewed articles on this issue. The available scientific evidence suggests that EMF, shadow flicker, low-frequency noise, and infrasound from wind turbines are not likely to affect human health; some studies have found that audible noise from wind turbines can be annoying to some. Annoyance may be associated with some self-reported health effects (e.g., sleep disturbance) especially at sound pressure levels >40 dB(A). Because environmental noise above certain levels is a recognized factor in a number of health issues, siting restrictions have been implemented in many jurisdictions to limit noise exposure. These setbacks should help alleviate annoyance from noise. Subjective variables (attitudes and expectations) are also linked to annoyance and have the potential to facilitate other health complaints via the nocebo effect. Therefore, it is possible that a segment of the population may remain annoyed (or report other health impacts) even when noise limits are enforced. Based on the findings and scientific merit of the available studies, the weight of evidence suggests that when sited properly, wind turbines are not related to adverse health. Stemming from this review, we provide a number of recommended best practices for wind turbine development in the context of human health.

Keywords: wind turbines, human health, noise, electromagnetic fields, annoyance, infrasound, low-frequency noise, shadow flicker

INTRODUCTION

Wind power has been harnessed as a source of energy around the world for decades. Reliance on this form of energy is increasing. In 1996, the global cumulative installed wind power capacity was 6,100 MW; in 2011, that value had grown to 238,126 MW and at the end of 2013 it was 318,137 MW (1). While public attitude is generally overwhelmingly in favor of wind energy, this support does not always translate into local acceptance of projects by all involved (2). Opposition groups point to a number of issues concerning wind turbines, and possible effects on human health is one of the most commonly discussed. Indeed, a small proportion of people that live near wind turbines have reported adverse health effects such as (but not limited to) ringing in ears, headaches, lack of concentration, vertigo, and sleep disruption that they attribute to the wind turbines. This collection of effects has received the colloquial name "Wind Turbine Syndrome" (3).

The reason for the self-reported health effects is highly debated and information fueling this debate is found primarily in four sources: peer-reviewed studies published in scientific journals, government agency reports, legal proceedings, and the popular literature and internet. Some argue that reported health effects are related wind turbine operational effects [e.g., electromagnetic fields (EMF), shadow flicker from rotor blades, audible noise, low-frequency noise (LFN) and infrasound]; others suggest that when turbines are sited correctly, reported effects are more likely attributable to a number of subjective variables, including nocebo responses, where the etiology of the self-reported effect is in beliefs and expectations rather than a physiologically harmful entity (4–8). In 2011, Knopper and Ollson (9) published a review that contrasted the human health effects that had been purported to be caused by wind turbines in popular literature sources with what had been reported in the peer-reviewed scientific literature as well as by various government agencies. At that time, only 15 articles in the peer-reviewed scientific literature that specifically addressed issues related to human health and wind turbines were available [i.e., (4, 5, 10–22)].

Based on their review, Knopper and Ollson (9) concluded that although there was evidence to suggest that wind turbines can be a source of annoyance to some people, there was no evidence demonstrating a direct causal link between living in proximity to wind turbines and more serious physiological health effects. Furthermore, although annoyance has been statistically significantly

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associated with wind turbine noise [especially at sound pressure levels >40 dB(A)], a convincing body of evidence exists to show that annoyance is more strongly related to visual cues and attitude than to wind turbine noise itself. In particular, this was highlighted by the fact that people who benefit economically from wind turbines (e.g., those who have leased their property to wind farm developers) reported significantly lower levels of annoyance than those who received no economic benefit, despite increased proximity to the turbines and exposure to similar (or louder) sound levels.

In the years following the publication of Knopper and Ollson (9), the debate surrounding the relationship between wind turbines and human health has continued, both in the public and within the scientific community. In this review, we provide a bibliographic-like summary and analysis of the science around this issue specifically in terms of noise (including audible, LFN, and infrasound), EMF, and shadow flicker. Stemming from this review, we provide weight of evidence conclusions and a number of best practices for wind turbine development in the context of human health.

METHODS

The authors worked with a professional Health Sciences Information Specialist to develop a search strategy of the literature. Combinations of key words (i.e., annoyance, noise, environmental change, sleep disturbance, epilepsy, stress, health effect(s), wind farm(s), infrasound, wind turbines(s), LFN, EMF, wind turbine syndrome, neighborhood change) were entered into PubMed, the Thomson Reuters Web of Knowledge[SM] and Google. No date restrictions were entered and literature was assessed up to the submission date of this manuscript (April 2014). The review was conducted in the spirit of the evaluation process outlined in the Cochrane Handbook for Systematic Reviews of Interventions.

As of the publication date of this review, there are close to 60 scientific peer-reviewed articles on the topic. Sources of information other than peer-reviewed scientific literature (e.g., websites, opinion pieces, conference proceedings, unpublished documents) were purposely excluded in this review because they are often unreliable and provide information that is typically anecdotal in nature or not traceable to scientific sources. A general summary, and key words of the articles reviewed herein, are presented in **Table 1**. These summaries provide results as they were reported by the authors of the articles and are without secondary interpretation.

Through the systematic review process, it was evident that there was significant variability in both the measures of exposure (i.e., proximity to turbines, field noise measures, lab noise measures, or magnetic field measurements) and the health outcomes examined (i.e., annoyance, sleep scores, and various quality of life metrics). The methodological heterogeneity in study designs across the selected health-based investigations inhibited a quantitative combination of results. In other words, meta-analytic methods were not appropriate for this updated systematic review of the literature on wind turbine and health effect. Rather qualitative interpretation is provided.

RESULTS

OVERALL NOISE

Knopper and Ollson (9) reviewed a number of studies that examined the noise levels produced by wind turbines, perception of wind turbine noise, and/or responses to wind turbine noise [e.g., (4, 5, 10, 12, 13, 15–18, 21)]. The results of more recent studies that investigated wind turbine noise with respect to potential human health effects are summarized below in chronological order of publication.

Shepherd et al. (23): Shepherd et al. reported on a cross-sectional study comparing health-related quality of life (HRQOL) of people living in proximity (i.e., <2 km) to a wind farm to a control group living >8 km away from the nearest wind farm. It involved self-administered questionnaires that included the World Health Organization (WHO) quality of life scale, in semi-rural New Zealand. The turbine group was drawn from residents of 56 homes in South Makara Valley, all within 2 km of a wind turbine. General outdoor noise levels in the area, obtained from a conference proceeding by Botha (53), were reported to range from 24 to 54 dB(A). The comparison group was taken from 250 homes in a geographically and socioeconomically matched area, at least 8 km from any wind farm in the region. General outdoor noise levels for the comparison group were not reported. The questionnaire was named the "*2010 Well-being and Neighborhood Survey*" in order to mask the true intent of the study and reduce bias against wind turbines. This is similar to the work of Pedersen in Europe, in that the surveys were not explicitly about wind turbines. Response rates were 34% from the Turbine group (number of participants $n = 39$) and 32% from the Comparison group ($n = 158$).

Overall, Shepherd et al. reported statistically worse ($p < 0.05$) scores in the Turbine group for physical HRQOL, environmental QOL and HRQOL in general. There was no statistical difference in social or psychological scores. Based on these results, the authors concluded that "utility-scale" wind energy generation was not without adverse health impacts on nearby residents and suggested setback distances need to be >2 km in hilly terrain. However, there are a number of limitations in this study that undermine the conclusion stated above. One key concern is that the results were based on only a limited number of participants ($n = 39$) for the Turbine group. In comparison, the survey datasets compiled in Sweden and the Netherlands by Pedersen and Persson Waye (4, 5) and Pedersen et al. (17), respectively, involved a total of 1,755 respondents overall. In these surveys, the only response found to be significantly related to A-weighted wind turbine noise exposure was annoyance, even though a number of physiological and psychological variables were also investigated. In addition, Shepherd et al. did not discuss the impact of participants' attitudes or visual cues that may have influenced the reports of decreased HRQOL. Given that other studies have indicated that annoyance was more closely related to visual cues and attitude, this could provide further explanation of why overall HRQOL scores were lower in the Turbine group. Presumably all residents within 2 km of a turbine would be able to see one, or more, of the turbines. Furthermore, although it was implied in the title of the article that noise from wind turbines was causing the observed effects, the study did not include either measured or estimated wind turbine noise exposure values for the individual survey respondents. Therefore, they were unable to demonstrate a dose–response relationship between the observed responses and exposure to wind turbine noise. In light of this, as recognized by Shepherd et al. (23), it is possible that the observed effects were driven by other causes such as conflicts between the community and the wind farm developers rather than a direct

Table 1 | General summary of reviewed articles.

General topic	Authors	Source	Key words	General summary
Audible noise	Shepherd et al. (23)	Noise and Health	Health-related quality of life (HRQOL)	Cross-sectional study involving questionnaires about quality of life living near and away from turbines. Statistically significant differences were noted in some HRQOL scores; residents within 2 km of a turbine reporting lower overall quality of life, physical quality of life, and environmental quality of life
	Janssen et al. (24)	Journal of the Acoustical Society of America	Annoyance, economic benefit, sensitivity, visual cues	Expanded on the datasets collected by Pedersen and Persson Waye (4, 5) and Pedersen et al. (17) in Sweden and the Netherlands. Authors evaluated self-reported annoyance indoors and outdoors compared to sound levels (Lden) from wind turbines. Like the authors before them who relied on these datasets, found that annoyance decreased with economic benefit and may have increased with noise sensitivity, visibility, and age. In comparison to other sources of environmental noise, annoyance due to wind turbine noise was found at relatively low noise exposure levels
	Verheijen et al. (25)	Science of the Total Environment	Annoyance, noise limits	Objective was to assess proposed Dutch standards for wind turbine noise and consequences for people and feasibility of meeting energy policy targets. Authors used a combination of audible and low-frequency noise models and functions to predict existing level of severely annoyed people living around existing wind turbines in the Netherlands. Found that at 45 dB(Lden) severe annoyance due to low-frequency noise unlikely; suggested that this noise limit is suitable as a trade-off between the need for protection against noise annoyance and the feasibility of national targets for renewable energy
	Bakker et al. (26)	Science of the Total Environment	Annoyance, distress, economic benefit, sleep disturbance	A dose–response relationship was found between immission levels of wind turbine sound and self-reported noise annoyance. Sound exposure was also related to sleep disturbance and psychological distress among those who reported that they could hear the sound, however not directly but with noise annoyance. Respondents living in areas with other background sounds were less affected than respondents in quiet areas. Found that people, animals, traffic and mechanical sounds were more often identified as a source of sleep disturbance than wind turbines
	Nissenbaum et al. (27)	Noise and Health	Epworth Sleepiness Score (ESS), Pittsburgh Sleep Quality Index (PSQI), SF36v2	Purpose of the investigations was to determine the relationship between reported adverse health effects and wind turbines among residents of two rural communities. Participants living 375–1,400 m and 3.3–6.6 km were given questionnaires to obtain data about sleep quality, daytime sleepiness and general physical and mental health. Authors reported that when compared to people living further away than 1.4 km from wind turbines, those people living within 1.4 km of wind turbines had worse sleep, were sleepier during the day and had worse mental health scores
	Ollson et al. (28)	Noise and Health	Rebuttal to Nissenbaum et al. (27)	Suggested that Nissenbaum et al. (27) extended their conclusions and discussion beyond the statistical findings of their study and that they did not demonstrated a statistical link between wind turbines – distance – sleep quality – sleepiness and health. In fact, their own statistical findings suggest that although, scores may be statistically different between near and far groups for sleep quality and sleepiness, they are no different than those reported in the general population. The claims of causation by the authors (i.e., wind turbine noise) for negative scores are not supported by their data
	Barnard (29)	Noise and Health	Rebuttal to Nissenbaum et al. (27)	Pointed out a number of problems with Nissenbaum et al. (27) study and suggested that data presented do not justify the very strong conclusions reached by the authors

(Continued)

Table 1 | Continued

General topic	Authors	Source	Key words	General summary
Audible noise (continued)	Mroczek et al. (30)	Annals of Agricultural and Environ-mental Medicine	SF-36, Visual Analog Scale (VAS)	Purpose of study was to assess how people's quality of life is affected by the close proximity of wind farms. Authors found that close proximity of wind farms does not result in the worsening of the quality of life based on the Norwegian version of the SF-36 General Health Questionnaire, the Visual Analog Scale (VAS) for health assessment, and original questions
	Taylor et al. (31)	Personality and Individual Differences	Personality traits	Study examined the influence of negative oriented personality (NOP) traits on the effects of wind turbine noise and reporting on non-specific symptoms (NSS). Results of the study showed that while calculated actual wind turbine noise did not predict reported symptoms, perceived noise did
	Evans and Cooper (32)	Acoustics Australia	Predicted and measured noise levels	A comparison of predicted noise levels from four commonly applied prediction methods against measured noise levels from six operational wind farms (at 13 locations) in accordance with the applicable guidelines in South Australia. Results indicate that the methods typically over-predicted wind farm noise levels but that the degree of conservatism appeared to depend on the topography between the wind turbines and the measurement location
	Maffei et al. (33)	International Journal of Environmen-tal Research and Public Health	Visual cues, perception	Investigated the effects of the visual impact of wind turbines on the perception of noise. Found distance was a strong predictor of an individual's reaction to the wind farm; data showed that increased distance resulted in a more positive general evaluation of the scenario and decreased perceived loudness, noise annoyance, and stress caused by sound. Found the color of the wind turbines (base and blade stripes) impacted an individuals' perception of noise
	Van Renterghem et al. (34)	Science of the Total Environment	Annoyance, attitude, laboratory experiment, visual cues	Conducted a two-stage listening experiment to assess annoyance, recognition, and detection of noise from a single wind turbine. Results support the hypothesis that non-noise variables, such as attitude and visual cues, likely contributed to the observation that people living near wind turbines (who do not receive an economic benefit from the turbines) report higher levels of annoyance at lower sound pressure levels than would be predicted for other community noise sources
	Baxter et al. (35)	Energy Policy	Risk perception, economic benefit, community conflict, policy	Conducted a study to investigate the role of health risk perception, economic benefit, and community conflict on wind turbine policy. Two communities were assessed: one located in proximity to two operating wind farms and a control community without turbines. Authors found that residents from the community with operational wind energy projects were more supportive of wind turbines than residents in the area without turbines
	Chapman et al. (6)	PLoS One	Psychogenic effects, nocebo, community complaints	Provided an overview of the growing body of literature supporting the notion that the attribution of symptoms and disease to wind turbine exposure is a modern health worry. Suggested that nocebo effects likely play an important role in the observed increase in wind farm-related health complaints. Suggested that reported historical and geographical variations in complaints were consistent with "communicated diseases" with nocebo effects likely to play an important role in the etiology of complaints rather than direct effects from turbines
	Whitfield Aslund et al. (36)	Energy Policy	Predicted annoyance, modeling	Used previously reported dose–response relationships between wind turbine noise and annoyance to predict the level of community noise annoyance that may occur in the province of Ontario. The results of this analysis indicate that the current wind turbine noise restrictions in Ontario will limit community exposure to wind turbine related noise such that levels of annoyance are unlikely to exceed previously established background levels of noise-related annoyance from other common noise sources

(Continued)

Table 1 | Continued

General topic	Authors	Source	Key words	General summary
Low-frequency noise and infrasound	Møller and Pedersen (37)	Journal of the Acoustical Society of America	Annoyance, insulation, indoor sound levels	Conducted a low-frequency noise study from four large turbines (>2 MW) and 44 other small and large turbines (7 > 2 MW and 37 < 2 MW). Low-frequency sound insulation was measured for 10 rooms under normal living conditions in houses exposed to low-frequency noise. Concluded that the spectrum of wind turbine noise moves down in frequency with increasing turbine size. Suggested that the low-frequency part of the noise spectrum plays an important role in the noise at neighboring properties. They hypothesized that if the noise from the investigated large turbines had an outdoor level of 44 dB(A) there was a risk that a substantial proportion of the residents would be annoyed by low-frequency noise, even indoors
	Bolin et al. (38)	Environmental Research Letters	Health effects, review, turbulence	Conducted a literature review over a 6-month period ending April 2011 into the potential health effects related to infrasound and low-frequency noise exposure surrounding wind turbines. Concluded that empirical support was lacking for claims that low-frequency noise and infrasound cause serious health affects in the form of "vibroacoustic disease," "wind turbine syndrome," or harmful effects on the inner ear
	Rand et al. (39)	Bulletin of Science, Technology and Society	Indoor sound levels, health effects, acute effects	Studies took place over a 2-day period inside a home where people were self-reporting serious adverse health effects. Authors reported on wind speed at hub of turbine, dB(A) and dB(G) filtering indoors and outdoors. Reported on acute effects
	Ambrose et al. (40)	Bulletin of Science, Technology and Society		
	Turnbull et al. (41)	Acoustics Australia	Underground measurement, comparative study	Developed an underground technique to measure infrasound. Measured infrasound at two Australian wind farms as well as in the vicinities of a beach, a coastal cliff, the city of Adelaide, and a power station. Reported that the measured levels at wind farms below the audibility threshold and similar to that of urban and coastal environments and near other engineered noise sources. Level of infrasound from wind farms at 360 and 85 m [61 and 72 dB(G), respectively] was comparable to that observed at a distance of 25 m from ocean waves [75 dB(G)]
	Crichton et al. (7)	Health Psychology	Negative expectations, symptom reporting, laboratory experiment	Examined the possibility that expectations of negative health effects from exposure to infrasound promote symptom reporting using a sham controlled, double-blind provocation study. Participants in the high-expectancy group reported significant increases in the number and intensity of symptoms experienced during exposure to both infrasound and sham infrasound. Conversely, there were no symptomatic changes in the low-expectancy group
	Crichton et al. (8)	Health Psychology	Negative and positive expectations, symptom reporting, laboratory experiment	Authors investigated how positive expectations can produce a reduction in symptoms. Expectations were found to significantly alter symptom reporting: participants who were primed with negative expectations became more symptomatic over time, suggesting that their experiences during the first exposure session reinforced expectations and led to heightened symptomatic experiences in subsequent sessions

(Continued)

Table 1 | Continued

General topic	Authors	Source	Key words	General summary
Electromagnetic fields	Havas and Colling (42)	Bulletin of Science, Technology and Society	Poor power quality, ground current, electrical hypersensitivity	Authors hypothesized that symptoms of some living near wind turbines could be caused by electromagnetic waves in the form of poor power quality (dirty electricity) and ground current resulting in health effects in those that are electrically hypersensitive. Indicated that individuals reacted differently to both sound and electromagnetic waves and this could explain why not everyone experienced the same health effects living near turbines
	Israel et al. (43)	Environ-mentalist	Vibration measurement, noise, risk	Conducted EMF, sound, and vibration measurements at wind energy parks in Bulgaria. Concluded that EMF levels were not of concern from wind farm
	McCallum et al. (44)	Environ-mental Health	Variable distances and wind, residential measures	Magnetic field measurements were collected in the proximity of 15 wind turbines, two substations, buried and overhead collector and transmission lines and nearby homes. Results suggest there is nothing unique to wind farms with respect to EMF exposure; in fact, magnetic field levels in the vicinity of wind turbines were lower than those produced by many common household electrical devices and were well below any existing regulatory guidelines with respect to human health
Review articles, editorials and social commentaries	Bulletin of Science, Technology and Society (BSTS) Special Edition	Bulletin of Science, Technology and Society	Various authors, health effects, social commentary, opinion pieces	Special edition made up of nine articles devoted entirely to wind farms and potential health effects. Many of the articles in the special edition were written as opinion pieces or social commentaries
	Hanning and Evans (45)	British Medical Journal	Sleep disturbance	Purpose was to opine on the relationship between wind turbines noise and health effects. Suggested that a large body of evidence exists to suggest that wind turbines disturb sleep and impair health at distances and external noise levels that are permitted in most jurisdictions
	Chapman (46)	British Medical Journal	Weight of evidence	In a rebuttal to Hanning and Evans (45) Chapman points to 17 independent reviews of the literature around wind turbines and human health that contrast the opinion of Hanning and Evans
	Farboud et al. (47)	Journal of Laryngology and Otology	Low-frequency noise (LFN), infrasound (IS), inner ear physiology, wind turbine syndrome	Conducted a literature search for articles published within the last 10 years, using the PubMed database and the Google Scholar search engine, to look at the effects of low-frequency noise and infrasound. Suggested the evidence available was incomplete and until the physiological effects of LFN and infrasound were fully understood, it was not possible to conclusively state that wind turbines were not causing any of the reported effects
	McCubbin and Sovacool (48)	Energy Policy	Comparative study, natural gas, health, and environmental benefits	Compared the health and environmental benefits of wind power in contrast to natural gas
	Roberts and Roberts (49)	Journal of Environmen-tal Sciences	PubMed-based review, low-frequency noise (LFN), infrasound (IS), health effects	Conducted a summary of the peer-reviewed literature on the research that examined the relationship between human health effects and exposure to low-frequency sound and sound generated from the operation of wind turbines. Concluded that a specific health condition or collection of symptoms has not been documented in the peer-reviewed, published literature that has been classified as a "disease" caused by exposure to sound levels and frequencies generated by the operations of wind turbines

(Continued)

Table 1 | Continued

General topic	Authors	Source	Key words	General summary
Review articles, editorials and social commentaries (continued)	Chapman and St. George (50)	Australian and New Zealand Journal of Public Health	Vibroacoustic disease (VAD); factoid	Investigated the extent to which VAD and its alleged association with wind turbine exposure had received scientific attention, the quality of that association and how the alleged association gained support by wind farms opponent. Based on a structured scientific database and Google search strategy, the authors showed that VAD has received virtually no scientific recognition and that there is no evidence of even rudimentary quality that vibroacoustic disease is associated with or caused by wind turbines. Stated that an implication of this "factoid" – defined as questionable or spurious statements – may have been contributing to nocebo effects among those living near turbines
	Jeffery et al. (51) Jeffery et al. (52)	Canadian Family Physician Canadian Journal of Rural Medicine	Health effects	Overall goal of these commentary pieces was to provide information to physicians regarding the possible health effects of exposure to noise produced by wind turbines and how these may manifest in patients

result of noise exposure. Based on the limitations discussed above, we consider that the authors' recommendation for a 2 km setback distance was not supported by the evidence presented in this study.

Janssen et al. (24): expanding on the datasets collected by Pedersen and Persson Waye (4, 5) and Pedersen et al. (17) in Sweden and the Netherlands, Janssen et al. evaluated self-reported annoyance indoors and outdoors compared to sound levels (Lden) from wind turbines. To derive the Lden, the authors added a correction factor of 4.7 dB(A) to outdoor A-weighted sound pressure levels from the datasets used in the previous studies. Annoyance in this study was ranked on a 4-point scale: 1 was "not annoyed," 2 was "slightly annoyed," 3 was "rather annoyed," and 4 was "very annoyed." Visual cue ("Can you see a wind turbine from your dwelling or your garden/balcony?"), economic benefit ["Are you a (co)owner of one or more wind turbines?"], and noise sensitivity (on either a 4 or 5 point scale with 1 representing "not sensitive" and 4 or 5 representing "very/extremely sensitive") were also assessed. Like the authors before them who relied on these datasets, Janssen et al. found that annoyance decreased with economic benefit and may have increased with noise sensitivity, visibility, and age. Rates of annoyance indoors from wind turbines to industrial noise from stationary sources and air, road and rail noise were also compared and it was concluded that: "*. . .annoyance due to wind turbine noise is found at relatively low noise exposure levels*" and that "*some similarity is found in the range Lden 40–45 dB between the percentage of annoyed persons by wind turbine noise and aircraft noise.*"

Verheijen et al. (25): the objective of this study was to assess the proposed Dutch protective standards for wind turbine noise, both on consequences for inhabitants and feasibility of meeting energy policy targets. The authors used a combination of audible and LFN models and functions derived by Janssen et al. (24) to predict the existing level of severely annoyed people living around existing wind turbines in the Netherlands. They estimated that there were approximately 1,500 severely annoyed individuals, in a total population of approximately 440,000 living at sound levels of 29 dB(Lden) around wind turbines. The authors reported that: "*For The Netherlands, a socially acceptable percentage of severely annoyed lies around 10%, which can be derived from the existing limits and dose–response functions of railway and road noise. This would result in an acceptable noise reception limit for wind turbines of about 47 to 49 dB.*" The authors decided to examine the feasibility of lowering the limit below 47–49 dB(Lden). They estimated that it may be feasible from a land mass perspective to lower the noise limit to 40 dB(Lden); however, given that lands are often rejected due to reasons other than noise that another value should be selected. They stated "*The percentage of severely annoyed at 45 dB is rated at 5.2% for wind turbine noise, which is well below 10% that corresponds to the existing road and railway traffic noise limits.*" They also determined that, at 45 dB(Lden), severe annoyance effects due to LFN were unlikely and suggested that this noise limit suited as a trade-off between the need for protection against noise annoyance and the feasibility of national targets for renewable energy.

Bakker et al. (26): the purpose of this study was to evaluate the relationship between exposure to the sound of wind turbines and annoyance, self-reported sleep disturbance, and psychological distress of people that live in their vicinity. This investigation relied on survey data, previously reported and discussed by Pedersen et al. (17), collected from 725 residents of the Netherlands living in the vicinity of wind turbines. As reported by Pedersen et al. (17), survey respondents answered questions about environmental factors and road traffic noise (and wind noise) as well as the effect of wind turbines on annoyance, sleep disturbance, and psychological distress.

Bakker et al. differed from Pedersen et al. (17) in that it provided a direct comparison of people who economically benefited from turbines with those who did not, specifically in relation to annoyance. Bakker et al. (26) reported that only 3% of survey respondents receiving economic benefit from wind turbines reported being "rather annoyed" or "very annoyed" by wind turbine noise when outdoors, while none reported being rather or very annoyed by wind turbine noise when indoors. In comparison, the proportions of survey respondents who did not receive an economic benefit who reported being rather or very annoyed indoors and outdoors were 12 and 8%, respectively, even though they were exposed to significantly lower levels of wind turbine sound.

What is more, Bakker et al. also compared sound-related sources of sleep disturbance in rural and urban areas in respondents who did not benefit economically from wind turbines. They found that people, animals, traffic, and mechanical sounds were more often identified as a source of sleep disturbance than wind turbines. In fact, in rural areas, only 6% of people identified wind turbines as the sound source of sleep disturbance compared to 11.7% for people/animals and 12.5% for traffic/mechanical sounds. In urban areas, only 3.8% of people identified wind turbines as the sound source of sleep disturbance compared to 14.4% for people/animals and 16.9% for traffic/mechanical sounds.

Nissenbaum et al. (27), Ollson et al. (28), and Barnard (29): the stated purpose of the investigations conducted by Nissenbaum et al. was to determine the relationship between reported adverse health effects and wind turbines among residents of two rural communities. Participants living 375–1,400 m and 3.3–6.6 km were given questionnaires to obtain data about sleep quality [using the Pittsburgh Sleep Quality Index (PSQI)], daytime sleepiness [using the Epworth Sleepiness Score (ESS)], and general physical and mental health (MH) (using the SF36v2 health survey). Overall, the authors reported that when compared to people living further away than 1.4 km from wind turbines, those people living within 1.4 km of wind turbines had worse sleep, were sleepier during the day, and had worse MH scores. Based on these findings the authors concluded that: "*...the noise emissions of IWTs disturbed the sleep and caused daytime sleepiness and impaired mental health in residents living within 1.4 km of the two IWT installations studied.*"

In a subsequent issue of Noise and Health, two letters to the editor were published that were critical of this study and its conclusions (28, 29). In particular, the letter from Barnard (29) criticized the statistical analysis in Nissenbaum et al. (27), which stated that there was a "strong" dose–response relationship between distance to the nearest wind turbine and both the "PSQI" and the "Epworth Sleepiness Scale." Barnard stated: "*I cannot see how this is justified, given the presented data. In contrast to the conclusions, Figure 1 and Figure 2 in the paper... show a very weak dose-response, if there is one at all. The near horizontal 'curve fits' and large amount of 'data scatter' are indications of the weak relationship between sleep quality and turbine distance. The authors seem to use a low P value as a support for the hypothesis that sleep disturbance is related to turbine distance. A better interpretation of the P value related to a near horizontal line fit would be that it suggests a high probability of a weak-dose response. Correlation coefficients are not given, but should have been given, to indicate the quality of the curve fits.*" Ollson et al. (28) pointed out that Nissenbaum et al. extended their conclusions and discussion beyond the statistical findings of their study. They stated "*We believe that they have not demonstrated a statistical link between wind turbines – distance – sleep quality – sleepiness and health. In fact, their own statistical findings suggest that although, scores may be statistically different between near and far groups for sleep quality and sleepiness, they are not different than those reported in the general population. The claims of causation by the authors (i.e., wind turbine noise) for negative MCS scores are not supported by their data. This work is exploratory in nature and should not be used to set definitive setback guidelines for wind-turbine installations.*"

Mroczek et al. (30): Mroczek et al. published the results of a study conducted in 2010 that evaluated the impact of living in close proximity to wind turbines on an individual's perceived quality of life. The study group consisted of 1,277 randomly selected Polish adults (703 women and 574 men) living in the vicinity of wind farms. The different distance (house to turbine) groups were: <700 m, from 700 to 1000 m, from 1,000 to 1,500 m, and >1,500 m. The quality of life was measured using the Norwegian version of the SF-36 General Health (GH) Questionnaire, the Visual Analog Scale (VAS) for health assessment, and some original questions about approximate distance to wind farm, age, gender, education, and profession. The SF-36 (Short Form 36) Questionnaire consists of 36 questions divided into 8 subscales: physical functioning (PF), role functioning physical (RP), bodily pain (BP), GH, vitality (V), social functioning (SF), role functioning emotional (RE), MH, and one additional question regarding health changes.

According to the authors "*The respondents assessed their health through answering questions included in the SF-36 and VAS. They were asked to mark the point corresponding with their well-being on the level from 0 to 100, where 0 denoted the worst possible state of health and 100 – excellent health.*" The results showed that regardless of the distance from the wind farm (i.e., from <700 to >1,500 m) respondents ranked their PF scores as highest out of all of the quality of life components. Overall, people living closest to wind farms assessed their quality of life as higher than those living in more distant areas. The scores for the MH component, GH, SF, and RE were highest in the group living closest to the wind farms and lowest by those living greater than 1.5 km away. The authors noted that there may have been confounding factors that contributed to the observed results (e.g., economic factors). Since other studies have shown links between self-reported health status, proximity to wind turbines and the direct influence of economic benefit on levels of annoyance [e.g., (17, 26)], these major confounding factors also need to be considered when interpreting the results of the Mroczek et al. study on quality of life and proximity to wind turbines.

Taylor et al. (31): this study examined the influence of negative oriented personality (NOP) traits on the effects of wind turbine noise and reporting on non-specific symptoms (NSS). The study was conducted based on the hypothesis that the public has become increasingly concerned with attributing NSS to environmental features (e.g., wind turbines). The study focused on three NOP traits in particular: neuroticism (N), negative affect (NA), and frustration intolerance (FI). The authors noted that previous research has demonstrated that individuals with high N and NA typically evaluate their environment more negatively. Furthermore, FI may have impacted the way an individual perceived and evaluated environmental factors from an inability to bear or cope with perceived negative emotions, thoughts and events. A survey was mailed out to 1,270 households within 500 m of eight 0.6 kW turbine installations and within 1 km of four 5 kW turbines in two cities in the U.K. Individuals within the household (>18 years old) could anonymously complete the survey and mail the results back or submit them online. In total, 138 completed surveys were returned. Actual sound levels were calculated for those households who completed the survey, and participants were asked to describe the perceived noise, including the type of noise (e.g., swooshing, whistling, buzzing), frequency, and loudness (based on a 0–4 ranking scale). Participants were also asked a series of questions to determine the level of NOP traits and related health/symptom reporting information.

The results of the study showed that while calculated actual wind turbine noise did not predict reported symptoms, perceived noise did. Specifically: "*. . .for those higher in NOP traits, there was a stronger link between perceived noise and symptom reporting. There was however, no relationship between calculated actual noise from the turbine and participants attitude to wind turbines. This means that those who had a more negative attitude to wind turbines perceived more noise from the turbine, but this effect was not simply due to individuals being able to actually hear the noise more.*"

Evans and Cooper (32): in their paper called "Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms," Evans and Cooper present a comparison of predicted noise levels from four commonly applied prediction methods against measured noise levels from six operational wind farms (conducted at 13 locations) in accordance with the applicable guidelines in South Australia. The results indicate that the methods typically over-predicted wind farm noise levels but that the degree of conservatism appeared to depend on the topography between the wind turbines and the measurement location. Briefly, Evans and Cooper found that the commonly used ISO 9613-2 model (with completely reflective ground) and the CONCAWE model generally over-predicted noise levels by 3–6 dB(A), but the amount of over-prediction was related to the topography (i.e., relatively flat topography or a steady slope from the turbines). However, at sites where there was a significant concave slope from the turbines down to the measurement sites, these commonly used prediction methods were typically accurate, with the potential of marginal under-prediction in some cases (when ISO 9613-2 used 50% absorptive ground).

A requirement of many regulatory agencies is that noise modeling be conducted by developers prior to the construction of wind turbines. A common criticism of this approach is that modeled values are not representative of actual noise from operational wind farms. Evans and Cooper's findings show that this is not the case, but caution about the role of topography.

Maffei et al. (33): despite the fact that wind farms are represented as environmentally friendly projects, wind turbines are viewed by some as visual and audible intruders that spoil the landscape and generate noise. Consequently, Maffei et al. (33) conducted a study investigating the effects of the visual impact of wind turbines on the perception of noise. The study consisted of 64 participants (34 males, 30 females) who resided in either urban or rural areas. Participants were asked to fill out a questionnaire to obtain information regarding age, gender, education, and local neighborhood characteristics. A number of statements were then submitted to the participants where they were asked to respond based on a 100-point Likert scale ranging from "disagree strongly" to "agree strongly." The statements were based on personal views about green energy, wind turbines, noise, and other related subject matter. Subsequently, a virtual reality scenario was created to emulate the visual impact of a wind farm on a rural landscape and included an audio component recorded from a 16 turbine wind farm in Frigento, Italy. In total, three factors were manipulated in the experiment: distance from the wind farm (150, 250, and 500 m); the number of wind turbines (1, 3, and 6); the color of the base of the turbine and any stripes on the blades (white, red, brown, green). Each participant was asked to view all of the scenarios using a 3D visor and asked to respond to a number of questions pertaining to perceived loudness, sound pleasantness, noise annoyance, sound stress, sound tranquility, and visual pleasantness.

The results found that distance was a strong predictor of an individual's reaction to the wind farm. In particular, the data showed that increased distance resulted in a more positive general evaluation of the scenario and decreased perceived loudness, noise annoyance, and stress caused by sound. Additionally, the authors found that the color of the wind turbines (base and blade stripes) impacted an individuals' perception of noise. Generally, white and green turbines were preferred to brown and red ones. Specifically, green turbines scored the highest since they were perceived as being the "most integrated" into the landscape. The authors concluded that their results confirmed the interconnectedness between auditory and visual components of individual perception.

Van Renterghem et al. (34): Van Renterghem et al. (34) conducted a two-stage listening experiment to assess annoyance, recognition, and detection of noise from a single wind turbine. A total of 50 participants with "normal" hearing abilities participated in the experiment and were classified as having a positive to neutral attitude toward renewable energy. *In situ* recordings made at close distance (30 m downwind) from a 1.8 MW turbine operating at 22 rotations per minute (rpm) were mixed with road traffic noise and processed to simulate indoor sound pressure levels at 40 dB(LAeq). In the first stage, where participants were unaware of the true purpose of the experiment, samples were played during a quiet leisure activity. Under these conditions (i.e., when people were unaware of the different sources of noise), pure wind turbine noise produced similar annoyance ratings as unmixed highway noise at the same equivalent level, while annoyance from local road traffic was significantly higher. These results supported the hypothesis that non-noise variables, such as attitude and visual cues, likely contributed significantly to the observation that people living near wind turbines (who do not receive an economic benefit from the turbines) report higher levels of annoyance at lower sound pressure levels than would be predicted for other community noise sources [e.g., (17, 24)].

In the second stage of the Van Renterghem et al. (34) study, participants were allowed to listen to a recording of unmixed wind turbine sound [at 40 dB(A)] for 30 s in order to familiarize themselves with the sound. After this, they listened to 10 sets of paired sound samples; one of which contained unmixed road traffic noise and the other that contained wind turbine noise mixed with road traffic at signal-to-noise ratios varying between −30 dB(A) and +10 dB(A). For each pair, participants were asked to identify which of the two samples contained the wind turbine noise. The detection of wind turbine noise in the presence of highway noise was found a "signal-to-noise" ratio as low as −23 dB(A). This demonstrated that once the subject was familiar with wind turbine noise, it could easily be detected even in the presence of highway traffic noise. This could also help explain the increased rates of noise annoyance at home reported by Pedersen et al. (17) and Janssen et al. (24) since residents would be familiar with the sound and be able to discern it if they listened for it when primed by visual cues. Overall, the findings support the idea that noticing the sound could be an important aspect of wind turbine noise annoyance. Awareness of the source and recognition of the wind turbine sound was also linked to higher levels of annoyance. Van Renterghem et al. noted that: "*The experiment reported in this paper supports the hypothesis that previous observations, reporting that retrospective annoyance for wind turbine noise is higher than that for highway noise at the same equivalent noise level, is grounded in higher level appraisal, emotional, and/or cognitive processes. In particular, it was observed that wind turbine noise is not so different from traffic noise when it is not known beforehand.*"

Baxter et al. (35): in 2010, Baxter and colleagues conducted a study to investigate the role of health risk perception, economic benefit, and community conflict on wind turbine policy. The study, published in 2013, had two parts: a literature review and quantitative survey meant to determine perceptions of wind turbines and how they are linked to support or opposition to wind turbines in the community. Two communities were assessed: one located in proximity to two operating wind farms and a control community without turbines. Overall, the authors found that residents from the community with operational wind energy projects (which were introduced prior to the *Green Energy Act* in Ontario) were more supportive of wind turbines than residents in the area without turbines (78 vs. 29%, with "support" defined as agreeing to vote in favor of local turbines). The authors also reported that residents in the turbine community were more accepting of turbine esthetics than people in the control community and less worried about health impacts, this despite the fact that the wind farms in the "case" group were in some cases closer to homes than currently permitted.

Baxter et al. indicated that the lack of support in the control community could have been due to political lobbying during the provincial election, where one candidate suggested a moratorium on wind turbine as part of their campaign. The authors also highlighted the role of health risk perception (which seemed linked to political lobbying) as a variable leading to the lack of support. The finding that "*Our study highlights the need to add health risk perception to the agenda for social research on turbines*" is valid, albeit dated in the Ontario context, since an integral part of any wind development project in Ontario is public consultation with wind turbines and health as a fundamental component. These findings supported the idea that perception of health risks is heavily impacted by expectation, media coverage, and that "hands on experience" could serve to increase familiarity and decrease concerns.

Chapman et al. (6): the authors provided an overview of the growing body of literature supporting the notion that the attribution of symptoms and disease to wind turbine exposure is a modern health worry. Chapman et al. also suggested that nocebo effects likely play an important role in the observed increase in wind farm-related health complaints. By evaluating records of complaints from wind farm companies about noise or health from residents living near 51 wind farms across Australia, two theories about the etiology of complaints were tested: one being direct effects from turbines and the other being "psychogenic" effects brought on by nocebo effects.

Chapman et al. found a number of historical and geographical variations in wind farm complaints from Australians.

1. Nearly 65% of Australian wind farms, 53% of which have turbines >1 MW, have never been subject to noise or health complaints. These farms have an estimated 21,633 residents within 5 km and have operated complaint-free for a cumulative 267 years. No complaints were reported in Western Australia and Tasmania.
2. One in 254 residents across Australia appeared to have ever complained about health and noise, and 73% of these residents live near 6 wind farms that have been targeted by anti-wind farm groups. Ninety percentage of complaints were made after anti-wind farm groups added health concerns to their wider opposition in 2009.
3. In the years after, health or noise complaints were rare despite large and small-turbine wind farms having operated for many years.

It was suggested that reported historical and geographical variations in complaints were consistent with "communicated diseases" with nocebo effects likely to play an important role in the etiology of complaints rather than direct effects from turbines. This novel work highlighted the role of negative expectations and how they could lead to the development of complaints near wind farms. These findings were supported by many other studies that were suggestive of subjective variables, rather than wind turbine specific variables, as the source of annoyance for some people.

Whitfield Aslund et al. (36): Whitfield Aslund et al. used previously reported dose–response relationships between wind turbine noise and annoyance to predict the level of community noise annoyance that may occur in the province of Ontario. Prediction for future wind farm developments (planned, approved, or in process) were compared to previously reported rates of annoyance that were associated with more common noise sources (e.g., road traffic). Modeled noise levels and distance to the nearest wind farm-related noise source were compiled for over 8,000 individual receptor locations (i.e., buildings, dwellings, campsites, places of worship, institutions, and/or vacant lots) from 13 wind power projects in the province of Ontario that had been approved since 2009 or were under Ministry of the Environment (MOE) review as of July 2012. This information was then compared to the wind turbine noise specific dose–response relationships for self-reported annoyance from Pedersen et al. (17) and Bakker et al. (26) using data collected from 725 survey respondents living in the proximity of wind turbines (<2.5 km) in the Netherlands.

One of the study findings was that a distinct exponentially decreasing relationship was observed between distance to the nearest noise source and the sound pressure level predicted. However, although distance to the nearest noise source could explain a large proportion (86%) of the total variance in predicted sound pressure levels, other sources of variation are also important; predicted sound pressure levels at a set distance varied by approximately 5–10 dB(A) and the distance at which a set sound pressure level was met varied by approximately 1000 m. These variations reflect differences in the noise model inputs such as the physical design and noise emission ratings of the turbines (and transformer substations, if present) used in different projects and the total number of turbines (and transformer substations, if present) in the vicinity of the receptor location. Given that noise levels can vary substantially at a given distance, these data highlighted the inadequacy of using distance to the nearest turbine as a proxy for wind turbine noise exposure.

One of the other findings was that, for non-participating receptors, predicted rates of noise-related annoyance (when indoors) would not exceed 8%, with further reductions in the rates of annoyance at increased distances (i.e., >1 km). In comparison, it had previously been established that approximately 8% of adult Canadians reported being either "very or extremely bothered, disturbed, or annoyed" by noise in general when they were at home and 6.7% of adult Canadians indicated they were either "very or extremely annoyed" by traffic noise specifically (54). Even in small Canadian communities (i.e., <5000 residents) that are typically associated with low background noise levels, 11% of respondents were moderately to extremely annoyed by traffic noise (54). This analysis suggested that the current wind turbine noise restrictions in Ontario will limit community exposure to wind turbine related noise such that levels of annoyance are unlikely to exceed previously established background levels of noise-related annoyance from other common noise sources.

LOW-FREQUENCY NOISE AND INFRASOUND

As reviewed by Knopper and Ollson (9), a number of sources have proposed that the self-reported health effects of some people living near wind turbines may be due to LFN and infrasound [e.g., (20, 39, 55)]. However, infrasound and LFN are not unique to wind turbines; natural sources of infrasound include meteors, volcanic eruptions, ocean waves, wind, and any effect that leads to slow oscillations of the air (11). Measured LFN and infrasound levels from wind turbines have been shown to comply with available standards and criteria published by numerous government agencies including the UK Department for Environment, Food, and Rural Affairs; the American National Standards Institute; and the Japan Ministry of Environment (22). Therefore, Knopper and Ollson (9) concluded that the hypothesis that infrasound is a causative agent in health effects does not appear to be supported. With some exceptions, more recent studies (summarized below) generally support this hypothesis.

Møller and Pedersen (37): Møller and Pedersen conducted a LFN study from four large turbines (>2 MW) and 44 other small and large turbines that were aggregated (7 > 2 and 37 < 2 MW). Low-frequency sound (LFS) insulation was measured for 10 rooms under normal living conditions in houses exposed to LFN. They concluded that the spectrum of wind turbine noise moves down in frequency with increasing turbine size. They also suggested that the low-frequency part of the noise spectrum plays an important role in the noise at neighboring properties. They hypothesized that if the noise from the investigated large turbines had an outdoor level of 44 dB(A) (the maximum of the Danish regulation for wind turbines) there was a risk that a substantial proportion of the residents would be annoyed by LFN, even indoors. However, the authors' work did not include a survey of annoyance surrounding the turbines and did not provide any data to support this hypothesis. In terms of infrasound (sound below 20 Hz), they concluded that the levels were relatively low when human sensitivity to these frequencies was accounted for. Even in close proximity to turbines, the infrasonic sound pressure level was below the normal hearing threshold. Overall, this study suggested that LFN could be an important component of the overall noise levels from wind turbines. However, it did not provide a link between modeled or measured values and potential health effects of nearby residents. Rather, it hypothesized that at 44 dB(A), at least a portion of the annoyance could be attributed to LFN levels.

Bolin et al. (38): Bolin et al. (38) conducted a literature review over a 6-month period ending April 2011 into the potential health effects related to infrasound and LFN exposure surrounding wind turbines. They conducted the search using PubMed, PsycInfo, and Science Citation Index. In addition, they conducted gray literature searches and personally contacted researchers and noise consultants working with wind turbine noise. They concluded that the dominant source of wind turbine generated LFN was from incoming turbulence interacting with the blades. They found no evidence in the literature that infrasound in the 1–20 Hz range contributed to perceived annoyance or other health effects. They also opined that LFN from modern wind turbines could be audible at typical levels in residential settings, but did not exceed levels from other common noise sources, such as road traffic noise.

The authors concluded that empirical support was lacking for claims that LFN and infrasound cause serious health affects in the form of "vibroacoustic disease (VAD)," "wind turbine syndrome," or harmful effects on the inner ear. This conclusion was similar to that provided in the Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH) expert panel review released in January 2012.

Rand et al. (39) and Ambrose et al. (40): in the fall of 2011, Rand et al. published their findings on noise measurements taken around a residential home online in the Bulletin of Science, Technology and Society (BSTS) (39). In 2012, a similar article appeared in BSTS, but with Ambrose as first author. After learning about reported noise and health issues from some residents living near three wind turbines (Vestas, Model V82, 1.65 MW each) in Falmouth, MA, USA, Ambrose et al. conducted a study to investigate the role of infrasound and LFS in these complaints. What led Ambrose et al. to focus on infrasound and LFS was the home owner's complaints about discomfort and a number of symptoms (i.e., headaches, ear pressure, dizziness, nausea, apprehension, confusion, mental fatigue, inability to concentrate, and lethargy). These observations were reported to be associated with being indoors when the wind turbines were operating during moderate to strong winds. Ambrose et al. state: "*Typically, indoors the A-weighted sound level is lower than outdoors when human activity is at a minimum. This strongly suggested that the A-weighted sound level might not correlate very well [sic] the wind turbine complaints. This may be indicative of another cause such as low- or very-low-frequency energy being involved.*"

The authors made acoustic measurements and viewed the data with dBL (unweighted) and dB(A), (C), and (G) filtering between April 17 and 19, 2011, at four locations [260 ft (~87 m), 830 ft (~277 m), 1,340 ft (~450 m), and 1,700 ft (~570 m)] between one turbine and one residence. The relationship between sound [dB(A), (G), and (L)] and health effects was based on measurements at 1,700 ft. Ambrose et al. reported that within

20 min, both authors had difficulties performing ordinary tasks and within 1 h both were "*debilitated and had to work much harder mentally.*" They also claimed that as time went on their symptoms became more severe.

The authors reported being affected when wind speeds were greater than 10 m/s at the hub height of the turbines and when measured sound levels were in the 18–24 dB(A) range inside [51–64 dB(G); 62–74 dB(L)] and 32–46 dB(A) outside [49–65 dB(G); 57–69 dB(L)]. They reported that they felt effects inside and outside but preferred being outside. They noted that it took a week to recover but one researcher had recurring symptoms (of nausea and vertigo) for over 7 weeks. There are a number of uncertainties in the Ambrose et al. white paper and the BSTS articles, which diminished the strength of their conclusions. This was the first written account we are aware of that suggested acute health effects from exposure to sound from wind turbines. The recent MassDEP and MDPH (56) report provided this comment regarding the Ambrose et al. study: *"Importantly, while there is an amplification at these lower frequencies, the indoor levels (unweighted) are still far lower than any levels that have ever been shown to cause a physical response (including the activation of the OHC) in humans."*

Further, studies where biological effects observed following infrasound exposure were conducted at sound pressure levels much greater than measured by Ambrose et al. [e.g., (11); 145 and 165 dB; (57): 130 dB] and much greater than what is produced by wind turbines. There are over 100,000 wind turbines in operation globally. Indeed, the idea of overt acute debilitating effects (even lasting several weeks after removal from exposure) appears to be unique to these authors.

Turnbull et al. (41): Turnbull et al. developed an underground technique to measure infrasound and applied this process at two Australian wind farms as well as in the vicinities of a beach, a coastal cliff, the city of Adelaide, and a power station. The measured levels were compared against one another and against the infrasound audibility threshold of 85 dB(G). The authors reported that the measured level of infrasound within the wind farms was well below the audibility threshold and was similar to that of urban and coastal environments and near other engineered noise sources. Indeed, the level of infrasound from wind farms at 360 and 85 m [61 and 72 dB(G), respectively] was comparable to that observed at a distance of 25 m from ocean waves [75 dB(G)].

Crichton et al. (7): this study examined the possibility that expectations of negative health effects from exposure to infrasound promote symptom reporting. A sham controlled, double-blind provocation study was conducted in which participants were exposed to 10 min of infrasound and 10 min of sham infrasound. A total of 54 participants (34 women, 20 men) were randomized into high- or low-expectancy groups and presented with audiovisual information (including internet material) designed to invoke either high or low expectations that exposure to infrasound causes specific symptoms (e.g., headache, ear pressure, itchy skin, sinus pressure, dizziness, vibrations within the body). Notably, participants in the high-expectancy group reported significant increases in the number and intensity of symptoms experienced during exposure to both infrasound and sham infrasound. Conversely, there were no symptomatic changes in the low-expectancy group.

Based on their findings, Crichton et al. (7) concluded: *"Healthy volunteers, when given information about the expected physiological effect of infrasound, reported symptoms that aligned with that information, during exposure to both infrasound and sham infrasound. Symptom expectations were created by viewing information readily available on the Internet, indicating the potential for symptom expectations to be created outside of the laboratory, in real world settings. Results suggest psychological expectations could explain the link between wind turbine exposure and health complaints."* These results were consistent with the findings of other researchers, who have observed increased concern about the health risks associated with exposure to certain environmental hazards can lead to elevated symptom reporting, even when no objective health risk is presented (58, 59).

Crichton et al. (8): building on their previous publication that negative expectations established by the media and internet can significantly increase health-related complaints by exposed individuals (8), the authors investigated how positive expectations can produce a reduction in symptoms. Sixty participants were exposed to audible wind farm sound [43 dB(A)] and infrasound [9 Hz, 50.4 dBL (unweighted)] previously recorded 1 km from a wind farm, in two, 7 min session. Following baseline measurements, expectations were developed by watching videos that either promoted the negative health effects or the potentially therapeutic health effects of exposure to infrasound. Expectations were found to significantly alter symptom reporting: participants who were primed with negative expectations became more symptomatic over time, suggesting that their experiences during the first exposure session reinforced expectations and led to heightened symptomatic experiences in subsequent sessions. Upwards of 77% of participants in the negative expectation group reported a worsening of symptoms. In contrast, 90% of participants in the positive expectation group reported improvements in physical symptoms after the listening session. This was the first study to show that a placebo response could be brought on by positive pre-exposure expectations and influence participants exposed to wind farm noise. The authors concluded that negative expectations created by the media could account for the increase in negative health effects reported by individuals exposed to wind farm noise. Overall, this investigation provided further evidence that physiological outcomes can be influenced by established expectations.

ELECTROMAGNETIC FIELDS

Concerns about the ever-present nature of EMF (also called electric and magnetic fields) and possible health effects have been raised by some in the global community for a number of years. However, the science around EMF and possible health concerns has been extensively researched, with tens of thousands of scientific studies published on the issue. Government and medical agencies including Health Canada (60), the World Health Organization (61), the International Commission on Non-Ionizing Radiation Protection (62), the International Agency for Research on Cancer (63), and the US National Institute of Health (NIH) and National Institute of Environmental Health Sciences (64) have all thoroughly reviewed the available information. While individual opinions on the issue vary, the weight of scientific evidence does not support a causal link between EMF and health issues at levels typically encountered by people.

Short-term exposure to EMF at high levels is known to cause nerve and muscle stimulation in the central nervous system. Based on this information, the ICNIRP, a group recognized by the WHO as the international independent advisory body for non-ionizing radiation protection, established an acute exposure guideline of 2,000 mG for the general public, based on power frequency EMF of 50–400 Hz (62). With respect to long-term exposure to low levels of EMF, it needs to be acknowledged that the IARC and WHO have categorized EMF as a Class 2B possible human carcinogen, based on a weak association of childhood leukemia and magnetic field strength above 3–4 mG (63). This means there is limited evidence of carcinogenicity in humans and inadequate evidence of carcinogenicity in experimental animals. These human studies are weakened by various methodological problems that the WHO has identified as a combination of selection bias, some degree of confounding and chance (65). There are also no globally accepted mechanisms that would suggest that low-level exposures are involved in cancer development and animal studies have been largely negative (65). Thus, the WHO has stated that, based on approximately 25,000 articles published over the past 30 years, the evidence linking childhood leukemia to EMF exposure is not strong enough to be considered causal (61). Concerns have also been raised by some about a relationship between EMF and a range of various health concerns, including cancers in adults, depression, suicide, and reproductive dysfunction, among several others. The WHO (65) has stated: "*. . .scientific evidence supporting an association between ELF [extremely low frequency] magnetic field exposure and all of these health effects is much weaker than for childhood leukaemia.*"

Recently, worries about exposure to EMF from wind turbines, and associated electrical transmission, has been raised at public meetings and legal proceedings. These fears have not been based on any actual measurements of EMF exposure surrounding existing projects but appear to follow from concerns raised from internet sources and misunderstanding of the science. There has been limited research conducted on wind turbine emissions of EMF, either from the turbines themselves, or from the power lines required for distribution of the generated electricity. However, based on the weight of evidence it is not expected that EMF from wind turbines is likely to be a causative agent for negative health effects in the community. Only three papers were retrieved in the preparation of this review that examined this issue specifically.

Havas and Colling (42): the paper indicated that there were some people who lived around wind turbines that complained of difficulty sleeping, fatigue, depression, irritability, aggressiveness, cognitive dysfunction, chest pain/pressure, headaches, joint pain, skin irritations, nausea, dizziness, tinnitus, and stress. The authors suggested that these symptoms could be caused by electromagnetic waves in the form of poor power quality (dirty electricity) and ground current resulting in health effects in those that are electrically hypersensitive. They indicated that individuals reacted differently to both sound and electromagnetic waves and this could explain why not everyone experienced the same health effects living near turbines. Ground current or stray voltage was also purported to be a potential cause of health effects surrounding wind turbines. However, this paper was hypothetical and speculative in nature and no data were presented to support the author's opinions. Presently, there are no quantitative data in the scientific literature to support the claims made in Havas and Colling (42).

Israel et al. (43): these authors conducted EMF, sound, and vibration measurements surrounding one of the largest wind energy parks in Bulgaria, located along the Black Sea. The purpose of the study was to determine if levels of wind turbine emissions were within Bulgarian and European limits for workers and the general population. In addition, they sought to determine if their previously established 500 m setback zone around the wind park was adequate. The wind park consisted of 55 Vestas V90 3 MW towers. The measurements took place over a 72-h period when temperatures were between 0 and 5.5°C. Actual distances to the receptor locations were not reported, although it is suspected that they would be in the vicinity of 500 m from the closest turbines.

The EMF levels measured within 2–3 m of the wind turbines were between 0.133 and 0.225 mG. These values are comparable to or lower than magnetic field measurements that have been reported in the proximity of typical household electrical devices (66). It should be noted that the values observed by Israel et al. were approximately four orders of magnitude lower than the ICNIRP (62) guideline of 2,000 mG for the general public for acute exposure. Based on these findings, Israel et al. concluded that the EMF levels from wind turbines were at such low level as to be insignificant compared to values found in residential areas and homes. The findings reported by Israel et al. of actual measurements of EMF surrounding wind turbines were contrary to the hypothesis presented by Havas and Colling (42).

The noise measurements performed by Israel et al. met the requirements of Bulgarian legislation for day [55 dB(A)], evening [50 dB(A)], and night [45 dB(A)] and it was concluded that the wind turbines contributed only 1–3 dB(A) above existing background levels. Vibration measurements surrounding the turbines had values close to zero, which indicated that this was not a contributing emission factor of exposure for people living around wind turbines. Overall, the authors concluded: "*. . .the studied wind power park complies with the requirements of the national and European legislation for human protection from physical factors–electric and magnetic fields up to 1 kHz, noise, vibration, and do not create risk for both workers in the area of the park and the general population living in the nearest villages.*"

McCallum et al. (44): this study was carried out at the Kingsbridge 1 Wind Farm located near Goderich, ON, Canada. Magnetic field measurements (milligauss) were collected in the proximity of 15 Vestas 1.8 MW wind turbines, two substations, various buried and overhead collector and transmission lines, and nearby homes. Data were collected during three operational scenarios to characterize potential EMF exposure: "high wind" (generating power), "low wind" (drawing power from the grid, but not generating power), and "shut off" (neither drawing, nor generating power).

Background levels of EMF (0.2–0.3 mG) were established by measuring magnetic fields around the wind turbines under the "shut off" scenario. Magnetic field levels detected at the base of the turbines under both the "high wind" and "low wind" conditions were low (mean = 0.9 mG; $n = 11$) and rapidly diminished with distance, becoming indistinguishable from background within 2 m of the base. Magnetic fields measured 1 m above buried collector lines were also within background (≤0.3 mG). Beneath overhead 27.5 and 500 kV transmission lines, magnetic field levels of up to 16.5 and 46 mG, respectively, were recorded. These levels also diminished rapidly with distance. None of these sources appeared to influence magnetic field levels at nearby homes located as close as just over 500 m from turbines, where measurements immediately outside of the homes were ≤0.4 mG. The results suggested that there was nothing unique to wind farms with respect to EMF exposure; in fact, magnetic field levels in the vicinity of wind turbines were lower than those produced by many common household electrical devices (e.g., refrigerator, dishwasher, microwave, hairdryer) and were well below any existing regulatory guidelines with respect to human health.

SHADOW FLICKER

The main health concern associated with shadow flicker is the risk of seizures in those people with photosensitive epilepsy. As reviewed by Knopper and Ollson (9), Harding et al. (14) and Smedley et al. (19) have published the seminal studies dealing with this concern. Both authors investigated the relationship between photo-induced seizures (i.e., photosensitive epilepsy) and wind turbine blade flicker (also known as shadow flicker). Both studies suggested that flicker from turbines that interrupt or reflect sunlight at frequencies >3 Hz pose a potential risk of inducing photosensitive seizures in 1.7 people per 100,000 of the photosensitive population. For turbines with three blades, this translates to a maximum speed of rotation of 60 rpm. Modern turbines commonly spin at rates well below this threshold. For example, the following spin rates for four different models of wind turbines have been obtained from the turbine specification sheets:

- Siemens SWT-2.3: 6–16 rpm
- REpower MM92: 7.8–15.0 rpm
- GE 1.6–100: 9.75–16.2 rpm
- Vestas V112-3.0: 6.2–17.1 rpm

In 2011, the Department of Energy and Climate Change (67) released a consultant's report entitled "Update of UK Shadow Flicker Evidence Base." The report concluded that: *"On health effects and nuisance of the shadow flicker effect, it is considered that the frequency of the flickering caused by the wind turbine rotation is such that it should not cause a significant risk to health."* Furthermore, the expert panel convened by MassDEP and MDPH (56) concluded that the scientific evidence suggests that shadow flicker does not pose a risk of inducing seizures in people with photosensitive epilepsy.

Germany is one of the only countries to implement formal shadow flicker guidelines, which are part of the *Federal Emission Control Act* (68). These guidelines allow:

- maximum 30 h per year of astronomical maximum shadow (worst case);
- maximum 30 min worst day of astronomical maximum shadow (worst case); and
- maximum 8 h per year actual.

Although shadow flicker from wind turbines is unlikely to lead to a risk of photo-induced epilepsy, there has been little if any research conducted on how it could heighten the annoyance factor of those living in proximity to turbines. It may however be included in the notion of visual cues.

REVIEW ARTICLES, EDITORIALS, AND SOCIAL COMMENTARIES

In addition to the articles reviewed above that reported the results of surveys and experiments designed to specifically investigate potential environmental stressors that have been associated with wind turbines (i.e., overall noise, LFN and infrasound, EMF, and shadow flicker), a number of published and peer-reviewed articles were identified that present reviews of the available data, opinion pieces, and/or social commentaries. These articles are reviewed in detail below.

Bulletin of Science, Technology and Society: Special Edition 2011, 31(4): in August 2011, authors of a number of popular literature studies published their findings as a series of nine articles in a special edition of the Bulletin of Science, Technology and Society (BSTS) devoted entirely to wind farms and potential health effects[1]. Many of the articles in the special edition were written as opinion pieces or social commentaries and did not provide detailed methodologies used to test hypotheses as is expected in the publication of scientific research articles. Based on a critical review of each of the articles (69), it is our opinion that the series suffers numerous flaws from a scientific, technological, and social basis. Many of the claims used as evidence of a relationship between health effects and wind turbines were unsubstantiated [e.g., Phillips (70) is entirely unsupported and contains alarmist extrapolations], without proper references [e.g., (70, 71)] and based on anecdotal or unconfirmed reports [e.g., (55, 70, 72, 73)], fallacious comparisons [e.g., (74)], and reaching arguments lacking a logical process [e.g., (70, 73, 75, 76)]. Further, much information given as fact was contrary to that published in the scientific literature; indeed, many authors appeared to selectively reference articles and information in a way that would benefit their own arguments [e.g., (55, 71)]. The results of this BSTS special issue failed to provide valid, defensible scientific and social arguments to suggest that wind turbines, regardless of siting considerations, cause harm to human health.

Hanning and Evans (45) and Chapman (46): in 2012, Hanning and Evans had an editorial published in the British Medical Journal (BMJ), the purpose of which was to opine on the relationship between wind turbines noise and health effects. By citing a short list of articles (12), half of which are from the non-indexed journal BSTS or from conference proceedings (3 and 3, respectively, out of 12), Hanning and Evans suggested that: *"A large body of evidence now exists to suggest that wind turbines disturb sleep and impair health at distances and external noise levels that are permitted in most jurisdictions."* and *"Robust independent research into the health effects of existing wind farms is long overdue, as is an independent review of existing evidence and guidance on acceptable noise levels."*

Shortly after publication, this editorial was rebuffed by Chapman (46), in another editorial placed in the BMJ. Chapman pointed out that there are a number of independent reviews of the literature around wind turbines and human health (Chapman points to 17 such papers not referenced by Hanning and Evans). Chapman opined that: *"These reviews strongly state that the evidence that wind turbines themselves cause problems is poor.*

[1] http://bst.sagepub.com/

They conclude that: Small minorities of exposed people claim to be adversely affected by turbines; Negative attitudes to turbines are more predictive of reported adverse health effects and annoyance than are objective measures of exposure; Deriving income from hosting wind turbines may have a "protective effect" against annoyance and health symptoms." Further debate about the original editorial is available online to view (and comment on) through the BMJ web site[2].

Farboud et al. (47): this review article looked at the effects of LFN and infrasound and questioned the existence of "wind turbine syndrome." The authors conducted a literature search for articles published within the last 10 years, using the PubMed database and the Google Scholar search engine. Their search terms included "wind turbine," "infrasound," or "LFN" and search results were limited to the English language, human trials, and either randomized control trials, meta-analyses, editorial letters, clinical trials, case reports, comments, or journal articles. A number of articles dealing with "wind turbine," "infrasound," or "LFN," and available in PubMed and Google Scholar, appear to have been missed by Farboud et al. [e.g., (9, 22, 38)]. The review included discussions on topics such as wind turbine noise measurements and regulations, wind turbine syndrome, and the effects of LFN and infrasound.

The authors discussed the use of A-weighting in noise measurements from wind turbines stating: *"The A-filter de-emphasizes all auditory energy with frequencies of less than 500 Hz, and completely ignores all auditory energy of less than 20 Hz, in an effort to estimate the noise thought to be actually processed by the ear. Hence, much of the noise produced by a wind turbine is effectively ignored."* The authors later described the results and implications of studies looking at the effects of infrasound in the ear, and noted that infrasound and LFN are currently not recognized as disease agents. Referencing a study by Salt and Hullar (20), the authors noted that the inner hair cells of the cochlea, which is the main hearing pathway in mammals, are not sensitive to infrasound. Conversely, the outer hair cells of the cochlea are more sensitive to LFN and infrasound and can be stimulated at levels below the auditory threshold. Nevertheless, the authors conceded that: *"...low-frequency noise may well influence inner ear physiology. However, whether this actually alters function or causes symptoms is unknown."*

It should be noted that, as discussed in the "Low-Frequency Noise and Infrasound" section of this review, there were a number of studies that specifically addressed the concerns of LFN and infrasound from wind turbines that suggested that these were unlikely to be causative agents in health effects of those living near wind turbines [e.g., (7, 11, 22, 37, 38)]. Unfortunately, none of these studies were included as part of the Farboud et al. review.

Regarding the existence of "Wind Turbine Syndrome," Farboud et al. stated that: *"There is an abundance of information available on the internet describing the possibility of wind turbine syndrome. However, the majority of this information is based on purely anecdotal evidence."* The authors briefly discussed the various symptoms that have been self-reported by individuals and attributed to noise from wind turbines. They also pointed out that "Wind Turbine Syndrome" was not a clinically recognized diagnosis, remained unproven, and was not generally accepted within the scientific and medical community. They also mentioned that some researchers maintained that the effects of "Wind Turbine Syndrome" were just examples of the well-known stress effects of exposure to noise, as displayed by a small proportion of the population.

Farboud et al. concluded their review by suggesting that the evidence available was incomplete and until the physiological effects of LFN and infrasound were fully understood, it was not possible to conclusively state that wind turbines were not causing any of the reported effects. However, it was not clear how this conclusion might have been altered had they considered the additional available information regarding LFN and infrasound from wind turbines described elsewhere in this review [i.e., (7, 11, 22, 37, 38)].

McCubbin and Sovacool (48): McCubbin and Sovacool (48) presented a comparison of the health and environmental benefits of wind power in contrast to natural gas. The authors selected two locations: the 580 MW wind farm at Altamont Pass in California and the 22 MW wind farm in Sawtooth, ID, USA. The paper considered the environmental and economic benefits associated with each wind farm. Human health benefits were calculated based on a reduction in ambient $PM_{2.5}$ levels using well-established health impact and valuation functions from the US EPA. Additionally, benefits to the health and well-being of wildlife and avian species were quantified.

With regard to the human health impacts, the potential cost savings were associated with effects such as premature mortality, hospital admissions, emergency rooms visits, asthma attacks, and respiratory symptoms. The details of the quantification methods and equations used to calculate the benefits to externalities such as human health, wildlife, and the natural environment were not provided herein but are available in the published manuscript.

McCubbin and Sovacool determined that from 2012 to 2031 the wind turbines at Altamont Pass will avoid anywhere from $560 million to $4.38 billion in human health and climate-related externalities, and the Sawtooth wind farm will avoid from $18 million to $24 million. The authors noted that there were uncertainties associated with their quantification methods and final cost estimates; however, they claimed that the values were likely underestimated based on numerous factors that were not considered (e.g., other pollutants). They concluded that: *"Despite the uncertainties, the evidence gathered here strongly suggests that natural gas had substantial external costs that should be included in an evaluation comparing wind energy to combined cycle natural gas-fired power plants. The overall costs of electricity generated by natural gas are greater than those from wind energy when environmental and human health externalities are quantified. It remains likely that over time the relative difference will widen, making the use of wind energy even more favorable."*

Roberts and Roberts (49): the authors conducted a summary of the peer-reviewed literature on the research that examined the relationship between human health effects and exposure to LFS and sound generated from the operation of wind turbines. The PubMed database (maintained by the US National Library of Medicine) was relied upon for retrieving the peer-reviewed literature used in this review. A number of search terms were used including: "infrasound and health effects"; "LFN and health effects"; "LFS and health effects"; "wind power and noise"; and "wind turbines AND

[2]http://www.bmj.com/content/344/bmj.e1527?tab=responses

noise." In total, 156 articles were identified with 28 articles addressing health effects and LFS related to wind turbines. Based on the collective results of the studies reviewed, Roberts and Roberts (49) found that: *"At present, a specific health condition or collection of symptoms has not been documented in the peer-reviewed, published literature that has been classified as a 'disease' caused by exposure to sound levels and frequencies generated by the operations of wind turbines. It can be theorized that reported health effects are a manifestation of the annoyance that individuals experience as a result of the presence of wind turbines in their communities."*

Chapman and St. George (50): in 2007, Alves-Pereira and Castelo Branco issued a press-release suggesting that their research demonstrated that living in proximity to wind turbines had led to the development of VAD in nearby home-dwellers (9). Alves-Pereira and Castelo Branco appear to be the primary researchers who have circulated VAD as a hypothesis for adverse health effects and wind turbines and to our knowledge this work has never appeared in a peer-reviewed article. In this paper, Chapman and St. George investigated the extent to which VAD and its alleged association with wind turbine exposure had received scientific attention, the quality of that association, and how the alleged association gained support by wind farms opponent.

Based on a structured scientific database and Google search strategy, the authors showed that *"VAD has received virtually no scientific recognition beyond the group who coined and promoted the concept. There is no evidence of even rudimentary quality that vibroacoustic disease is associated with or caused by wind turbines."* They went on to state that an implication of this "factoid" – defined as questionable or spurious statements – may have been contributing to nocebo effects among those living near turbines. That is the spread of negative, often emotive information would be followed by increases in complaints and that without such suggestions being spread, complaints would be less. These results highlighted the role that perception plays in the human health wind turbine debate and underscored the role of proper risk communication in communities.

Jeffery et al. (51, 52): the overall goal of these commentary pieces was to provide information to physicians regarding the possible health effects of exposure to noise produced by wind turbines and how these may manifest in patients. In the 2013 article, information about the *Green Energy Act* was presented in such a way that implied that the overall goal of the Act was to remove protective noise regulations and allow wind turbines to be placed "in close proximity to family homes." The authors suggested that there has been a concerted effort to minimize the potential health risks while convincing the general public and physicians that wind turbines are beneficial. No evidence was given to support these claims. Case reports and publications that reported adverse effects following wind turbines noise exposure were briefly discussed; however, only the negative health effects were highlighted. Older literature and a number of non-peer-reviewed articles and media reports were used to support the author's opinions. The 2014 paper is very similar to that published in 2013. The authors provided a very one-sided opinion in their review of the issue of wind turbines and adverse health effects. They have missed a number of key and pertinent articles that have been published on the issue. Overall the authors did not provide adequate data or support for their arguments, in both papers, nor did they provide accurate information regarding the weight of scientific data on the issue.

WEIGHT OF EVIDENCE CONCLUSIONS

There are roughly 60 studies that have been conducted worldwide on the issue of wind turbines and human health. In terms of effects being related to wind turbine operational effects and wind turbine noise, there are fewer than 20 articles. The vast majority has been published in one journal (BSTS) and many of these authors sit on advisory board of the Society for Wind Vigilance, an advocacy group in the province of Ontario. However, with respect to effects being more likely attributable to a number of subjective variables (when turbines are sited correctly), there are closer to 45 articles. These articles are published by a variety of different authors with wide and diverse affiliations. Indeed, conclusions stemming from these articles are supported by studies where audible and inaudible noise has been quantified from operational wind turbines.

Based on the findings and scientific merit of the research conducted to date, it is our opinion that the weight of evidence suggests that when sited properly, wind turbines are not related to adverse health effects. This claim is supported (and made) by findings from a number of government health and medical agencies and legal decisions [e.g., (56, 77–80)]. Collectively, the evidence has shown that while noise from wind turbines is not loud enough to cause hearing impairment and is not causally related to adverse effects, wind turbine noise can be a source of annoyance for some people and that annoyance may be associated with certain reported health effects (e.g., sleep disturbance), especially at sound pressure levels >40 dB(A).

The reported correlation between wind turbine noise and annoyance is not unexpected as noise-related annoyance [described by Berglund and Lindvall (81) as a *"feeling of displeasure evoked by a noise"*] has been extensively linked to a variety of common noise sources such as rail, road, and air traffic (81–83). Noise-related annoyance from these more common sources is prevalent in many communities. For instance, results of national surveys in Canada and the U.K. by Michaud et al. (54) and Grimwood et al. (84), respectively, suggested that annoyance from noise (predominantly traffic noise) may impact approximately 8% of the general population. Even in small communities in Canada (i.e., <5000 residents) where traffic is relatively light compared to urban centers, Michaud et al. (54) reported that 11% of respondents were moderately to extremely annoyed by traffic noise.

Although annoyance is considered to be the least severe potential impact of community noise exposure (83, 85), it has been hypothesized that sufficiently high levels of annoyance could lead to negative emotional responses (e.g., anger, disappointment, depression, or anxiety) and psychosocial symptoms (e.g., tiredness, stomach discomfort, and stress) (83, 86–90). However, it is important to note that noise annoyance is known to be strongly affected by attitudinal factors such as fear of harm connected with the source and personal evaluation of the source (91–93) as well as expectations of residents (92). For wind turbines, this has been reflected in studies that have shown that subjective variables like evaluations of visual impact (e.g., beautiful vs. ugly), attitude to wind turbines (benign vs. intruders), and personality traits are more strongly related to annoyance and health effects than noise itself [e.g., (4, 5, 16, 17, 31)]. Thus, it is likely that the adverse effects exhibited by some people who live near wind turbines are a response to stress and annoyance, which are driven by multiple environmental and personal factors, and are not specifically caused by any unique characteristic of wind turbines. This hypothesis is also supported by the observation that people who economically benefit from wind turbines have significantly decreased levels of annoyance compared to individuals that received no economic benefit, despite exposure to similar, if not higher, sound levels (17).

There is also a growing body of research that suggests that nocebo effects may play a role in a number of self-reported health impacts related to the presence of wind turbines. Negative attitudes and worries of individuals about perceived environmental risks have been shown to be associated with adverse health-related symptoms such as headache, nausea, dizziness, agitation, and depression, even in the absence of an identifiable cause (94–96). Psychogenic factors, such as the circulation of negative information and priming of expectations have been shown to impact self-assessments following exposure to wind turbine noise (6–8). It is therefore important to consider the role of mass media in influencing public attitudes about wind turbines and how this may alter responses and perceived health impacts of wind turbines in the community. For example, Deignan et al. (97) recently demonstrated that newspaper coverage of the potential health effects of wind turbines in Ontario has tended to emphasize "fright factors" about wind turbines. Specifically, Deignan et al. (97) reported that 94% of articles provided *"negative, loaded or fear-evoking"* descriptions of *"health-related signs, symptoms or adverse effects of wind turbine exposure"* and 58% of articles suggested that the effects of wind turbines on human health were *"poorly understood by science."* It is possible that this type of coverage may have a significant impact on attitudinal factors, such as fear of the noise source, that are known to increase noise annoyance (91–93).

Stress/annoyance is not unique to living in proximity to wind turbines. The American Psychological Association (98) published a report stating that the majority of Americans are living with moderate (4 to 7 on a scale of 1 to 10) or high (8 to 10 on a scale of 1 to 10) levels of stress. APA identified money, work, and the economy as the most often cited sources of stress in Americans followed by family responsibilities, relationships, job stability, housing costs, health concerns, health problems, and safety. Stress from these and other sources can lead to a number of adverse health effects that are commonplace in society. The Mayo Clinic (99) identifies irritability, anger, anxiety, sadness/guilt, change in sleep, fatigue, difficulty concentrating or making decisions, loss of interest/enjoyment, nausea, headache, and tinnitus as common symptoms of stress. Interestingly, these symptoms are nearly identical to those suggested by McMurtry (55) as criteria for a *"diagnosis of adverse health effects in the environs of industrial wind turbines."*

Based on the available evidence, we suggest the following best practices for wind turbine development in the context of human health. However, it should be noted that subjective variables (e.g., attitudes and expectations) are strongly linked to annoyance and have the potential to facilitate other health complaints via the nocebo effect. Therefore, it is possible that a segment of the population may remain annoyed (or report other health impacts) even when noise limits are enforced.

1. Setbacks should be sound-based rather than distance-based alone.
2. Preference should be given to sound emissions of ≤40 dB(A) for non-participating receptors, measured outside, at a dwelling, and not including ambient noise. This value is the same as the WHO (Europe) night noise guideline (100) and has been demonstrated to result in levels of wind turbine community annoyance similar to, or lower than, known background levels of noise-related annoyance from other common noise sources.
3. Post construction monitoring should be common place to ensure modeled sound levels are within required noise limits.
4. If sound emissions from wind projects is in the 40–45 dB(A) range for non-participating receptors, we suggest community consultation and community support.
5. Setbacks that permit sound levels >45 dB(A) (wind turbine noise only; not including ambient noise) for non-participating receptors directly outside a dwelling are not supported due to possible direct effects from audibility and possible levels of annoyance above background.
6. When ambient noise is taken into account, wind turbine noise can be >45 dB(A), but a combined wind turbine-ambient noise should not exceed >55 dB(A) for non-participating and participating receptors. Our suggested upper limit is based on WHO (100) conclusions that noise above 55 dB(A) is "*considered increasingly dangerous for public health,*" is when "*adverse health effects occur frequently, a sizeable proportion of the population is highly annoyed and sleep-disturbed*" and "*cardiovascular effects become the major public health concern, which are likely to be less dependent on the nature of the noise.*"

Over the past 20 years, there has been substantial proliferation in the use of wind power, with a global increase of over 50-fold from 1996 to 2013 (1). Such an increase of investment in renewable energy is a critical step in reducing human dependency on fossil fuel resources. Wind-based energy represents a clean resource that does not produce any known chemical emissions or harmful wastes. As highlighted in a recent editorial in the British Medical Journal, reducing air pollution can provide significant health benefits, including reducing asthma, chronic obstructive pulmonary disease, cancer, and heart disease, which in turn could provide significant savings for health care systems (101). By following our proposed health-based best practices for wind turbine siting, wind energy developers, the media, members of the public and government agencies can work together to ensure that the full potential of this renewable energy source is met.

AUTHOR CONTRIBUTIONS

All authors contributed in varying degrees to writing, editing, and reviewing this manuscript.

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ENVIRONMENTAL HEALTH

REVIEW **Open Access**

Health effects and wind turbines: A review of the literature

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Abstract

Background: Wind power has been harnessed as a source of power around the world. Debate is ongoing with respect to the relationship between reported health effects and wind turbines, specifically in terms of audible and inaudible noise. As a result, minimum setback distances have been established world-wide to reduce or avoid potential complaints from, or potential effects to, people living in proximity to wind turbines. People interested in this debate turn to two sources of information to make informed decisions: scientific peer-reviewed studies published in scientific journals and the popular literature and internet.

Methods: The purpose of this paper is to review the peer-reviewed scientific literature, government agency reports, and the most prominent information found in the popular literature. Combinations of key words were entered into the Thomson Reuters Web of Knowledge[SM] and the internet search engine Google. The review was conducted in the spirit of the evaluation process outlined in the Cochrane Handbook for Systematic Reviews of Interventions.

Results: 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. To date, no peer reviewed articles demonstrate a direct causal link between people living in proximity to modern wind turbines, the noise they emit and resulting physiological health effects. If anything, reported health effects are likely attributed to a number of environmental stressors that result in an annoyed/stressed state in a segment of the population. In the popular literature, self-reported health outcomes are related to distance from turbines and the claim is made that infrasound is the causative factor for the reported effects, even though sound pressure levels are not measured.

Conclusions: What both types of studies have in common is the conclusion that wind turbines can be a source of annoyance for some people. The difference between both types is the reason for annoyance. While 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), given that annoyance appears to be more strongly related to visual cues and attitude than to noise itself, self reported health effects of people living near wind turbines are more likely attributed to physical manifestation from an annoyed state than from wind turbines themselves. In other words, it appears that it is the change in the environment that is associated with reported health effects and not a turbine-specific variable like audible noise or infrasound. Regardless of its cause, a certain level of annoyance in a population can be expected (as with any number of projects that change the local environment) and the acceptable level is a policy decision to be made by elected officials and their government representatives where the benefits of wind power are weighted against their cons. Assessing the effects of wind turbines on human health is an emerging field and conducting further research into the effects of wind turbines (and environmental changes) on human health, emotional and physical, is warranted.

Keywords: Wind turbines, health, annoyance, infrasound, sound pressure level, noise

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Background

Wind power has been identified as a clean renewable energy source that does not contribute to global warming and is without known emissions or harmful wastes [1]. Studies on public attitudes in Europe and Canada show strong support for the implementation of wind power [2]. Indeed, wind power has become an integrated part of provincial energy strategies across Canada; in Ontario, the Ontario Power Authority has placed a great deal of emphasis on procuring what they term "renewable and cleaner sources of electricity", such as wind [3].

Although wind power has been harnessed as a source of electricity for several decades around the world, its widespread use as a significant source of energy in Ontario is relatively recent. As with the introduction of any new technology, concerns have been raised that wind power projects could lead to impacts on human health. These concerns are related to two primary issues: wind turbine design and infrastructure (i.e., electromagnetic frequencies from transmission lines, shadow flicker from rotor blades, ice throw from rotor blades and structural failure) and wind turbine noise (i.e., levels of audible noise [including low frequency noise] and infrasound). If left unchecked and unmanaged, it is possible that individually or cumulatively, these issues could lead to potential health impacts. In terms of noise, high sound pressure levels (loudness) of audible noise and infrasound have been associated with learning, sleep and cognitive disruptions as well as stress and anxiety [4-8].

As a result, minimum setback distances have been established world-wide to reduce or avoid potential effects for people living in proximity to wind turbines. Under the Ontario Renewable Energy Approval (REA) Regulation (O. Reg. 359/09, as amended by O. Reg. 521/10), a minimum setback distance of 550 m must exist between the centre of the base of the wind turbine and the nearest noise receptor (e.g., a building or campground). This minimum setback distance was developed through noise modeling under worst-case conditions to give a conservative estimate of the required distance to attain a sound level of 40 dB(A) [9], the noise level that corresponds to the WHO (Europe) night-noise guideline, a health-based limit value "necessary to protect the public, including most of the vulnerable groups such as children, the chronically ill and the elderly, from the adverse health effects of night noise" [8]. Globally, rural residential noise limits are generally set at 35 to 55 dB(A) [10].

This paper focuses on the research involving land-based wind turbine projects. There are several international off-shore marine projects that are in operation. There was considerable interest in Ontario in developing off-shore wind projects on the Great Lakes. However, in February, 2011 the Province announced that it would not proceed with proposed offshore wind projects until further scientific research is conducted http://www.news.ontario.ca/ene/en/2011/02/ontario-rules-out-off-shore-wind-projects.html. This does not appear to have been related, however, to health concerns.

Regardless, debate is ongoing with respect to the relationship between reported health effects and wind turbines, specifically in terms of audible and inaudible noise. People interested in this debate tend to turn to two sources of information in order to make decisions: scientific peer-reviewed studies published in scientific journals, and the popular literature and internet. For the general public, the latter sources are the most readily available and numerous websites have been constructed by individuals or groups to support or oppose the development of wind farms. Often these websites state the perceived impacts on, or benefits to, human health to support the position of the individual or group. The majority of information posted on these websites cannot be traced back to a scientific peer-reviewed source and is typically anecdotal in nature. This serves to spread misconceptions about the potential impacts of wind energy on human health making it difficult for the general public (and scientists) to ascertain which claims can be substantiated by scientific evidence.

Accordingly, the purpose of this paper is to provide results of a review of the peer-reviewed scientific literature and the most prominent information found in the popular literature. We have selected this journal as the source of publication because it is a scientifically credible journal with peer-reviewed articles that are easily accessible by the general population who are interested in the subject of wind turbines and health effects. Results of this review are used to draw conclusions about wind turbines and health effects using a weight-of-evidence approach.

Methods

Peer-Reviewed Literature

Publication of scientific findings is the basis of scientific discourse, communication and debate. The peer review process is considered a fundamental tenet of quality control in scientific publishing. Once a research paper has been submitted to a journal for publication it is reviewed by external independent experts in the field. The experts review the validity, reliability and importance of the results and recommend that the manuscript be accepted, revised or rejected. This process, though not perfect, ensures that the methods employed and the findings of the research receive a high level of scrutiny, such that an independent researcher could repeat the experiment or calculation of results, prior to their publication. This process seeks to ensure that the published research is of a high standard of quality, accurate, can be reproduced and demonstrates academic/professional integrity.

In order to assess peer-reviewed studies designed to test hypotheses about the association between potential health effects in humans and wind turbines, a review of the primary scientific literature was conducted. While our review did not strictly follow the evaluation process outlined in the Cochrane Handbook for Systematic Reviews of Interventions [11], the standard for conducting information reviews in healthcare and pharmaceutical industries, it was conducted in the spirit of the Cochrane systematic review in that it was designed based on the principle that "science is cumulative", and by considering all available evidence, decisions could be made that reflect the best science available. It also involves critical review and critique of the published literature and at times weighting some manuscripts over others in the same scientific field.

To facilitate this review, combinations of key words (i.e., annoyance, noise, environmental change, sleep disturbance, epilepsy, stress, health effect(s), wind farm(s), infrasound, wind turbines(s), low frequency noise, wind turbine syndrome, neighborhood change) were selected and entered into the Thomson Reuters (formerly ISI) Web of Knowledge^{SM}. The Web of Knowledge^{SM} is a database that covers over 10,000 high-impact journals in the sciences, social sciences, and arts and humanities, as well as international proceedings coverage for over 120,000 conferences. The Web of Knowledge^{SM} comprises seven citation databases, two of which are relevant to the search: the Science Citation Index Expanded (SCI-Expanded) and the Social Sciences Citation Index (SSCI). The SCI-Expanded includes over 6,650 major journals across 150 scientific disciplines and includes all cited references captured from indexed articles. Coverage of the literature spans the year 1900 to the present. On average, 19,000 new records per week are added to the SCI-Expanded. SSCI is a multidisciplinary index of the social sciences literature. SSCI includes over 1,950 journals across 50 social sciences disciplines from the year 1956 to the present. It averages 2,900 new records per week. Use of this literature search platform means the most up-to-date multidisciplinary studies published and peer-reviewed could be obtained.

Although hundreds of articles were found during the search, very few were related to the association between potential health effects and wind turbines. For example, numerous articles have been published about infrasound, but very few have been published about infrasound and wind turbines. Indeed, only fifteen articles, published between 2003 and 2011, were found relevant [12-26]. What can be seen from these articles is that the relationship between wind turbines and human responses to them is extremely complex and influenced by numerous variables, the majority of which are nonphysical. What is clear is that some people living near wind turbines experience annoyance due to wind turbines, and visual impact tends to be a stronger predictor of noise annoyance than wind turbine noise itself. Swishing, whistling, resounding and pulsating/throbbing are sound characteristics most highly correlated with annoyance by wind turbine noise for those people who noticed the noise outside their dwellings. Some people are also disturbed in their sleep by wind turbines. In general, five key points have come out of these peer-reviewed studies with regards to health and wind turbines.

1. People tend to notice sound from wind turbines almost linearly with increasing sound pressure level

In the studies designed to evaluate the interrelationships amongst annoyance and wind turbine noise, as well as the influence of subjective variables such as attitude and noise sensitivity, Pedersen and Persson Waye [13-15] showed that people tend to notice sound from wind turbines almost linearly with increasing sound pressure level. Briefly, Pedersen and Persson Waye conducted cross-sectional studies (in 2004: n = 351; in 2007: n = 754) and gave people questionnaires regarding housing and satisfaction with the living environment, including questions about degree of annoyance experienced outdoors and indoors and sensitivity to environmental factors, wind turbines (noise, shadows, and disturbances), respondents' level of perception and annoyance, and verbal descriptors of sound and perceptual characteristics. The third section had questions about chronic health (e.g., diabetes, tinnitus, cardiovascular diseases), general wellbeing (e.g., headache, undue tiredness feeling tensed/stressed, irritable) and normal sleep habits (e.g., quality of sleep, whether or not sleep was disturbed by any noise source). The last section comprised questions on employment and working hours. Of import, the purpose of the study was masked in the questionnaires, which was done to reduce the potential for survey bias.

Of the 754 respondents involved in the Pedersen and Persson Waye study [14], 307 (39%) noticed sound from wind turbines outside their dwelling (range of sound pressure level: < 32.5, 32.5-35.0, 35.0-37.5, 37.5-40.0, and > 40.0 dB(A)) and the proportion of respondents who noticed sound increased almost linearly with increasing noise. In the 37.5-40.0 dB(A) range, 76% of the 71 respondents reported that they noticed sound from the wind turbines; 90% of respondents (n = 18) in the > 40.0 dB(A) category noticed sound from the wind turbines. The odds of noticing sound increased by 30% for each increase in dB(A) category. When data from both studies [13,14] were combined (n = 1095) results were the same: the proportion of respondents who noticed sound from wind turbines showed increased almost linearly with increasing sound pressure level from roughly 5-15% of people noticing noise at 29 dB(A) to 45-90% noticing noise at 41 dB (A)[15].

In 2011 Pedersen [25] reported on the results of three cross-sectional studies conducted in two areas of Sweden (a flat rural landscape (n = 351) and suburban sites with hilly terrain (n = 754) and one location in the Netherlands (flat landscape but with different degrees of road traffic intensity (n = 725)) designed assess the relationship between wind turbine noise and possible adverse health effects. Questionnaires were mailed to people in the three areas to obtain information about annoyance and health effects in response to wind turbines noise. Pedersen included questions about several potential environmental stressors and did not allow participants to know that the focus of the study was on wind turbine noise, again in an attempt to reduce self-reporting survey bias. For each respondent, sound pressure levels (dB(A)) were calculated for nearby wind turbines. The questionnaires were designed to obtain information about people's response to noise (i.e., annoyance), diseases or symptoms of impaired health (i.e., chronic disease, diabetes, high blood pressure, cardiovascular disease, tinnitus, impaired hearing), stress symptoms (i.e., headache, undue tiredness, feeling tense or stressed, feeling irritable), and disturbed sleep (i.e., interruption of the sleep by any noise source). Results showed that the frequency of those annoyed with wind turbines was related to an increase in sound pressure level as shown by odds ratios (OR) with 95% confidence intervals (CI) greater than 1.0. Sleep interruption was associated with sound level in two of the three studies (the areas with flat terrain), but unlike the finding that people tend to notice sound from wind turbines almost linearly with increasing sound pressure level, sleep disturbance did not increase gradually with noise levels, but spiked at 40 dBA and 45 dBA.

2. A proportion of people that notice sound from wind turbines find it annoying

Results of the Pedersen and Persson Waye studies [13-15] also suggested that the proportion of participants who were fairly annoyed or very annoyed remained quite level through the 29-37 dB(A) range (no more than roughly 5%) but increased at noise levels above 37 dB(A), with peaks at 38 db(A) and 41 dB(A), where up to 30% of people were very annoyed. Respondents in the cross-sectional studies (and other studies [12]) noted that swishing, whistling, resounding and pulsating/throbbing were the sound characteristics that were most highly correlated with annoyance by wind turbine noise among respondents who noticed the noise outside their dwellings. This was also found by Leventhall [16]. Seven percent of respondents (n = 25) from the Pedersen and Persson Waye study [13] were annoyed by noise from wind turbines indoors, and this was related to noise category; 23% (n = 80) were disturbed in their sleep by noise. Of the 128 respondents living at sound exposure above 35.0 dB(A), 16% (n = 20) stated that they were disturbed in their sleep by wind turbine noise. The authors comment that some people may find wind turbine noise more annoying than that of other types of noise (e.g., airplane and traffic) experienced at similar decibel levels.

Similar results were shown by Pedersen and Persson Waye [14]: a total of 31 of the 754 respondents said they were annoyed by wind turbine noise. In the < 32.5 to the 37.5 dB(A) category 3% to 4% of people said they were annoyed by wind turbine noise; in the 37.5-40.0 dB(A) category, 6% of the 71 respondents were annoyed; and in the > 40.0 category, 15% of 20 of respondents said they were annoyed by wind turbine noise. In addition, 36% of those 31 respondents who were annoyed by wind turbine noise reported that their sleep was disturbed by a noise source. Nine percent of those 733 respondents not annoyed said their sleep was disturbed by a noise source. Results of Pedersen [25] showed similar results: the frequency of those annoyed was related to an increase in sound pressure level. Moreover, self reported health effects like feeling tense, stressed, and irritable, were associated with noise annoyance and not to noise itself (OR and 95% CI > 1.0). Sleep interruption, however, was associated with sound level and annoyance (OR and 95%CI > 1.0). Pedersen notes that this finding is not necessarily evidence of a causal relationship between wind turbine noise and stress but may be explained by cognitive stress theory whereby "an individual appraises an environmental stressor, such as noise, as beneficial or not, and behaves accordingly". In other words, it appears that it is the change in the environment that is associated with the self-reported health effects, not the presence of wind turbines themselves.

Keith et al. [17] proposed that in a quiet rural setting, the predicted sound level from wind turbines should not exceed 45 dB(A) at a sensitive receptor location (e.g., residences, hospitals, schools), a value below the World Health Organization guideline for sleep and speech disturbance, moderate annoyance and hearing impairment. The authors [17] suggest this level of noise could be expected to result in a 6.5% increase in the percentage of highly annoyed people. Since publication of the Keith et al. study, the WHO Europe Region has released new Night Noise Guidelines for Europe [8] and state that: "The new limit is an annual average night exposure not exceeding 40 decibels (dB), corresponding to the sound from a quiet street in a residential area". The value of 40 dB is considered the lowest observed adverse effect level (LOAEL) for night noise based on the finding that an average night noise level over a year of 30-40 dB can result in a number of effects on sleep such as body movements, awakening, self-reported sleep disturbance and arousals [8]. The WHO states that even in the worst cases these effects seem modest [8].

3. Annoyance is not only related to wind turbine noise but also to subjective factors like attitude to visual impact, attitude to wind turbines and sensitivity to noise

Pedersen and Persson Waye [13] revealed that attitude to visual impact, attitude to wind turbines in general, and sensitivity to noise were also related to the way people perceived noise from turbines. For example, 13% of the variance in annoyance from wind farms could be explained by noise and the odds that respondents would be annoyed by noise from wind turbines increased 1.87 times from one sound category to the next. When noise and attitude to visual impact was statistically assessed, 46% of the variance in annoyance from wind farms could be explained and the odds that respondents would be annoyed from wind turbines increased 5.05 times from one sound category to the next. Statistical analyses showed that while attitude to wind turbines in general and sensitivity to noise were also related to annoyance, they did not have a greater influence on annoyance than visual effect. Building on their 2004 paper, Pedersen and Persson Waye [14] conducted a cross-sectional study in seven areas in Sweden across dissimilar terrains and with different degrees of urbanization. Three areas were classified as suburban; four as rural. Noise annoyance related to wind turbines was also statistically related to whether or not people live in suburban or rural areas and landscape (flat vs. hilly/complex). Visual impact has come out as a stronger predictor of noise annoyance than wind turbine noise itself. People who economically benefit from wind turbines had significantly decreased levels of annoyance compared to individuals that received no economic benefit, despite exposure to similar sound levels [18].

One suggestion of the difference between rural and suburban areas is level of background sound and interestingly, perception and annoyance was associated with type of landscape, "indicating that the wind turbine noise interfered with personal expectations in a less urbanised area... pointing towards a personal factor related to the living environment" [14]. The authors also concluded that visual exposure enhances the negative associations with turbines when coupled with audible exposure. They also point out that this study showed that aesthetics play a role in annoyance: "respondents who think of wind turbines as ugly are more likely to appraise them as not belonging to the landscape and therefore feel annoyed" [14].

In 2007 Pedersen et al. [19] conducted a grounded theory study to gain a deeper understanding of how people living near wind turbines perceive and are affected by them. Findings indicated that the relationship between exposure and response is complex and possibly influenced by variables not yet identified, some of which are nonphysical. The notion that wind turbines are "intruders" is a finding not reported elsewhere. A conclusion of this paper is that when the impacts of wind turbines are assessed, values about the living environment are important to consider as values are firmly rooted within a personality and difficult to change.

In 2008, Pedersen and Larsman [20] conducted a study to assess visibility of wind turbines, visual attitude and vertical visual angle (VVA) in different landscapes. This study follows up on the findings of previous work showing a relationship between noise annoyance in people living near wind turbines and the impact of visual factors as well as an individual's attitude toward noise [13-15,25]. Overall, Pedersen and Larsman concluded that respondents in a landscape where wind turbines could be perceived as contrasting with their surroundings (i.e., flat areas) had a greater probability of noise annoyance than those in hilly areas (where turbines were not as obvious), regardless of sound pressure level, if they thought wind turbines were ugly, unnatural devices that would have a negative impact on the scenery. The enhanced negative response could be linked to aesthetical response, rather than to multi-modal effects of simultaneous auditory and visual stimulation. Moreover, VVA was associated with noise annoyance, especially for respondent who could see at least one wind turbine from their dwelling, if they were living in flat terrain and rural areas. Pedersen and Larsman suggest that these results underscore the importance of visual attitude towards the noise source when exploring response to environmental noise. In 2010 Pedersen et al. [21] hypothesized that if high levels of background sound can reduce annoyance by masking the noise from a wind farm, then turbines could cause less noise annoyance when placed next to motorways instead of quiet agricultural areas. In general, the hypothesis was not supported by the available data [15], further providing support for the notion of visual cue being a strong driver of annoyance.

4. Turbines are designed not to pose a risk of photo-induced epilepsy

Harding et al. [22] and Smedley et al. [23] investigated the relationship between photo-induced seizures (i.e., photosensitive epilepsy) and wind turbine blade flicker (also known as shadow flicker). This is an infrequent event, typically modelled to occur less than 30 hours a year from wind turbine projects we have reviewed and would be most common at dusk and dawn, when the sun is at the horizon. Both studies suggested that flicker from turbines that interrupt or reflect sunlight at frequencies greater than 3 Hz pose a potential risk of inducing photosensitive seizures in 1.7 people per 100,000 of the photosensitive population. For turbines with three blades, this translates to a maximum speed of rotation of 60 rpm. The normal practice for large wind farms is for frequencies well below this threshold.

Although shadow flicker from wind turbines is unlikely lead to a risk of photo-induced epilepsy there has been little if any study conducted on how it could heighten the annoyance factor of those living in proximity to turbines. It may however be included in the notion of visual cues. In Ontario it has been common practice to attempt to ensure no more than 30 hours of shadow flicker per annum at any one residence.

5. The human ear responds to infrasound

Infrasound is produced by physiological processes like respiration, heartbeat and coughing, as well as man-made sources like air conditioning systems, vehicles, some industrial processes and wind turbines. Salt and Hullar [24] provide data to suggest that the assumption that infrasound presented at an amplitude below what is audible has no influence on the ear is erroneous and summarize the results of previous studies that show a physiological response of the human ear to low frequency noise (LFN) and infrasound. At very low frequencies the outer hair cells (OHC) of the cochlea may be stimulated by sounds in the inaudible range. Salt and Hullar hypothesize that “if infrasound is affecting cells and structures at levels that cannot be heard this leads to the possibility that wind turbine noise could be influencing function or causing unfamiliar sensations”. These authors do not test this hypothesis in their paper but suggest the need for further research.

To assess the possibility that the operation of wind turbines may create unacceptable levels of low frequency noise and infrasound, O’Neal et al. [26] conducted a study (commissioned by a wind energy developer, NextEra Energy Resources, LLC) to measure wind turbine noise outside and within nearby residences of turbines. At the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas, broadband (A-weighted) and one-third octave band data (3.15 hertz to 20,000 hertz bands) were simultaneously collected from General Electric (GE) 1.5sle (1.5 MW) and Siemens SWT-2.3-93 (2.3 MW) wind turbines. Data were collected outdoors and indoors over the course of one week under a variety of operational conditions (it should be noted that wind speeds were low during the measurements; between 3.2 and 4.1 m/s) at two distances from the nearest wind turbines: 305 meters and 457 meters. O’Neal et al. found that the measured low frequency sound and infrasound at both distances (from both turbine types at maximum noise conditions) were less than the standards and criteria published by the cited agencies (e.g., UK DEFRA (Department for Environment, Food, and Rural Affairs); ANSI (American National Standards Institute); Japan Ministry of Environment). The authors concluded that results of their study suggest that there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 305 meters from the two wind turbine types measured.

Popular Literature

Scientific studies peer reviewed and published in scientific journals are one way of disseminating information about wind turbines and health effects. The general public does not always have access to scientific journals and often get their information, and form opinions, from sources that are less accountable (e.g., the popular literature and internet). Some of the same key words used to obtain references from the primary literature were entered into the common internet search engine Google: “health effects wind farms” returned 300,000 hits; “health effects wind turbines” returned 120,000 hits; “annoyance wind turbines” returned 185,000 hits and “sleep disturbance wind turbines” returned 19,500 hits. What is apparent is that numerous websites have been constructed by individuals or groups to support or oppose the development of wind turbine projects, or media sites reporting on the debate. Often these websites state the perceived impacts on, or benefits to, human health to support the position of the individual or group hosting the website. The majority of information posted on these websites cannot be traced back to a scientific, peer-reviewed source and is typically anecdotal in nature. In some cases, the information contained on and propagated by internet websites and the media is not supported, or is even refuted, by scientific research. This serves to spread misconceptions about the potential impacts of wind energy on human health, which either fuels or diminishes opposition to wind turbine project development.

Works by Dr. Michael Nissenbaum conducted at Mars Hill and Vinalhaven Maine [27] and Dr. Nina Pierpont in New York [28] seem to be the primary popular literature studies referenced on websites. These works suggest a causal link between human health effects and wind turbines. Works by Dr. Robert McMurtry and Carmen Krogh, and Lorrie Gillis, Carmen Krogh and Dr. Nicholas Kouwen [29] have also been used to suggest a relationship between health and turbines. These works have been presented as reports or as slide presentations on websites and authors of these studies have presented their findings in various forua such as invited lectures, affidavits, public meetings and open houses. Briefly, Nissenbaum evaluated 22 exposed adults (defined as living within 3500 ft of an arrangement of 28 1.5 MW wind turbines) and 27 unexposed adults (living about 3 miles away from the nearest turbine). Participants were interviewed and asked a number of questions about their perceived health, levels of stress and reliance on prescription medications in relation to the turbines [27].

In 2009, a book entitled Wind Turbine Syndrome: A Report on a Natural Experiment by Dr. Nina Pierpont, was self-published and describes "Wind Turbine Syndrome", the clinical name Dr. Pierpont coined for the collection of symptoms reported to her by people residing near wind turbines [28]. The book describes a case series study she conducted involving interviews of 10 families experiencing adverse health effects and who reside near wind turbines. Similar to the process followed by Nissenbaum, people living in proximity wind turbines were interviewed about their health. For all of these works, self-reported symptoms generally included sleep disturbance, headache, tinnitus (ringing in the ears), ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia (rapid heart rate), irritability, problems with concentration and memory and panic episodes. These symptoms have been purported to be associated with proximity to wind turbines, and specifically, to the infrasound emitted by the turbines. It should be noted that of the 351 people assessed by Pedersen and Persson Waye [13], 26% (91) reported chronic health issues (e.g., diabetes, tinnitus, cardiovascular diseases), but these issues were not statistically associated with noise levels. Results of Pedersen [25] showed similar results: self reported health effects like feeling tense, stressed, and irritable, were associated with noise annoyance and not to noise itself. Sleep interruption, however, was associated with sound level and annoyance.

In 2007, Alves-Pereira and Castelo Branco http://www.wind-watch.org/documents/industrial-wind-turbines-infrasound-and-vibro-acoustic-disease-vad/ issued a press-release suggesting that their research demonstrated that living in proximity to wind turbines has led to the development of vibro-acoustic disease (VAD) in nearby home-dwellers. It appears that this research has only been presented at a conference, has not been published in a peer-reviewed journal nor has it undergone thorough scientific review. Moreover, Alves-Pereira and Castelo Branco appear to be the primary researchers that have promulgated VAD as a hypothesis for adverse health effects and wind turbines. Indeed, Dr. Pierpont has noted that VAD is not the same "wind turbine syndrome" [28].

To date, these studies have not been subjected to rigorous scientific peer review, and given the venue for their distribution and limited availability of data, it is extremely difficult to assess whether or not the information provided is reliable or valid. What is apparent, however, is that these studies are not necessarily scientifically defensible: they do not contain noise measurements, only measured distances from study participants to the closest turbines; they do not have adequate statistical representation of potential health effects; only limited rationale is provided for the selection of study participants (in some cases people living in proximity to turbines have been excluded from the study); they suffer from a small number of participants and appear to lack of objectivity as authors are also known advocates who oppose wind turbine developments. Unlike the questionnaires used by Pedersen et al. [13-15,25], the purpose of the studies are not hidden from participants. In fact, the selection process is highly biased towards finding a population who believes they have been affected by turbines. This is not an attempt to discount the self-reported health issues of residents living near wind turbines. Rather, it points out that the self-reported health issues have not been definitively linked to wind turbines.

What the peer reviewed literature and popular literature have in common is the conclusion that wind turbines can be a source of annoyance for some people. Of note are the different reasons and possible causes for annoyance. In the peer reviewed studies, annoyance tends to peak in the > 35 dB(A) range but tends to be more strongly related to subjective factors like visual impact, attitude to wind turbines in general (benign vs. intruders) and sensitivity to noise rather than noise itself from turbines. In the popular literature, health outcomes tend to be more strongly related to distance from turbines and the claim that infrasound is the causative factor. Though sound pressure level in most of the peer reviewed studies was scaled to dB(A) (but refer to O'Neal et al. [26] for actual measurements of low frequency noise and infrasound), infrasound is a component of the sound measurements and was inherently accounted for in the studies.

Annoyance

Studies on the health effects of wind turbines, both published and peer-reviewed and presented in the popular literature, tend to conclude that wind turbines can cause annoyance for some people. A number of governmental health agencies agree that while noise from wind turbines is not loud enough to cause hearing impairment and are not causally related to adverse effects, wind turbines can be a source of annoyance for some people [1,30-34].

It has been hypothesized that the self reported health effects (e.g., sleep disturbance, headache, tinnitus (ringing in the ears), ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia (rapid heart rate), irritability, problems with concentration and memory, and panic episodes) are related to infrasound emitted from wind turbines [28]. Studies where biological effects were observed due to infrasound exposure were conducted at sound pressure levels (e.g., 145 dB and 165 dB [5,16]; 130 dB [7]) much greater than what is produced by wind turbines (e.g., see O'Neal et al. [26]). Infrasound is not unique to wind turbines but is ubiquitous in the environment due to natural and man-made sources, meaning that people living near wind turbines were exposed to infrasound prior to turbine operation. For example, Berglund and Hassmen [35] reported that infrasound (a component of low frequency sound) is emitted from road vehicles, aircraft, industrial machinery, artillery and mining explosions, air movement machinery including wind turbines, compressors, and air-conditioning units, and Leventhall [5] reported that infrasound comes from natural sources like meteors, volcanic eruptions and ocean waves. Indeed, many mammals communicate using infrasound [36]. Given the low sound pressure levels of infrasound emitted from wind turbines and the ubiquitous nature of these sounds, the hypothesis that infrasound is a causative agent in health effects does not appear to be supported.

Peer reviewed and scientifically defensible studies suggest that annoyance and health effects are more strongly related to subjective factors like visual impact and attitude to wind turbines rather than to noise itself (both audible and inaudible [i.e., infrasound]). Indeed, many of the self reported health effects are associated with numerous issues, many of which can be attributed to anxiety and annoyance (e.g., Pedersen 2011 [25]). Shargorodsky et al. [37] published that roughly 50 million adults in the United States reported having tinnitus, which is statistically correlated (based on 14,178 participants) to age, racial/ethnic group, hypertension, history of smoking, loud leisure-time, firearm, and occupational noise, hearing impairment and generalized anxiety disorder (based on 2265 participants) identified using a World Health Organization Composite Diagnostic Interview). In fact, the odds of tinnitus being related to anxiety disorder were greatest for any of the variables tested. Folmer and Griest [38], based on a study of 174 patients undergoing treatment for tinnitus at the Oregon Health Sciences University Tinnitus Clinic between 1994 and 1997, reported that insomnia is associated with greater severity of tinnitus. Insomnia is also associated with anxiety and annoyance. Bowling et al. [39] described statistically that people's perceptions of neighbourhood environment can influence health. Perceptions of problems in the area (e.g., noise, crime, air quality, rubbish/litter, traffic, graffiti) were predictive of poorer health score. In their 2003 publication Henningsen and Priebe [40] discussed the characteristics of "New Environmental Illness", illnesses where patients strongly believe their symptoms are caused by environmental factors, even though symptoms are not consistent with empirical evidence and medically unexplained. A key component to such illnesses is the patient's attitude toward the source of the environmental factor. What is more, health effects from annoyance have been shown to be mitigated though behavioural and cognitive behavioural interventions [30,41], lending support to Pedersen's [25] conclusion that health effects can be explained by cognitive stress theory. In other words, it appears that it is the change in the environment that is associated with health effects, not a turbine-specific variable like infrasound.

Conclusions

Wind power has been harnessed as a source of power around the world. Debate is ongoing with respect to the relationship between reported health effects and wind turbines, specifically in terms of audible and inaudible noise. As a result, minimum setback distances have been established world-wide to reduce or avoid potential effects for people living in proximity to wind turbines. People interested in this debate turn to two sources of information to make informed decisions: scientific peer-reviewed studies published in scientific journals and the popular literature and internet.

We found that conclusions of the peer reviewed literature differ in some ways from the conclusions of the studies published in the popular literature. What both types of studies have in common is the conclusion that wind turbines can be a source of annoyance for some people. In the peer reviewed studies, wind turbine annoyance and some reported health effects (e.g., sleep disturbance) have been statistically associated with wind turbine noise especially when found at sound pressure levels greater than 40 db(A), but found to be more strongly related to subjective factors like visual impact, attitude to wind turbines in general and sensitivity to noise. To date, no peer reviewed scientific journal articles demonstrate a causal link between people living in proximity to modern wind turbines, the noise (audible, low frequency noise, or infrasound) they emit and resulting physiological health effects. In the popular literature, self-reported health outcomes and annoyance are related to distance from turbines and the claim is made that infrasound is the causative factor for the reported effects, even though sound pressure levels are not measured. Infrasound is not unique to wind turbines and the self reported health effects of people living in proximity to wind turbines are not unique to wind turbines. Given that annoyance appears to be more strongly related to visual cues and attitude than to noise itself, self reported health effects of people living near wind turbines are more likely attributed to physical manifestation from an annoyed state than from infrasound. This hypothesis is supported by the peer-reviewed literature pertaining to environmental stressors and health.

The authors have spent countless hours at community public consultation events hosted by proponents announcing new projects and during updates to their environmental assessment process. Historically, citizens' concerns about wind turbine projects appeared to involve potential impact on property values and issues surrounding avian and bat mortality. Increasingly in North America the issue surrounding fears of potential harm to residents' health have come to the forefront of these meetings. It is clear that the announcement of a new project can led to a heightened sense of anxiety and annoyance in some members of the public, even prior to construction and operation of a wind turbine project. The authors have been involved in all manner of risk communication, consultation and risk assessment projects in the energy sector in Canada and it has been our experience that this heightened sense of annoyance, agitation or fear is not unique to the wind turbine sector. Whether the proposed project is a wind turbine, gas-fired station, coal plant, nuclear power plant, or energy-from-waste incinerator we have seen a level of concern in a sub-set of the population that goes well beyond anything that would be considered the traditional sense of not-in-my-back-yard (NIMBY). These people genuinely are fearful about the potential health effects that the project may cause, regardless of the outcomes of quantitative assessments that demonstrate that there is a *de minimus* of potential risk in living next to a particular facility. The literature and our own experience highlight the need for informative discussions between wind power developers and community members in order to attempt to reduce the level of apprehension. We encourage continued dialogue between concerned citizens and developers once projects become operational.

Canadian public health agencies subscribe to the World Health Organization definition of health. *"Health is a state of complete physical, mental and social well-being and not merely the absence of infirmity or disease"*, a quote often used by both sides of the wind turbine debate. We believe that the primary role of the environmental health/risk assessment practitioner is to ensure that physiological manifestation of infirmity or disease is not predicted to occur from exposure to an environmental contaminant. In terms of wind power, ethics dictate an honest reporting of the issues surrounding annoyance and the fact that it appears that a limited number of people have self-reported health effects that may be attributed to the indirect effects of visual and attitudinal cue. We believe that any physiological based effect can be mitigated through the use of appropriate setback distances. However, it is not clear that for this hypersensitive annoyed population that any set back distance could mitigate the indirect effects. Therefore, it is up to our elected officials and ministerial staff when establishing an energy source hierarchy to weigh all of the information before them to determine the trade-offs between "mental and social well-being" of these individuals against the larger demand for energy and its source.

A number of governmental health agencies agree that while noise from wind turbines is not loud enough to cause hearing impairment and are not causally related to adverse effects, wind turbines can be a source of annoyance for some people. Ultimately it is up to governments to decide the level of acceptable annoyance in a population that justifies the use of wind power as an alternative energy source.

Assessing the effects of wind turbines on human health is an emerging field, as demonstrated by the limited number of peer-reviewed articles published since 2003. Conducting further research into the effects of wind turbines (and environmental change) on human health, emotional and physical, as well as the effect of public consultation with community groups in reducing pre-construction anxiety, is warranted. Such an undertaking should be initiated prior to public announcement of a project, and could involve baseline community health and attitude surveys, baseline noise and infrasound monitoring, observation and questionnaires administered to public during the siting and assessment process, noise modeling and then post-construction follow-up on all of the aforementioned aspects. Regardless it would be imperative to ensure robust study design and a clear statement of purpose prior to study initiation.

We believe that research of this nature should be undertaken by multi-disciplinary teams involving, for example, acoustical engineers, health scientists, epidemiologists, social scientists and public health physicians. Ideally developers, government agencies, consulting professionals and non-government organizations would form collaborations in attempt to address these issues.

List of Abbreviations

ANSI: American National Standards Institute; CI: Confidence intervals; dB(A): A-weighted decibels; DEFRA: Department for Environment, Food, and Rural Affairs; LFN: low frequency noise; LOAEL: lowest observed adverse effect level; MW: mega watt; O.Reg.: Ontario Regulation; OR: odds ratio; OHC: outer hair cells; REA: Renewable Energy Approval; SCI: Science Citation Index; SSCI: Social Sciences Citation Index; VAD: vibro-acoustic disease; VVA: vertical visual angle; WHO: World Health Organization

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None

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Authors' contributions

LDK and CAO both researched and wrote the manuscript. Both authors read and approved the final version.

Competing interests

In terms of competing interests (financial and non-financial), the authors work for a consulting firm and have worked with wind power companies. The authors are actively working in the field of wind turbines and human health. Dr. Ollson has acted as an expert witness for wind power companies during a number of legal hearings. Although we make this disclosure, we wish to reiterate that as independent scientific professionals our views and research are not influenced by these contractual obligations. The authors are environmental health scientists, trained and schooled, in the evaluation of potential risks and health effects of people and the ecosystem through their exposure to environmental issues such as wind turbines.

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International Legislation and Regulations for Wind Turbine Shadow Flicker Impact

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Summary

When a wind farm is being developed, citizens are often concerned about the effects of shadow flicker which is caused as a result of the rotating turbine blades periodically blocking the sun light. Shadow flicker impacts are often limited by regulations which require the wind turbine is shut down at critical periods when the effects of shadow flicker occur for too long. This may lead to energy production losses depending on the specific situation.

This study presents the results of a comparative study into shadow flicker regulations in a number of countries. The results show not all countries have guidelines or regulations for assessing and limiting shadow flicker impacts. Of those countries that do have regulations or guidelines for shadow flicker impact assessment, most countries have based their regulations on the German Guideline "Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen (WEA-Schattenwurf-Hinweise)" *(Guideline for Identification and Evaluation of the Optical Emissions of Wind Turbines)*. This guideline states a limit value of 30 hours per year and 30 minutes per day for the astronomical maximum possible shadow (worst case). When a shadow flicker control module is used, the German guideline states the real shadow impact must be limited to 8 hours per year. However, there are differences in the exact implementation, like the consideration of only the worst case, only the real case or both the worst and the real case shadow impact. Other common differences are the exact definition of shadow flicker sensitive receptors and the zone of influence which has to be considered. This can lead to considerable differences in energy production losses by a shadow flicker control module. Denmark and the Netherlands have their own specific limit values. The Dutch legislation is most deviating since the limit value comprises a combination of days per year and minutes per day.

1. Introduction

In sunny conditions wind turbines cast a shadow on the neighbouring area. Shadow flicker is the flickering effect caused by the rapid periodic occurrence of shadow by the rotating turbine blades. The impacts of shadow flicker impact vary with time and place depending on several factors such as the position and height of the sun relative to the wind turbines and the receptors, the wind turbine hub height and its rotor diameter, cloud cover and wind direction.

Shadow flicker may cause annoyance depending on how long and how often the effect occurs, the flicker frequency and the contrast. The annoyance mostly occurs inside buildings, where the shadow flicker is perceived through a window opening. Shadow impacts are often limited by regulations stating the wind turbine is shut down at critical periods when the effects of shadow flicker occur for too long. This may lead to energy production losses depending on the specific situation.

This paper is an attempt to identify and compare existing government legislation and guidelines regarding the impacts of shadow flicker. The information is gathered from government websites, government documents, policies, guidelines, and wind farm shadow flicker assessment reports. Since not all information was available in English some details might be lost in the translation. Overall, this paper is believed to be accurate.

2. Shadow Flicker Assessment

When assessing shadow flicker impacts, the worst case and/or real case impacts are determined.

Worst case impact

The worst case shadow flicker impact - the astronomical maximum possible shadow flicker duration - is defined as the shadow flicker duration which occurs when the sun is always shining during daylight hours (i.e. the sky is always clear), the wind turbine is always rotating and the rotor is always perpendicular to the receptor areas.

Real case impact

The real case shadow flicker impact – the really expected shadow flicker duration – is the shadow flicker duration when taking into account average sunshine hour probabilities and wind statistics of the particular region.

3. Legislation and Guidelines Governing Wind Turbine Shadow Flicker

3.1 Overview

To give the reader a sense of disparity of wind turbine shadow flicker regulations, an overview is presented in Table 1 summarising the shadow flicker regulations and acceptable threshold limits as published by different countries and their respective jurisdictions.

Most countries that have regulations or guidelines for the impacts of shadow flicker and their assessment have based their regulations on the German Guideline "Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen (WEA-Schattenwurf-Hinweise)" *(Guideline for Identification and Evaluation of the Optical Emissions of Wind Turbines)* [1]. This guideline is described in paragraph 3.2.

The subsequent paragraphs describe the shadow flicker regulations in a selected number of countries in more detail: Australia, Belgium, Denmark, the Netherlands and the United Kingdom. The regulations in the other considered countries are less distinguishing and only listed in the table below.

Table 1: Overview of Shadow Flicker Limit Values and Receptor Locations

Country	Shadow Flicker Limit Values	Receptor Locations	Legislation / Guideline
Australia – National Level [2]	- Worst case: 30 hours/year - No daily limit - Real case: 10 hours/year (only required if worst case exceeds 30 hours/year)	Each dwelling 50m from its centre within distance of 265 x maximum blade chord	Guideline, no legislation at national level
Australia – Queensland [3]	- Worst case: 30 hours/year and 30 min./day - Real case: 10 hours/year (only required if worst case exceeds 30 hours/year)	Each dwelling 50m from its centre within distance of 265 x maximum blade chord	Guideline
Australia – Tasmania [4]	Refers to national guideline	Refers to national guideline	Guideline
Australia - New South Wales [5]	30 Hours/year	Dwellings within 2km distance	Guideline
Australia - Western Australia [6]	Set back distance of 1km	Noise-sensitive buildings not associated with the wind farm	Guideline
Australia – Victoria [7]	30 Hours/year	Dwellings, including garden fenced areas of dwellings	Guideline
Australia - South Australia [8]	Refers to national guideline	Refers to national guideline	Guideline
Austria [9]	Worst case: 30 hours/year and 30 min./day	Sensitive buildings, zone of influence approximately 2000m-2500m	No legislation
Belgium – Flanders Region [10] [11]	Real case: - 8 hours/year and 30 min./day - On industrial sites, with the exception of	Dwellings, hospitals, nursing homes, school buildings, office buildings etcetera	Legislation

Country	Shadow Flicker Limit Values	Receptor Locations	Legislation / Guideline
	dwellings, 30 hours/year and 30 min./day		
Belgium – Walloon Region [12]	Worst case: 30 hours/year and 30 min./day	Dwellings, hospitals, nursing homes, school buildings etcetera	Legislation
Brazil [13]	Worst case (recommended): 30 hours/year and 30 min./day	Sensitive buildings	No legislation, EHS guideline for wind energy World Bank Group
Canada [14]	Worst case: 30 hours/year and 30 min./day	Sensitive buildings	No legislation or guideline, but common practice
Denmark [15]	Real case: 10 hours/year	Dwellings	Guideline
Germany [1]	- Worst case: 30 hours/year and 30 min./day - Real case: 8 hours/year (only required if shadow flicker control system is used)	Living rooms, lounges, bedrooms, classrooms in school buildings, offices, laboratories and workplaces within a distance in which rotor blade covers at least 20% of the sun disk	Guideline adopted by many Federal States
India [16]	Worst case: 30 hours/year and 30 min./day	Dwellings	No legislation or guideline, but common practice
Ireland [17] [18]	Maximum 30 hours/year recommended	Dwellings within 10 rotor diameters distance	Guideline
Japan [19]	30 Hours/year	Dwellings	No legislation, only for EIA purposes
Netherlands [20]	Maximum 17 days per year more than 20 minutes' real case shadow flicker	Dwellings, school buildings, hospitals, nursing homes, day-care centres etcetera within a distance of 12 times the rotor diameter	Legislation
Poland [21]	30 Hours/year	Dwellings	No legislation, but common practice

Country	Shadow Flicker Limit Values	Receptor Locations	Legislation / Guideline
Serbia [22]	30 Hours/year and 30 min./day	Dwellings and offices within 500m distance	Guideline
Sweden [23]	- Worst case: 30 hours/year and 30 min./day - Real case: 8 hours/year	Sensitive buildings	Guideline
UK – England, Wales [24] [25] [26]	No set limit value, but common practice is maximum 30 hours/year, and 30 minutes/day	Dwellings within zone of 10 rotor diameters from each turbine and between 130 degrees either side of north (relative to each turbine)	Guideline and common practice
UK – Scotland [27]	No set limit value, but as a general rule at distance 10 rotor diameters shadow flicker is not expected to be a problem	Dwellings	Guideline
USA – National Level [28]	30 Hours/year and 30 min./day	Occupied buildings	Guideline
USA - Connecticut [29]	30 Hours/year	Occupied buildings	Legislation
USA – Wisconsin [30]	- 30 Hours/year - Reasonable shadow flicker mitigation when experiencing 20 hours or more per year of shadow flicker	Dwellings and community buildings	Legislation

3.2 Germany

Germany has a detailed guideline for calculating and assessing the impacts of shadow flicker. This guideline "Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen (WEA-Schattenwurf-Hinweise) " *(Guideline for Identification and Evaluation of the Optical Emissions of Wind Turbines) [1]*, was issued by the´Länderausschuss für Immissionsschutz' *(States Committee for Pollution Control)* in 2002. It has since been adopted by many federal states and is considered common practice for wind turbines and wind farms in Germany.

The German guideline states shadow flicker must be considered up to the distance where at least 20% of the sun disk is covered by the rotor blade. At larger distances the shadow flicker will be too diffused to cause annoyance. Further, the shadow flicker is assessed only for sun angles over the horizon of at least 3 degrees. For lower angles the shadow flicker is neglected due to the less bright sun light and screening by vegetation and buildings.

The German guideline considers the following as sensitive rooms:

- living rooms including lounges;
- bedrooms, including overnight rooms in lodges and bedrooms in hospitals and sanatoriums;
- classrooms in school buildings, colleges and similar institutions;
- offices, laboratories, workplaces, training rooms and similar workplaces.

Outdoor areas such as terraces and balconies, adjacent to buildings are considered sensitive areas between 6 a.m. and 10 p.m.

Geographical areas which have been designated for future developments with sensitive rooms shall be assessed at the most critical spots at a height of 2 meter above ground level.

For indoor rooms the assessment height is the window center. For outdoor areas the assessment height is 2 meter above ground level.

The limit values for the worst case - the astronomical maximum possible - shadow flicker impact are:

- 30 minutes per day, and;
- 30 hours per year.

If a shadow flicker control system is used which automatically stalls the wind turbine at the times shadow flicker is expected to occur, the real case shadow flicker impact must be limited to 8 hours per year.

3.3 Australia

National Government

Australia has no national legislation for the impacts of shadow flicker from wind turbines, but in 2010 the Environment Protection and Heritage Council (EPHC) issued a (draft) guideline [2]. This guideline recommends an exposure limit of 30 hours/year modelled (i.e. worst case). There is no limit for daily exposure duration. In most circumstances where a dwelling experiences a modelled level of shadow flicker less than 30 hours per year, no further (real case) investigation is required. In cases where the modelled impacts of shadow flicker are more than 30 hours/year, then the measured shadow flicker (i.e. real case) must be determined. The limit value for the measured shadow flicker is 10 hours/year.

The maximum zone of influence is defined as 265 x maximum blade chord. This means no assessment is required for dwellings beyond this distance. The shadow flicker is assessed only for sun angles over the horizon of at least 3 degrees. The assessment method requires reporting of the maximum value of shadow flicker duration within 50 m of the centre of a dwelling. Depending on jurisdictions, shadow flicker assessment may not be required for participating landowners.

Queensland
The Australian State of Queensland issued planning guidelines in 2016 [3]. This guideline recommends the same limit values and maximum zone of influence as the national guideline.

Tasmania
The Australian State of Tasmania has no legislation or guideline for shadow flicker, but refers to the national guideline [4].

New South Wales
The Australian State of New South Wales also has no legislation for shadow flicker, but did issue a guideline. The impact of shadow flicker should be assessed for dwellings within a 2km distance from a turbine. The shadow flicker duration should not exceed 30 hours per year [5].

Western Australia
The State of Western Australia has no legislation or a guideline for shadow flicker, but recommends a distance of 1km between the turbine and receptors [6].

Victoria
The Australian State Victoria has no legislation for shadow flicker, but did issue guidelines [7]. Victoria recommends a setback distance of 1km from the turbine, unless evidence is provided that the owner of the dwelling has consented in writing to the location of the turbine. The shadow flicker experienced surrounding the area of a dwelling (garden fenced area) must not exceed 30 hours per year.

South Australia
The State of South Australia has no legislation for shadow flicker, but a guideline that refers to the national guideline [8].

3.4 Belgium

Flanders
The Flanders region of Belgium has legislation for regulating shadow flicker impact [11]. The current legislation was implemented in 2012 [10], but was revised in 2016 regarding receptors on industrial sites.

The legislation states a wind turbine should be equipped with an automatic shadow flicker control system if a shadow flicker sensitive receptor is present within a zone experiencing 4 hours per year of expected shadow flicker. The operator is required to keep a log book per wind turbine with the relevant data to determine shadow flicker and for each turbine and relevant sensitive receptors a shadow flicker calendar with the astronomical maximum possible shadow flicker duration. For at least the first two years of operation the operator will draft a report showing the effective shadow flicker for each relevant object per year and detailing the mitigating measures that have been taken.

For dwellings and all other relevant shadow flicker sensitive receptors the limit value is a maximum of 8 hours’ effective shadow flicker per year and 30 minutes per day. The only exceptions are shadow flicker sensitive receptors other than dwellings on industrial sites. For these receptors the limit value is a maximum of 30 hours' effective shadow flicker per year and 30 minutes per day.

In order to understand the legislation, expected shadow flicker is the real case shadow flicker impact and effective shadow flicker is the number of hours of shadow flicker at the sensitive object as determined from measurements or the log book of the turbines.

The explanatory memorandum defines a shadow flicker sensitive receptor as an inner space where shadow flicker can cause nuisance. This includes but is not limited to receptors such as dwellings, hospitals, nursing homes, school buildings and office buildings. Further, it states that the expected shadow flicker will be calculated for sun angles over the horizon of more than 3 degrees assuming a standard window size of 5-meter-wide and 2-meter-high at 1 meter above ground level.

The wind turbines have to be automatically halted when they cause an excess of shadow flicker at sensitive receptors, unless it is shown that due to physical reasons no nuisance can occur (e.g. sun blinds installed, screening by receptors or vegetation etc.). Also, the turbines do not need to be stopped if during the shadow flicker period no persons will be present or if individual agreements with private persons can be reached.

Wallonia
The Walloon Region of Belgium has legislation for regulating shadow flicker impact, implemented in 2014 [12]. The astronomical maximum possible shadow flicker is limited to 30 hours per year and 30 minutes per day for dwellings and other sensitive receptors.

3.5 Denmark

Denmark has no legislation on the impacts of shadow flicker, but does have guidance to limit the impact [15]. The Ministry of Environment recommends that the real case shadow flicker impact on dwellings should not exceed 10 hours per year. If this is threatened to be exceeded an automatic shadow flicker control system has to be installed to limit the impact.

3.6 Netherlands

The Netherlands has legislation for regulating the impacts of shadow flicker [20]. The current legislation was implemented in 2007. The legislation states the wind turbine shall be equipped with automatic shadow flicker control system which stalls the turbine if shadow flicker occurs at sensitive receptors and the distance between the turbine and the sensitive receptor is less than 12 times the rotor diameter and if on average shadow flicker occurs more than 17 days per year for more than 20 minutes per day. Shadow flicker is only considered relevant if a sensitive receptor has windows at the side where shadow flicker occurs.

The legislation considers sensitive receptors such as dwellings, school buildings, hospitals, nursing homes, mental institutions, day-care centres etcetera. Receptors like office buildings and hotels are not considered to be sensitive receptors.

3.7 United Kingdom

England and Wales

In England and Wales planning policy for onshore wind turbines is contained in a number of documents, principally the Government's National Planning Policy Framework (NPPF) [24], the National Policy Statement for Renewable Energy Infrastructure [25], and online planning practice guidance for renewable and low carbon energy. Local authorities may also contain policies on onshore wind development in up-to-date local planning policy for a particular area.

The NPPF does not specifically provide guidance on shadow flicker; however, guidance is included within the Planning Practice Guidance for Renewable and Low Carbon Energy [26] document originally published in July 2013. This states that "Only properties within 130 degrees either side of north, relative to the turbines can be affected at these latitudes in the UK".

According to the National Policy Statement for Renewable Energy Infrastructure, in England and Wales the maximum potential number of hours that shadow flicker could occur at each affected occupied building should be calculated, using industry good practice. However, there are no standards set for acceptable exposure limits. Best practice guidance on the interpretation of the significance of effects as a result of shadow flicker on receptors generally references European best practice. As described in paragraph 3.2, Germany references two methods for setting limits as follows [1]:

- An astronomic worst case scenario limited to a maximum of 30 hours per year and 30 minutes on the worst affected day, and;
- A realistic scenario including meteorological parameters limited to a maximum of 8 hours per year.

A significant effect is therefore generally considered to occur where the proposed wind turbine will affect the receptor over substantial parts of the day and/or over the year. This is assumed to be over 30 hours a year, and 30 minutes per day.

Within the UK, there are no nationally set separation distances between wind turbines and housing. Appropriate distances should be maintained between wind turbines and sensitive receptors to protect amenity, and the two main impact issues that determine the acceptable separation distances are visual amenity and noise. The arrangement of wind turbines should be carefully designed within a site to minimise effects on the landscape and visual amenity while meeting technical and operational siting requirements and other constraints. The National Policy Statement for Renewable Energy Infrastructure, in England and Wales sets out that shadow flicker assessment should be undertaken where wind turbines have been proposed within 10 rotor diameters of an existing occupied building".

Some local councils have determined setback distances within their Local Plan's, however as set out in the Department for Communities and Local Government document, Renewable and Low Carbon Energy, local planning authorities should not rule out otherwise acceptable renewable energy developments through inflexible rules on buffer zones or separation distances. Other than when dealing with setback distances for safety, distance of itself does not necessarily determine whether the impact of a proposal is unacceptable.

Scotland

The Scottish Government's document 'Onshore Wind Turbines' states where shadow flicker could be a problem, developers should provide calculations to quantify the effect. In most cases when a separation between wind turbines and nearby dwellings is provided (as a general rule 10 rotor diameters) shadow flicker is not expected to be a problem [27].

4. Conclusion

The study shows not all countries have guidelines or regulations for assessing and limiting shadow flicker impacts. Most countries that do have regulations or guidelines for shadow flicker impact assessment have based their regulations on the German Guideline “Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen (WEA-Schattenwurf-Hinweise)” (Guideline for Identification and Evaluation of the Optical Emissions of Wind Turbines). In countries lacking regulations for shadow flicker the German guideline is often applied as best practice.

The German guideline states a limit value of 30 hours per year and 30 minutes per day for the astronomical maximum possible shadow duration (worst case scenario). In case a shadow flicker control module is used the expected shadow impact (real case scenario) must be limited to 8 hours per year.

There are a number of differences in the exact implementation of the shadow flicker regulations. Some countries and jurisdictions only consider the worst case scenario, sometimes both the impact per year and per day and sometimes just the impact per year. Relatively few countries consider also the real case impact. Also, there are differences in the definition of sensitive receptors and the relevant zone of influence.

All countries and jurisdictions that consider the worst case scenario have set a limit value of 30 hours per year. Those that also consider the impact per day have all set a limit of 30 minutes per day. In the relatively few cases where the real case impact is regulated the limit value for dwellings is 8 hours per year, with the exception of Australia, Denmark and the Netherlands. Australia and Denmark have a recommended limit value of 10 hours per year. The Dutch legislation is most deviating since the limit value comprises a combination of days per year and minutes per day. In the Netherlands, an automatic shadow flicker control system which stalls the turbine is required if on average shadow flicker occurs for more than 17 days per year for more than 20 minutes per day within a zone of 12 times the rotor diameter from the wind turbine.

It must be noted that is not always clear that those countries that have a limit value of 30 hours per year refer to the worst case scenario. Therefore, we cannot exclude that some countries might apply this limit value to the real case impact instead of the worst case impact as intended by the German guideline.

The differences in the exact definition of shadow flicker sensitive receptors and the zone of influence which has to be considered have impacts on the results. This can lead to considerable differences in production losses by a shadow flicker control module. For example, in Germany and the Flanders Region of Belgium office buildings and workplaces are considered sensitive receptors, whilst in a number of other countries like for example the Netherlands these are not considered sensitive. This means that a turbine close to an office building or another workplace can in one country lead to a considerable production loss while in another country there would be no loss at all.

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Wind Turbines and Health

A Critical Review of the Scientific Literature

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Objective: This review examines the literature related to health effects of wind turbines. **Methods:** We reviewed literature related to sound measurements near turbines, epidemiological and experimental studies, and factors associated with annoyance. **Results:** (1) Infrasound sound near wind turbines does not exceed audibility thresholds. (2) Epidemiological studies have shown associations between living near wind turbines and annoyance. (3) Infrasound and low-frequency sound do not present unique health risks. (4) Annoyance seems more strongly related to individual characteristics than noise from turbines. **Discussion:** Further areas of inquiry include enhanced noise characterization, analysis of predicted noise values contrasted with measured levels postinstallation, longitudinal assessments of health pre- and postinstallation, experimental studies in which subjects are "blinded" to the presence or absence of infrasound, and enhanced measurement techniques to evaluate annoyance.

The development of renewable energy, including wind, solar, and biomass, has been accompanied by attention to potential environmental health risks. Some people who live in proximity of wind turbines have raised health-related concerns about noise from their operations. The issue of wind turbines and human health has also now been explored and considered in a number of policy, regulatory, and legal proceedings.

This review is intended to assess the peer-reviewed literature regarding evaluations of potential health effects among people living in the vicinity of wind turbines. It will include analysis and commentary of the scientific evidence regarding potential links to health effects, such as stress, annoyance, and sleep disturbance, among others, that have been raised in association with living in proximity to wind turbines. Efforts will also be directed to specific components of noise associated with wind turbines such as infrasound and low-frequency sound and their potential health effects.

We will attempt to address the following questions regarding wind turbines and health:

1. Is there sufficient scientific evidence to conclude that wind turbines adversely affect human health? If so, what are the circumstances associated with such effects and how might they be prevented?
2. Is there sufficient scientific evidence to conclude that psychological stress, annoyance, and sleep disturbance can occur as a result of living in proximity to wind turbines? Do these effects lead to adverse health effects? If so, what are the circumstances associated with such effects and how might they be prevented?
3. Is there evidence to suggest that specific aspects of wind turbine sound such as infrasound and low-frequency sound have unique potential health effects not associated with other sources of environmental noise?

The coauthors represent professional experience and training in occupational and environmental medicine, acoustics, epidemiology, otolaryngology, psychology, and public health.

Earlier reviews of wind turbines and potential health implications have been published in the peer-reviewed literature[1–6] by state and provincial governments (Massachusetts, 2012, and Australia, 2014, among others) and trade associations.[7]

This review is divided into the following five sections:

1. Noise: The type associated with wind turbine operations, how it is measured, and noise measurements associated with wind turbines.
2. Epidemiological studies of populations living in the vicinity of wind turbines.
3. Potential otolaryngology implications of exposure to wind turbine sound.
4. Potential psychological issues associated with responses to wind turbine operations and a discussion of the health implications of continuous annoyance.
5. Governmental and nongovernmental reports that have addressed wind turbine operations.

METHODS

To identify published research related to wind turbines and health, the following activities were undertaken:

1. We attempted to identify and assess peer-reviewed literature related to wind turbines and health by conducting a review of PubMed, the National Library of Medicines' database that indexes more than 5500 peer-reviewed health and scientific journals with more than 21 million citations. Search terms were wind turbines, wind turbines and health effects, infrasound, infrasound and health effects, low-frequency sound, wind turbine syndrome, wind turbines and annoyance, and wind turbines and sleep disturbances.
2. We conducted a Google search for nongovernmental organization and government agency reports related to wind turbines and environmental noise exposure (see Supplemental Digital Content Appendix 1, available at: http://links.lww.com/JOM/A179).

From the Department of Biological Engineering (Dr McCunney), Massachusetts Institute of Technology, Cambridge; Department of Epidemiology (Dr Mundt), Environ International, Amherst, Mass; Travel Immunization Clinic (Dr Colby), Middlesex-London Health Unit, London, Ontario, Canada; Dobie Associates (Dr Dobie), San Antonio, Tex; Environment, Energy and Acoustics (Mr Kaliski), Resource Systems Group, White River Junction, Vt; and Psychological Evaluation and Research Laboratory (Dr Blais), Massachusetts General Hospital, Boston.

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The authors declare no conflicts of interest.

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3. After identifying articles obtained via these searches, they were categorized into five main areas that are noted below (section D) and referred to the respective authors of each section for their review and analysis. Each author then conducted their own additional review, including a survey of pertinent references cited in the identified articles. Articles were selected for review and commentary if they addressed exposure and a health effect—whether epidemiological or experimental—or were primary exposure assessments.
4. Identified studies were categorized into the following areas:

    I. Sound, its components, and field measurements conducted in the vicinity of wind turbines;
    II. Epidemiology;
    III. Effects of sound components such as infrasound and low-frequency sound on health;
    IV. Psychological factors associated with responses to wind turbines;
    V. Governmental and nongovernmental reports.

5. The authors are aware of reports and commentaries that are not in the scientific or medical peer-reviewed literature that have raised concern about potential health implications for people who live near wind turbines. These reports describe relatively common symptoms with numerous causes, including headache, tinnitus, and sleep disturbance. Because of the difficulties in comprehensively identifying non–peer-reviewed reports such as these, and the inherent uncertainty in the quality of non–peer-reviewed reports, they were not included in our analysis, aside from some books and government reports that are readily identified. A similar approach of excluding non–peer-reviewed literature in scientific reviews is used by the World Health Organization (WHO)'s International Agency for Research on Cancer (IARC) in its deliberations regarding identification of human carcinogens.[8] International Agency for Research on Cancer, however, critically evaluates exposure assessments not published in the peer-reviewed literature, if conducted with appropriate quality and in accordance with international standards and guidelines. International Agency for Research on Cancer uses this policy for exposure assessments because many of these efforts, although containing valuable data in evaluating health risks associated with an exposure to a hazard, are not routinely published. The USA National Toxicology Program also limits its critical analysis of potential carcinogens to the peer-reviewed literature. In our view, because of the critical effect of scientific studies on public policy, it is imperative that peer-reviewed literature be used as the basis. Thus, in this review, only peer review studies are considered, aside from exposure-related assessments.

RESULTS

Characteristics of Wind Turbine Sound

In this portion of the review, we evaluate studies in which sound near wind turbines has been measured, discuss the use of modeled sound levels in dose–response studies, and review literature on measurements of low-frequency sound and infrasound from operating wind turbines. We evaluate sound levels measured in areas, where symptoms have been reported in the context of proximity to wind turbines. We address methodologies used to measure wind turbine noise and low-frequency sound. We also address characteristics of wind turbine sound, sound levels measured near existing wind turbines, and the response of humans to different levels and characteristics of wind turbine sound. Special attention is given to challenges and methods of measuring wind turbine noise, as well as low-frequency sound (20 to 200 Hz) and Infrasound (less than 20 Hz).

Wind turbines sound is made up from both moving components and interactions with nonmoving components of the wind turbine (Fig. 1). For example, mechanical components in the nacelle can generate noise and vibration, which can be radiated from the structure, including the tower. The blade has several components that create aerodynamic noise, such as the blade leading edge, which contacts the wind first in its rotation, the trailing edge, and the blade tip. Blade/tower interactions, especially where the blades are downwind of the tower, can create infrasound and low-frequency sound. This tower orientation is no longer used in large wind turbines.[9]

Sound Level and Frequency

Sound is primarily characterized by its pitch or frequency as measured in Hertz (Hz) and its level as measured in decibels (dB). The frequency of a sound is the number of times in a second that the medium through which the sound energy is traveling (ie, air, in the case of wind turbine sound) goes through a compression cycle. Normal human hearing is generally in the range of 20 to 20,000 Hz. As an example, an 88-key piano ranges from about 27.5 to 4186 Hz with middle C at 261.6 Hz. As in music, ranges of frequencies can be described in "octaves," where the center of each octave band has a frequency of twice that of the previous octave band (this is also written as a "1/1 octave band"). Smaller subdivisions can be used such as 1/3 and 1/12 octaves. The level of sound pressure for each frequency band is reported in decibel units.

To represent the overall sound level in a single value, the levels from each frequency band are logarithmically added. Because human hearing is relatively insensitive to very low- and high-frequency sounds, frequency-specific adjustments or weightings are added to the unweighted sound levels before summing to the overall level. The most common of these is the A-weighting, which simulates the human response to various frequencies at relatively low levels (40 phon or about 50 dB). Examples of A-weighted sound levels are shown in Fig. 2.

Other weightings are cited in the literature, such as the C-weighting, which is relatively flat at the audible spectrum; G-weighting, which simulates human perception and annoyance of sound that lie wholly or partly in the range from 1 to 20 Hz; and Z-weighting, which does not apply any weighting. The weighting of the sound is indicated after the dB label. For example, an A-weighted sound level of 45 dB would be written as 45 dBA or 45 dB(A). If no label is shown, the weighting is either implied or unweighted.

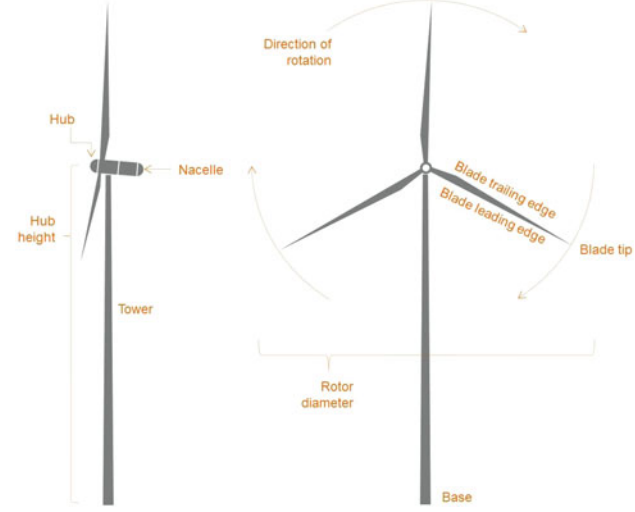

FIGURE 1. Schematic of a modern day wind turbine.

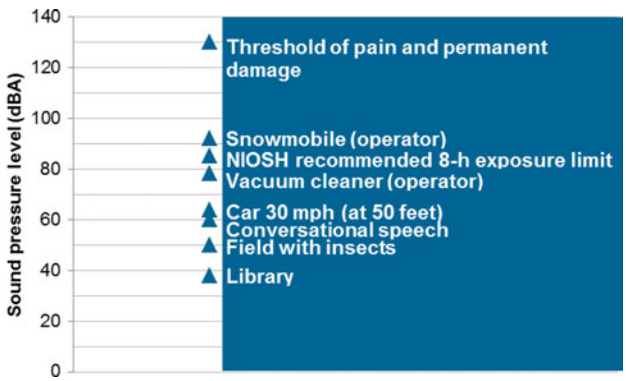

FIGURE 2. Sample A-weighted sound pressure levels.

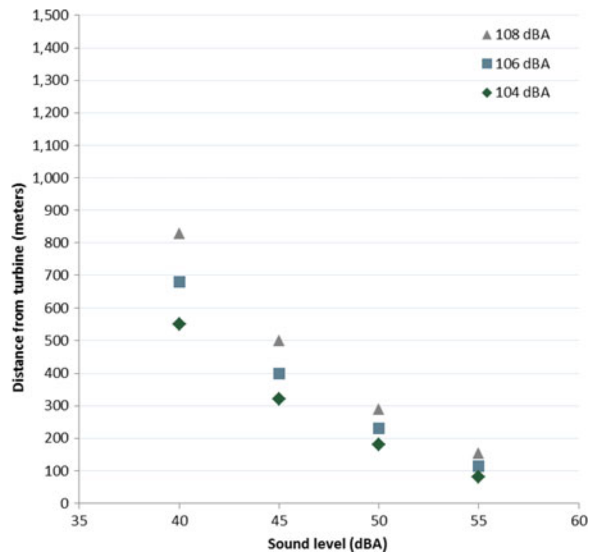

FIGURE 3. Sound levels at varying setbacks and turbine sound power levels—RSG Modeling, Using ISO 9613-2.

Beyond the overall level, wind turbine noise may be amplitude modulated or have tonal components. Amplitude modulation is a regular cycling in the level of pure tone or broadband sound. A typical three-bladed wind turbine operating at 15 RPM would have a modulation period or cycle length of about 1.3 seconds. Tones are frequencies or narrow frequency bands that are much louder than the adjacent frequencies in sound spectra. Prominent tones can be identified through several standards, including ANSI S12.9 Part 4 and IEC 61400-11. Relative high-, mid-, and low-frequency content can also define how the sound is perceived, as well as many qualitative factors unique to the listener. Consequently, more than just the overall levels can be quantified, and studies have measured the existence of amplitude modulation, prominent tones, and spectral content in addition to the overall levels.

Wind Turbine Sound Power and Pressure Levels

The sound *power* level is the intrinsic sound energy radiated by a source. It is not dependent on the particular environment of the sound source and the location of the receiver relative to the source. The sound *pressure* level (SPL), which is measured by a sound-level meter at a location, is a function of the sound *power* emitted by neighboring sources and is highly dependent on the environment and the location of the receiver relative to the sound source(s).

Wind turbine sound is typically broadband in character with most of the sound energy at lower frequencies (less than 1000 Hz). Although wind turbines produce sound at frequencies less than the 25 Hz 1/3 octave band, sound power data are rarely published below that frequency. Most larger, utility-scale wind turbines have sound power levels between 104 and 107 dBA. Measured sound levels because of wind turbines depend on several factors, including weather conditions, the number of turbines, turbine layout, local topography, the particular turbine used, distance between the turbines and the receiver, and local flora. Meteorological conditions alone can cause 7 to 14 dB variations in sound levels.[10] Examples of the SPLs because of a single wind turbine with three different sound powers, and at various distances, are shown in Fig. 3 as calculated with ISO 9613-2.[11] Measurement results of A-weighted, C-weighted, and G-weighted sound levels have confirmed that wind turbine sound attenuates logarithmically with respect to distance.[12]

With respect to noise standards, Hessler and Hessler[13] found an arithmetic average of 45 dBA daytime and 40 dBA nighttime for governments outside the United States, and a nighttime average of 47.7 dBA for US state noise regulation and siting standards. The metrics for those levels can vary. Common metrics are the day-evening-night level (Lden), day-night level (Ldn), equivalent average level (Leq), level exceeded 90% of the time (L90), and median (L50). The application of how these are measured and the time period over which they are measured varies, meaning that, from a practical standpoint, sound-level limits are even more varied than the explicit numerical level. The Leq is one of the more commonly used metric. It is the logarithmic average of the squared relative pressure over a period of time. This results in a higher weighting of louder sounds.

Owing to large number of variables that contribute to SPLs because of wind turbines at receivers, measured levels can vary dramatically. At a wind farm in Texas, O'Neal et al[14] measured sound levels with the nearest turbine at 305 m (1000 feet) and with four turbines within 610 m (2000 feet) at 50 to 51 dBA and 63 dBC (10-minute Leq), with the turbines producing sufficient power to emit the maximum sound power. During the same test, sound levels were 27 dBA and 47 dBC (10-minute Leq) inside a home that was located 290 m (950 feet) from the nearest turbine and within 610 m (2000 feet) of four turbines[15] (see Fig. 4).

Bullmore et al[16] measured wind turbine sound at distances from 100 to 754 m (330 to 2470 feet), where they found sound levels ranging from 40 to 55 dBA over various wind conditions. At typical receiver distances (greater than 300 m or 1000 feet), sound was attenuated to below the threshold of hearing at frequencies above the 1.25 kHz 1/3 octave band. In studies mentioned here, measurements were made with the microphone between 1 and 1.6 m (3 and 5 feet) above ground.

Wind Turbine Emission Characteristics

Low-Frequency Sound and Infrasound

Low-frequency sound is typically defined as sound from 20 to 200 Hz, and infrasound is sound less than 20 Hz. Low-frequency sound and infrasound measurement results at distances close to wind turbines (< 500 meters) typically show infrasound because of wind farms, but not above audibility thresholds (such as ISO 226 or as published by the authors[12,15,17–21,149]). One study found sound levels 360 m and 200 m from a wind farm to be 61 dBG and 63 dBG, respectively. The threshold of audibility for G-weighted sound levels is 85 dBG. The same paper found infrasound levels of 69 dBG 250 m from a coastal cliff face and 76 dBG in downtown Adelaide, Australia.[18] One study found that, even at distances less than 450 feet (136 m), infrasound levels were 80 dBG or less. At more typical receiver distances (greater than 300 m or 1000 feet), infrasound levels were 72 dBG or less. This corresponded to A-weighted sound

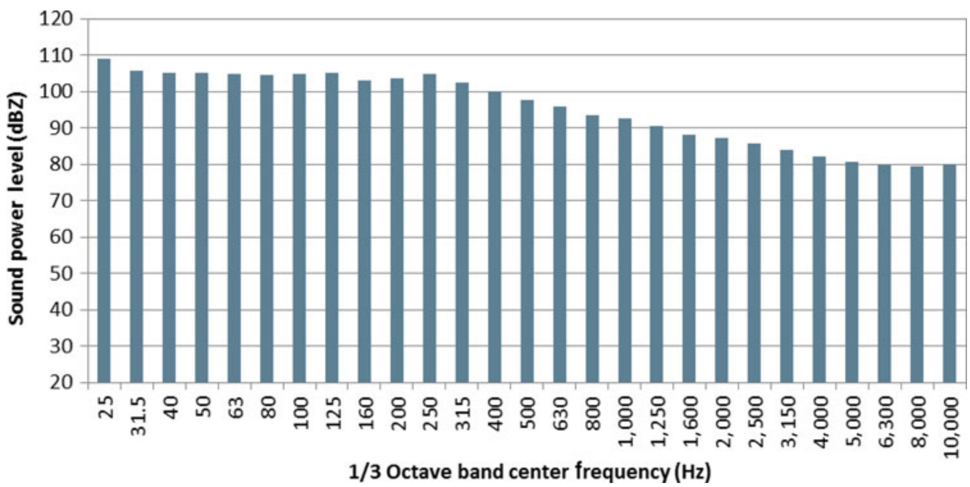

FIGURE 4. Sound power of the Siemens SWT 2.3-93 (TX) wind turbine.[15]

levels of 56 and 49 dBA, respectively, higher than most existing regulatory noise limits.[12]

Farther away from wind farms (1.5 km) infrasound is no higher than what would be caused by localized wind conditions, reinforcing the necessity for adequate wind-caused pseudosound reduction measures for wind turbine sound-level measurements.[22]

Low-frequency sound near wind farms is typically audible, with levels crossing the threshold of audibility between 25 and 125 Hz depending on the distance between the turbines and measurement location.[12,15,19,20,23] Figure 5 shows the frequency spectrum of a wind farm measured at about 3500 feet compared with a truck at 50 feet, a field of insects and birds, wind moving through vegetation, and the threshold of audibility according to ISO 387-7.

Amplitude Modulation

Wind turbine sound emissions vary with blade velocity and are characterized in part by amplitude modulation, a broadband oscillation in sound level, with a cycle time generally corresponding to the blade passage frequency. The modulation is typically located in the 1/1 octave bands from 125 Hz to 2 kHz. Fluctuation magnitudes are typically not uniform throughout the frequency range. These fluctuations are typically small (2 to 4 dB) but under more unusual circumstances can be as great as 10 dB for A-weighted levels and as much as 15 dB in individual 1/3 octave bands.[19,24] Stigwood et al[24] found that, in groups of several turbines, the individual modulations can often synchronize causing periodic increases in the modulation magnitude for periods of 6 to 20 seconds with occasional periods where the individual turbine modulations average each other out, minimizing the modulation magnitude. This was not always the case though, with periods of turbine synchronization occasionally lasting for hours under consistent high wind shear, wind strength, and wind direction.

Amplitude modulation is caused by many factors, including blade passage in front of the tower (shadowing), sound emission directivity of the moving blade tips, yaw error of the turbine blades (where the turbine blades are not perpendicular to the wind), inflow turbulence, and high levels of wind shear.[19,24,25] Amplitude modulation level is not correlated with wind speed. Most occurrences of "enhanced" amplitude modulation (a higher magnitude of modulation) are caused by anomalous meteorological conditions.[19] Amplitude modulation varies by site. Some sites rarely exhibit amplitude modulation, whereas at others amplitude modulation has been measured up to 30% of the time.[10] It has been suggested by some that amplitude modulation may be the cause of "infrasound" complaints because of confusing of amplitude modulation, the modulation of a broadband sound, with actual infrasound.[19]

Tonality

Tones are specific frequencies or narrow bands of frequencies that are significantly louder than adjacent frequencies. Tonal sound is not typically generated by wind turbines but can be found in some cases.[20,26] In most cases, the tonal sound occurs at lower frequencies (less than 200 Hz) and is due to mechanical noise originating from the nacelle, but has also been found to be due to structural vibrations originating from the tower, and anomalous aerodynamic characteristics of the blades[27] (see Fig. 5).

Sound Levels at Residences where Symptoms Have Been Reported

One recent research focus has been the sound levels at (and in) the residences of people who have complained about sound levels emitted by turbines as some have suggested that wind turbine noise may be a different type of environmental noise.[28] Few studies have actually measured sound levels inside or outside the homes of people. Several hypotheses have been proposed about the characteristics of wind turbine noise complaints, including infrasound,[28] low-frequency tones,[20] amplitude modulation,[19,29] and overall noise levels.

Overall Noise Levels

Because of the large variability of noise sensitivity among people, sound levels associated with self-reported annoyance can vary considerably. (Noise sensitivity and annoyance are discussed in more detail later in this review.) People exposed to measured external sound levels from 38 to 53 dBA (10-minute or 1-hour Leq). Department of Trade and Industry,[19] Walker et al,[28] Gabriel et al,[29] and van den Berg et al[30,149] have reported annoyance. Sound levels have also been measured inside complainant residences at between 22 and 37 dBA (10-minute Leq).[19]

Low Frequency and Infrasonic Levels

Concerns have been raised in some settings that low-frequency sound and infrasound may be special features of wind turbine noise that lead to adverse health effects.[31] As a result, noise measurements in areas of operating wind turbines have focused specifically

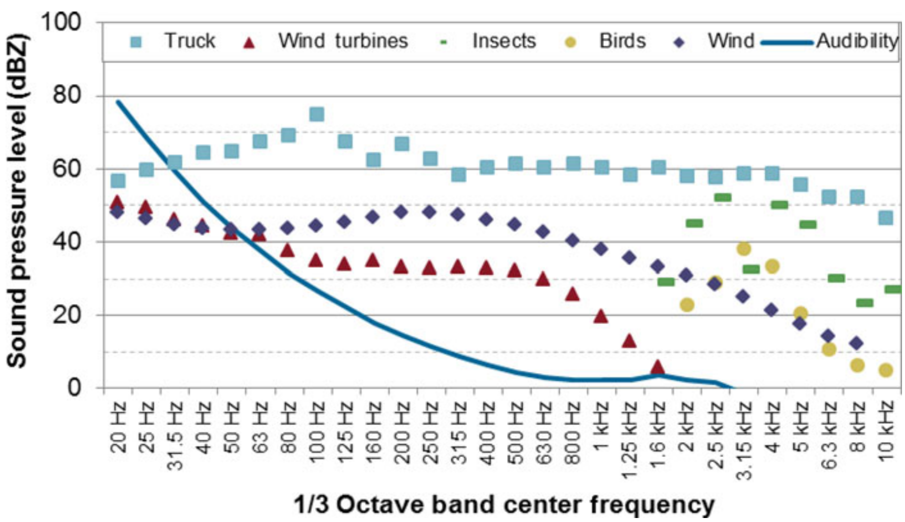

FIGURE 5. Comparison of frequency spectrum of a truck passby at 50 feet, wind turbines at 3500 feet, insects, birds, wind, and the threshold of audibility according to ISO 387-7.

on sound levels in the low-frequency range and occasionally the infrasonic range.

Infrasonic sound levels at residences are typically well below published audibility thresholds, even thresholds for those particularly sensitive to infrasound. Nevertheless, low-frequency sound typically exceeds audibility thresholds in a range starting between 25 and 125 Hz.[19,20,23] In some cases, harmonics of the blade passage frequency (about 1 Hz, ie infrasound) have been measured at homes of people who have raised concerns about health implications of living near wind turbine with sound levels reaching 76 dB; however, these are well below published audibility thresholds.[28]

Amplitude Modulation

Amplitude modulation has been suggested as a major cause of complaints surrounding wind turbines, although little data have been collected to confirm this hypothesis. A recent study of residents surrounding a wind farm that had received several complaints showed predicted sound levels at receiver distances to be 33 dBA or less. Residents were instructed to describe the turbine sound, when they found it annoying. Amplitude modulation was present in 68 of 95 complaints. Sound recorders distributed to the residents exhibited a high incidence of amplitude modulation.[29]

Limited studies have addressed the percentage of complaints surrounding utility-scale wind farms, with only one comparing the occurrence of complaints with sound levels at the homes. The complaint rate among residents within 2000 feet (610 m) of the perimeter of five mid-western United States wind farms was approximately 4%. All except one of the complaints were made at residences, where wind farm sound levels exceeded 40 dBA.[13] The authors used the LA90 metric to assess wind farm sound emissions. LA90 is the A-weighted sound level that is exceeded 90% of the time. This metric is used to eliminate wind-caused spikes and other short-term sound events that are not caused by the wind farm.

In Northern New England, 5% of households within 1000 m of turbines complained to regulatory agencies about wind turbine noise.[32] All complaints were included, even those that were related to temporary issues that were resolved. Up to 48% of the complainants were at wind farms, where at least one noise violation was found or a variance from the noise standard. A third of the all complaints were due to a single wind farm.

Sound Measurement Methodology

Collection of accurate, comparable, and useful noise data depends on careful and consistent methodology. The general methodology for environmental sound level monitoring is found in ANSI 12.9 Part 2. This standard covers basic requirements that include the type of measurement equipment necessary, calibration procedures, windscreen specifications, microphone placement guidance, and suitable meteorological conditions. Nevertheless, there are no recommendations for mitigating the effects of *high* winds (greater than 5 m/s) or measuring in the infrasonic frequency range (less than 20 Hz).[33] Another applicable standard is IEC 61400-11, which provides a method for determining the sound power of individual wind turbines. The standard gives specifications for measurement positions, the type of data needed, data analysis methods, report content requirements, determination of tonality, determination of directivity, and the definitions and descriptors of different acoustical parameters.[34] The standard specifies a microphone mounting method to minimize wind-caused pseudosound, but some have found the setup to be insufficient under gusty wind conditions, and no recommendations are given for infrasound measurement.[35] Because the microphone is ground mounted, it is not suitable for long-term measurements.

Low-Frequency Sound and Infrasound Measurement

There are no standards currently in place for the measurement of wind turbine noise that includes the infrasonic range (ie, frequencies less than 20 Hz), although one is under development (ANSI/ASA S12.9 Part 7). Consequently, all current attempts to measure low-frequency sound and infrasound have either used an existing methodology, an adapted existing methodology, or proposed a new methodology.

The main problem with measuring low-frequency sound and infrasound in environmental conditions is wind-caused pseudosound due to air pressure fluctuation, because air flows over the microphone. With conventional sound-level monitoring, this effect is minimized with a wind screen and/or elimination of data measured during windy periods (less than 5 m/s [11 mph] at a 2-m [6.5 feet] height).[36] In the case of wind turbines, where maximum sound levels may be coincident with ground wind speeds greater than 5 m/s (11 mph), this is not the best solution. With infrasound in particular, wind-caused pseudosound can influence measurements, even at wind speeds down to 1 m/s.[12] In fact, many sound-level meters do not measure infrasonic frequencies.

A common method of dealing with infrasound is using an additional wind screen to further insulate the microphone from air flow.[18,35] In some cases, this is simply a larger windscreen that further insulates the microphone from air flow.[35] One author used a windscreen with a subterranean pit to shelter the microphone, and another used wind resistant cloth.[35] A compromise to an underground microphone mounting is mounting the microphone close (20-cm height) to the ground, minimizing wind influence, or using a standard ground mounted microphone with mounting plate, as found in IEC 61400-11.[35] Low-frequency sound and infrasound differences between measurements made with dedicated specialized windscreens and/or measurement setup and standard wind screens/measurements setups can be quite large.[12,37] Nevertheless, increased measurement accuracy can come at the cost of reduced accuracy at higher frequencies using some methods.[38]

To further filter out wind-caused pseudosound, some authors have advocated a combination of microphone arrays and signal processing techniques. The purpose of the signal processing techniques is to detect elements of similarity in the sound field measured at the different microphones in the array.

Levels of infrasound from other environmental sources can be as high as infrasound from wind turbines. A study of infrasound measured at wind turbines and at other locations away from wind turbines in South Australia found that the infrasound level at houses near the wind turbines is no greater than that found in other urban and rural environments. The contribution of wind turbines to the infrasound levels is insignificant in comparison with the background level of infrasound in the environment.[22]

Conclusions

Wind turbine noise measurement can be challenging because of the necessity of measuring sound levels during high winds, and down to low frequencies. No widely accepted measurement methodologies address all of these issues, meaning that methods used in published measurements can differ substantially, affecting the comparability of results.

Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines, but the levels at customary distances to homes are typically well below audibility thresholds, even at residences where complaints have been raised. Low-frequency sound, often audible in wind turbine sound, typically crosses the audibility threshold between 25 and 125 Hz depending on the location and meteorological conditions.[12,15,19,20,23] Amplitude modulation, or the rapid (once per second) and repetitive increase and decrease of broadband sound level, has been measured at wind farms. Amplitude modulation is typically 2 to 4 dB but can vary more than 6 dB in some cases (A-weighted sound levels).[19,24]

A Canadian report investigated the total number of noise-related complaints because of operating wind farms in Alberta, Canada, over its entire history of wind power. Wind power capacity exceeds 1100 MW; some of the turbines have been in operation for 20 years. Five noise-oriented complaints at utility-scale wind farms were reported over this period, none of which were repeated after the complaints were addressed. Complaints were more common during construction of the wind farms; other power generation methods (gas, oil, etc) received more complaints than wind power. Farmers and ranchers did not raise complaints because of effects on crops and cattle.[41] An Australian study found a complaint rate of less than 1% for residents living within 5 km of turbines greater than 1 MW. Complaints were concentrated among a few wind farms; many wind farms never received complaints.[15]

Reviewing complaints in the vicinity of wind farms can be effective in determining the level and extent of annoyance because of wind turbine noise, but there are limitations to this approach. A complaint may be because of higher levels of annoyance (rather annoyed or very annoyed), and the amount of annoyance required for an individual to complain may be dependent on the personality of the person and the corresponding attitude toward the visual effect of the turbines, their respective attitudes toward wind energy, and whether they derive economic benefit from the turbines. (All of these factors are discussed in more detail later in this report.)

Few studies have addressed sound levels at the residents of people who have described symptoms they consider because of wind turbines. Limited available data show a wide range of levels (38 to 53 dBA [10-minute or 1-hour Leq] outside the residence and from 23 to 37 dBA [10-minute Leq] inside the residence).[19,26,28,28] The rate of complaints surrounding wind farms is relatively low; 3% for residents within 1 mile of wind farms and 4% to 5% within 1 km.[13,32,41]

Epidemiological Studies of Wind Turbines

Key to understanding potential effects of wind turbine noise on human health is to consider relevant evidence from well-conducted epidemiological studies, which has the advantage of reflecting risks of real-world exposures. Nevertheless, environmental epidemiology is an observational (vs experimental) science that depends on design and implementation characteristics that are subject to numerous inherent and methodological limitations. Nevertheless, evidence from epidemiological studies of reasonable quality may provide the best available indication of whether certain exposures—such as industrial wind turbine noise—may be harming human health. Critical review and synthesis of the epidemiological evidence, combined with consideration of evidence from other lines of inquiry (ie, animal studies and exposure assessments), provide a scientific basis for identifying causal relationships, managing risks, and protecting public health.

Methods

Studies of greatest value for validly identifying risk factors for disease include well-designed and conducted cohort studies and case–control studies—provided that specific diseases could be identified—followed by cross-sectional studies (or surveys). Case reports and case series do not constitute epidemiological studies and were not considered because they lack an appropriate comparison group, which can obscure a relationship or even suggest one where none exists.[39,40,42] Such studies may be useful in generating hypotheses that might be tested using epidemiological methods but are not considered capable of demonstrating causality, a position also taken by international agencies such as the WHO.[8]

Epidemiological studies selected for this review were identified through searches of PubMed and Google Scholar using the following key words individually and in various combinations: "wind," "wind turbine," "wind farm," "windmill," "noise," "sleep," "cardiovascular," "health," "symptom," "condition," "disease," "cohort," "case–control," "cross-sectional," and "epidemiology." In addition, general Web searches were performed, and references cited in all identified publications were reviewed. Approximately 65 documents were identified and obtained, and screened to determine whether (1) the paper described a primary epidemiological study (including experimental or laboratory-based study) published in a peer-reviewed health, medical or relevant scientific journal; (2) the study focused on or at least included wind turbine noise as a risk factor; (3) the study measured at least one outcome of potential relevance to health; and (4) the study attempted to relate the wind turbine noise with the outcome.

Results

Of the approximately 80 articles initially identified in the search, only 20 met the screening criteria (14 observational and six controlled human exposure studies), and these were reviewed in detail to determine the relative quality and validity of reported findings. Other documents included several reviews and commentaries[4,5,7,43–51]; case reports, case studies, and surveys[23,52–54]; and documents published in media other than peer-reviewed journals. One study published as part of a conference proceedings did not meet the peer-reviewed journal eligibility criterion but was included because it seemed to be the first epidemiological study on this topic and an impetus for subsequent studies.[55]

The 14 observational epidemiological studies were critically reviewed to assess their relative strengths and weaknesses on the basis of the study design and the general ability to avoid selection bias (eg, the selective volunteering of individuals with health complaints), information bias (eg, under- or overreporting of health complaints, possibly because of reliance on self-reporting), and confounding bias (the mixing of possible effects of other strong risk factors for the same disease because of correlation with the exposure).

Figure 6 depicts the 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys. As can be seen from the figure, the 14 publications were based on analyses of data from only eight different study populations, that is, six publications were based on analyses of a previously published study (eg, Pedersen et al[56] and Bakker et al[57] were based on the data from Pedersen et al[58]) or on combined data from previously published studies (eg, Pedersen and Larsman[59] and Pedersen and Waye[60] were based on the combined data from Pedersen and Waye[61,62]; and Pedersen[63] and Janssen et al[64] were based on the combined data from Pedersen et al,[58] Pedersen and Waye,[61] and Pedersen and Waye[62]). Therefore, in the short summaries of individual studies below, publications based on the same study population(s) are grouped.

Summary of Observational Epidemiological Studies

Possibly the first epidemiological study evaluating wind turbine sound and noise annoyance was published in the proceedings of the 1993 European Community Wind Energy Conference.[55] Investigators surveyed 574 individuals (159 from the Netherlands, 216 from Germany, and 199 from Denmark). Up to 70% of the people

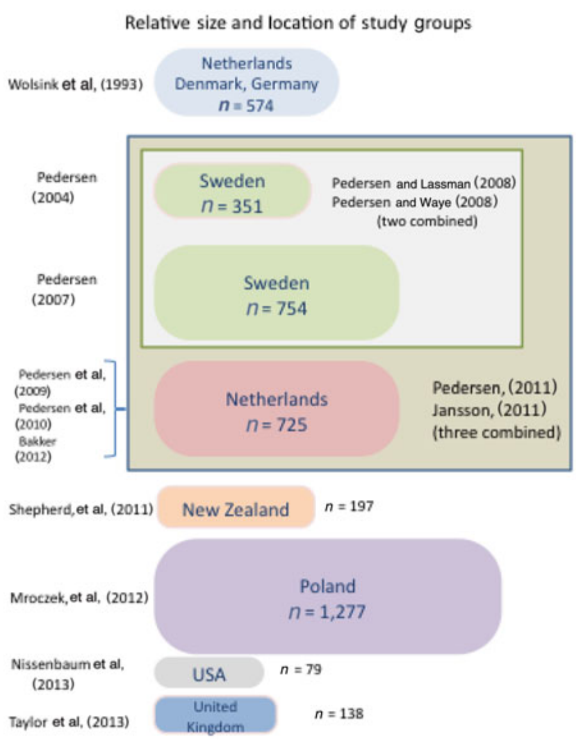

FIGURE 6. The 14 observational epidemiological studies published in peer-reviewed health or medical journals, all of which were determined to be cross-sectional studies or surveys.

resided near wind turbines for at least 5 years. No response rates were reported, so the potential for selection or participation bias cannot be evaluated. Wind turbine sound levels were calculated in 5 dBA intervals for each respondent, on the basis of site measurements and residential distance from turbines. The authors claimed that noise-related annoyance was weakly correlated with objective sound levels but more strongly correlated with indicators of respondents' attitudes and personality.[55]

In a cross-sectional study of 351 participants residing in proximity to wind turbines (power range 150 to 650 kW), Pederson (a coauthor of the Wolsink[55] study) and Persson and Waye[61] described a statistically significant association between modeled wind turbine audible noise estimates and self-reported annoyance. In this section, "statistically significant" means that the likelihood that the results were because of chance is less than 5%. No respondents among the 12 exposed to wind turbine noise less than 30 dBA reported annoyance with the sound; however, the percentage reporting annoyance increased with noise exceeding 30 dBA. No differences in health or well-being outcomes (eg, tinnitus, cardiovascular disease, headaches, and irritability) were observed. With noise exposures greater than 35 dBA, 16% of respondents reported sleep disturbance, whereas no sleep disturbance was reported among those exposed to less than 35 dBA. Although the authors observed that the risk of annoyance from wind turbine noise exposure increased statistically significantly with each increase of 2.5 dBA, they also reported a statistically significant risk of reporting noise annoyance among those self-reporting a negative attitude toward the visual effect of the wind turbines on the landscape scenery (measured on a five-point scale ranging from "very positive" to "very negative" opinion). These results suggest that attitude toward visual effect is an important contributor to annoyance associated with wind turbine noise. In addition to its reliance on self-reported outcomes, this study is limited by selection or participation bias, suggested by the difference in response rate between the highest-exposed individuals (78%) versus lowest-exposed individuals (60%).

Pederson[62] examined the association between modeled wind turbine sound pressures and self-reported annoyance, health, and well-being among 754 respondents in seven areas in Sweden with wind turbines and varying landscapes. A total of 1309 surveys were distributed, resulting in a response rate of 57.6%. Annoyance was significantly associated with SPLs from wind turbines as well as having a negative attitude toward wind turbines, living in a rural area, wind turbine visibility, and living in an area with rocky or hilly terrain. Those annoyed by wind turbine noise reported a higher prevalence of lowered sleep quality and negative emotions than those not annoyed by noise. Because of the cross-sectional design, it cannot be determined whether wind turbine noise caused these complaints or if those who experienced disrupted sleep and negative emotions were more likely to notice and report annoyance from noise. Measured SPLs were not associated with any health effects studied. In the same year, Petersen et al reported on what they called a "grounded theory study" in which 15 informants were interviewed in depth regarding the reasons they were annoyed with wind turbines and associated noise. Responses indicated that these individuals perceived the turbines to be an intrusion and associated with feelings of lack of control and influence.[65] Although not an epidemiological study, this exercise was intended to elucidate the reasons underlying the reported annoyance with wind turbines.

Further analyses of the combined data from Pedersen and Waye[61,62] (described above) were published in two additional papers.[59,60] The pooled data included 1095 participants exposed to wind turbine noise of at least 30 dBA. As seen in the two original studies, a significant association between noise annoyance and SPL was observed. A total of 84 participants (7.7%) reported being fairly or very annoyed by wind turbine noise. Respondents reporting wind turbines as having a negative effect on the scenery were also statistically significantly more likely to report annoyance to wind turbine noise, regardless of SPLs.[59] Self-reported stress was higher among those who were fairly or very annoyed compared with those not annoyed; however, these associations could not be attributed specifically to wind turbine noise. No differences in self-reported health effects such as hearing impairment, diabetes, or cardiovascular diseases were reported between the 84 (7.7%) respondents who were fairly or very annoyed by wind turbine noise compared with all other respondents.[60] The authors did not report the power of the study.

Pederson et al[56–58] evaluated the data from 725 residents in the Netherlands living within 2.5 km of a site containing at least two wind turbines of 500 kW or greater. Using geographic information systems methods, 3727 addresses were identified in the study target area, for which names and telephone numbers were found for 2056; after excluding businesses, 1948 were determined to be residences and contacted. Completed surveys were received from 725 for a response rate of 37%. Although the response rate was lower than in previous cross-sectional studies, nonresponse analyses indicated that similar proportions responded across all landscape types and sound pressure categories.[57] Calculated sound levels, other sources of community noise, noise sensitivity, general attitude, and visual attitude toward wind turbines were evaluated. The authors reported an exposure–response relationship between calculated A-weighted SPLs and self-reported annoyance. Wind turbine noise was reported to be more annoying than transportation noise or industrial noise at comparable levels. Annoyance, however, was also correlated with a negative attitude toward the visual effect of wind turbines on the landscape. In addition, a statistically significantly decreased level of annoyance from wind turbine noise was observed among those who benefited economically from wind turbines, despite equal perception of noise and exposure to generally higher (greater than 40 dBA) sound levels.[58] Annoyance was strongly correlated with self-reporting a negative attitude toward the visual effect of wind turbines on the landscape scenery (measured on a five-point scale ranging from "very positive" to "very negative" opinion). The low response rate and reliance on self-reporting of noise annoyance limit the interpretation of these findings.

Results of further analyses of noise annoyance were reported in a separate report,[56] which indicated that road traffic noise had no effect on annoyance to wind turbine noise and vice versa. Visibility of, and attitude toward, wind turbines and road traffic were significantly related to annoyance from their respective noise source; stress was significantly associated with both types of noise.[56,157]

Additional analyses of the same data were performed using a structural equation approach that indicated that, as with annoyance, sleep disturbance increased with increasing SPL because of wind turbines; however, this increase was statistically significant only at pressures of 45 dBA and higher. Results of analyses of the combined data from the two Swedish[61,62] and the Dutch[58] cross-sectional studies have been published in two additional papers. Using the combined data from these three predecessor studies, Pedersen et al[56,58] identified 1755 (ie, 95.9%) of the 1830 total participants for which complete data were available to explore the relationships between calculated A-weighted SPLs and a range of indicators of health and well-being. Specifically, they considered sleep interruption; headache; undue tiredness; feeling tense, stressed, or irritable; diabetes; high blood pressure; cardiovascular disease; and tinnitus.[63] As in the precursor studies, noise annoyance indoors and outdoors was correlated with A-weighted SPLs. Sleep interruption seemed at higher sound levels and was also related to annoyance. No other health or well-being variables were consistently related to SPLs. Stress was not directly associated with SPLs but was associated with noise-related annoyance.

Another report based on these data (in these analyses, 1820 of the 1830 total participants) modeled the relationship between wind turbine noise exposure and annoyance indoors and outdoors.[64] The authors excluded respondents who benefited economically from wind turbines, then compared their modeled results with other modeled relationships for industrial and transportation noise; they claimed that annoyance from wind turbine noise at or higher than 45 dBA is associated with more annoyance than other noise sources.

Shepherd et al,[66] who had conducted an earlier evaluation of noise sensitivity and Health Related Quality of Life (HRQL),[158] compared survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No indicator of exposure to wind turbine noise was considered beyond the selection of individuals based on the proximity of their residences from the nearest wind turbine. Health-related quality-of-life (HRQOL) scales were used to describe and compare the general well-being and well-being in the physical, psychological, and social domains of each group. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental quality-of-life (QOL) scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). No differences were reported for social or psychological HRQOL domain scores. The group residing closer to a wind turbine also reported lower amenity but not related to traffic or neighborhood noise annoyance. Lack of actual wind turbine and other noise source measurements, combined with the poor response rate (both noted by the authors as limitations), limits the inferential value of these results because they may pertain to wind turbine emissions.[66]

Possibly the largest cross-sectional epidemiological study of wind turbine noise on QOL was conducted in an area of northern Poland with the most wind turbines.[67] Surveys were completed by a total of 1277 adults (703 women and 574 men), aged 18 to 94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate was estimated at 30% (B. Mroczek, dr hab n. zdr., e-mail communication, January 2, 2014). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m; 279 (21.9%) between 700 and 1000 m; 221 (17.3%) between 1000 and 1500 m; and 424 (33.2%) residing more than 1500 m from the nearest wind turbine. Indicators of QOL and health were measured using the Short Form–36 Questionnaire (SF-36). The SF-36 consists of 36 questions specifically addressing physical functioning, role-functioning physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, and mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale for health assessment. It is unclear whether age, sex, education, and occupation were controlled for in the statistical analyses. The authors report that, within all subscales, those living closest to wind farms reported the best QOL, and those living farther than 1500 m scored the worst. They concluded that living in close proximity of wind farms does not result in the worsening of, and might improve, the QOL in this region.[67]

A small survey of residents of two communities in Maine with multiple industrial wind turbines compared sleep and general health outcomes among 38 participants residing 375 to 1400 m from the nearest turbine with another group of 41 individuals residing 3.3 to 6.6 km from the nearest wind turbine.[68] Participants completed questionnaires and in-person interviews on a range of health and attitudinal topics. Prevalence of self-reported health and other complaints was compared by distance from the wind turbines, statistically controlling for age, sex, site, and household cluster in some analyses. Participants living within 1.4 km of a wind turbines reported worse sleep, were sleepier during the day, and had worse SF-36 Mental Component Scores compared with those living farther than 3.3 km away. Statistically significant correlations were reported between Pittsburgh Sleep Quality Index, Epworth Sleepiness Scale, SF-36 Mental Component Score, and log-distance to the nearest wind turbine. The authors attributed the observed differences to the wind turbines[68]; methodological problems such as selection and reporting biases were overlooked. This study has a number of methodological limitations, most notably that all of the "near" turbine groups were plaintiffs in a lawsuit against the wind turbine operators and had already been interviewed by the lead investigator prior to the study. None of the "far" group had been interviewed; they were "cold called" by an assistant. This differential treatment of the two groups introduces a bias in the integrity of the methods and corresponding results. Details of the far group, as well as participation rates, were not noted.[68]

In another study, the role of negative personality traits (defined by the authors using separate scales for assessing neuroticism, negative affectivity, and frustration intolerance) on possible associations between actual and perceived wind turbine noise and medically unexplained nonspecific symptoms was investigated via a mailed survey.[69] Of the 1270 identified households within 500 m of eight 0.6 kW micro-turbine farms and within 1 km of four 5 kW small wind turbine farms in two cities in the United Kingdom, only 138 questionnaires were returned, for a response rate of 10%. No association was noted between calculated and actual noise levels and nonspecific symptoms. A correlation between perceived noise and nonspecific symptoms was seen among respondents with negative personality traits. Despite the participant group's reported representativeness of the target population, the low survey response rate precludes firm conclusions on the basis of these data.[69]

In a study of residents living near a "wind park" in Western New York State, surveys were administered to 62 individuals living in 52 homes.[70] The wind park included 84 turbines. No association was noted between self-reported annoyance and short duration sound measurements. A correlation was noted between the measure of a person's concern regarding health risks and reported measures of the prevalence of sleep disturbance and stress. While a cross-sectional study is based on self-reported annoyance and health indicators, and therefore limited in its interpretation, one of its strengths is that it is one of the few studies that performed actual sound measurements (indoors and outdoors).

A small but detailed study on response to the wind turbine noise was carried out in Poland.[71] The study population consisted of 156 people, age 15–82 years, living in the vicinity of 3 wind farms located in the central and northwestern parts of Poland. No exclusion criteria were applied, and each individual agreeing to participate was sent a questionnaire patterned after the one used in the Pederson 2004 and Pederson 2007 studies and including questions on living conditions, self-reported annoyance due to noise from wind turbines, and self-assessment of physical health and well-being (such as headaches, dizziness, fatigue, insomnia, and tinnitus). The response rate was 71%. Distance from the nearest wind turbine and modeled A-weighted SPLs were considered as exposure indicators. One third (33.3%) of the respondents found wind turbine noise annoying outdoors, and one fifth (20.5%) found the noise annoying while indoors. Wind turbine noise was reported as being more annoying than other environmental noises, and self-reported annoyance increased with increasing A-weighted SPLs. Factors such as attitude toward wind turbines and "landscape littering" (visual impact) influenced the perceived annoyance from the wind turbine noise. This study, as with most others, is limited by the cross-sectional design and reliance on self-reported health and well-being indicators; however, analyses focused on predictors of self-reported annoyance, and found that wind turbine noise, attitude toward wind turbines, and attitude toward "landscape littering" explain most of the reported annoyance.

Other Possibly Relevant Studies

A publication based on the self-reporting of 109 individuals who "perceived adverse health effects occurring with the onset of an industrial wind turbine facility" indicated that 102 reported either "altered health or altered quality of life." The authors appropriately noted that this was a survey of self-selected participants who chose to respond to a questionnaire specifically designed to attract those who had health complaints they attributed to wind turbines, with no comparison group. Nevertheless, the authors inappropriately draw the conclusion that "Results of this study suggest an underlying relationship between wind turbines and adverse health effects and support the need for additional studies."[48(p.336)] Such a report cannot provide valid evidence of any relationship for which there is no comparison and is of little if any inferential value.

Researchers at the School of Public Health, University of Sydney, in Australia conducted a study to explore psychogenic explanations for the increase around 2009 of wind farm noise and/or health complaints and the disproportionate corresponding geographic distribution of those complaints.[52] They obtained records of complaints about noise or health from residents living near all 51 wind farms (1634 turbines) operating between 1993 and 2012 from wind farm companies and corroborated with documents such as government public enquiries, news media records, and court affidavits. Of the 51 wind farms, 33 (64.7%) had no record of noise or health complaints, including all wind farms in Western Australia and Tasmania. The researchers identified 129 individuals who had filed complaints, 94 (73%) of whom lived near six wind farms targeted by anti-wind advocacy groups. They observed that 90% of complaints were registered after anti-wind farm groups included health concerns as part of their advocacy in 2009. The authors concluded that their findings were consistent with their psychogenic hypotheses.

Discussion

No cohort or case–control studies were located in this updated review of the peer-reviewed literature. The lack of published case–control studies is less surprising and less critical because there has been no discrete disease or constellation of diseases identified that likely or might be explained by wind turbine noise. Anecdotal reports of symptoms associated with wind turbines include a broad array of nonspecific symptoms, such as headache, stress, and sleep disturbance, that afflict large proportions of the general population and have many recognized risk factors. Retrospectively associating such symptoms with wind turbines or even measured wind turbine noise—as would be necessary in case–control studies—does not prevent recall bias from influencing the results.

Although cross-sectional studies and surveys have the advantage of being relatively simple and inexpensive to conduct, they are susceptible to a number of influential biases. Most importantly, however, is the fact that, because of the simultaneous ascertainment of both exposure (eg, wind turbine noise) and health outcomes or complaints, the temporal sequence of exposure–outcome relationship cannot be demonstrated. If the exposure cannot be established to precede the incidence of the outcome—and not the reverse, that is, the health complaint leads to increased perception of or annoyance with the exposure, as with insomnia headaches or feeling tense/stressed/irritable—the association cannot be evaluated for a possible causal nature.

Conclusions

A critical review and synthesis of the evidence available from the eight study populations studied to date (and reported in 14 publications) provides some insights into the hypothesis that wind turbine noise harms human health in those living in proximity to wind turbines. These include the following:

- No clear or consistent association is seen between noise from wind turbines and any reported disease or other indicator of harm to human health.
- In most surveyed populations, some individuals (generally a small proportion) report some degree of annoyance with wind turbines; however, further evaluation has demonstrated:
  - Certain characteristics of wind turbine sound such as its intermittence or rhythmicity may enhance reported perceptibility and annoyance;
  - The context in which wind turbine noise is emitted also influences perceptibility and annoyance, including urban versus rural setting, topography, and landscape features, as well as visibility of the wind turbines;
  - Factors such as attitude toward visual effect of wind turbines on the scenery, attitude toward wind turbines in general, personality characteristics, whether individuals benefit financially from the presence of wind turbines, and duration of time wind turbines have been in operation all have been correlated with self-reported annoyance; and
  - Annoyance does not correlate well or at all with objective sound measurements or calculated sound pressures.
- Complaints such as sleep disturbance have been associated with A-weighted wind turbine sound pressures of higher than 40 to 45 dB but not any other measure of health or well-being. Stress was associated with annoyance but not with calculated sound pressures.[63]
- Studies of QOL including physical and mental health scales and residential proximity to wind turbines report conflicting findings– one study (with only 38 participants living within 2.0 km of the nearest wind turbine) reported lower HRQOL among those living closer to wind turbines than respondents living farther away,[66] whereas the largest of all studies (with 853 living within 1500 m of the nearest wind turbine)[67] found that those living closer to wind turbines reported higher QOL and health than those living farther away.[67]

Because these statistical correlations arise from cross-sectional studies and surveys in which the temporal sequence of the exposure and outcome cannot be evaluated, and where the effect of various forms of bias (especially selection/volunteer bias and recall bias) may be considerable, the extent to which they reflect causal relationships cannot be determined. For example, the claims such as "We conclude that the noise emissions of wind turbines disturbed the sleep and caused daytime sleepiness and impaired mental health in residents living within 1.4 km of the two wind turbines installations studied" cannot be substantiated on the basis of the actual study design used and some of the likely biases present.[70]

Notwithstanding the limitations inherent to cross-sectional studies and surveys—which alone may provide adequate explanation for some of the reported correlations—several possible explanations have been suggested for the wind turbines–associated annoyance reported in many of these studies, including attitudinal and even personality characteristics of the survey participants.[69] Pedersen and colleague,[59] who have been involved in the majority of publications on this topic, noted "The enhanced negative response [toward wind turbines] could be linked to aesthetical response, rather than to multi-modal effects of simultaneous auditory and visual stimulation, and a risk of hindrance to psycho-physiological restoration could not be excluded."[(p.389)] They also found that wind turbines might be more likely to elicit annoyance because some perceive them to be "intrusive" visually and with respect to their noise.[65] Alternative explanations on the basis of evaluation of all health complaints filed between 1993 and 2012 with wind turbine operators across Australia include the influence of anti-wind power activism and the surrounding publicity on the likelihood of health complaints, calling the complaints "communicated diseases."[52]

As noted earlier, the 14 papers meeting the selection criteria for critical review and synthesis were based on only eight independent study groups—three publications were based on the same study group from the Netherlands[58] and four additional publications were based on the combined data from the two Swedish surveys[61,62] or from the combined data from all three. The findings across studies based on analyses of the same data are not independent observations, and therefore the body of available evidence may seem to be larger and more consistent than it should. This observation does not necessarily mean that the relationships observed (or the lack of associations between calculated wind turbines sound pressures and disease or other indicators of health) are invalid, but that consistency across reports based on the same data should not be overinterpreted as independent confirmation of findings. Perhaps more important is that all eight were cross-sectional studies or surveys, and therefore inherently limited in their ability to demonstrate the presence or absence of true health effects.

Recent controlled exposure laboratory evaluations lend support to the notion that reports of annoyance and other complaints may reflect, at least in part, preconceptions about the ability of wind turbine noise to harm health[52,71,72] or even the color of the turbine[73] more than the actual noise emission.

Sixty years ago, Sir Austin Bradford Hill delivered a lecture entitled "Observations and Experiment" to the Royal College of Occupational Medicine. In his lecture, Hill stated that "The observer may well have to be more patient than the experimenter—awaiting the occurrence of the natural succession of events he desires to study; he may well have to be more imaginative—sensing the correlations that lie below the surface of his observations; and he may well have to be more logical and less dogmatic—avoiding as the evil eye the fallacy of '*post hoc ergo propter hoc*,' the mistaking of correlation for causation."[74(p.1000)]

Although it is typical and appropriate to point out the obvious need for additional research, it may be worth emphasizing that more research of a similar nature—that is, using cross-sectional or survey approaches—is unlikely to be informative, most notably for public policy decisions. Large, well-conducted prospective cohort studies that document baseline health status and can objectively measure the incidence of new disease or health conditions over time with the introduction would be the most informative. On the contrary, the phenomena that constitute wind turbine exposures—primarily noise and visual effect—are not dissimilar to many other environmental (eg, noise of waves along shorelines) and anthropogenic (eg, noise from indoor Heating Ventilation and Air Conditioning or road traffic) stimuli, for which research and practical experience indicate no direct harm to human health.

Sound Components and Health: Infrasound, Low-Frequency Sound, and Potential Health Effects

Introduction

This section addresses potential health implications of infrasound and low-frequency sound because claims have been made that the frequency of wind turbine sound has special characteristics that may present unique health risks in comparison with other sources of environmental sound.

Wind turbines produce two kinds of sound. Gears and generators can make mechanical noise, but this is less prominent than the

TABLE 1. Human Thresholds for Different Frequencies

Frequency (Hz)	Threshold (dB SPL)
100	27
25	69
10	97

SPL, sound pressure level.

aerodynamic noise of the blades, whose tips may have velocities in excess of 200 mph. Three-bladed turbines often rotate about once every 3 seconds; their "blade-pass" frequency is thus about 1 Hz (Hz: cycle per second). For this reason, the aerodynamic noise often rises and falls about once per second, and some have described the sounds as "whooshing" or "pulsing."

Several studies[44,75,76] have shown that at distances of 300 m or more, wind turbine sounds are below human detection thresholds for frequencies less than 50 Hz. The most audible frequencies (those whose acoustic energies exceed human thresholds the most) are in 500 to 2000 Hz range. At this distance from a single wind turbine, overall levels are typically 35 to 45 dBA.[77,78] These levels can be audible in a typical residence with ambient noise of 30 dBA and windows open (a room with an ambient level of 30 dBA would be considered by most people to be quiet or very quiet). In outdoor environments, sound levels drop about 6 dB for every doubling of the distance from the source, so one would predict levels of 23 to 33 dBA, that is, below typical ambient noise levels in homes, at a distance of 1200 m. For a wind farm of 12 large turbines, Møller and Pedersen[79] predicted a level of 35 dBA at a distance of 453 m.

As noted earlier in this report, sound intensity is usually measured in decibels (dB), with 0 dB SPL corresponding to the softest sounds young humans can hear. Nevertheless, humans hear well only within the frequency range that includes the frequencies most important for speech understanding—about 500 to 5000 Hz. At lower frequencies, hearing thresholds are much higher.[75] Although frequencies lower than 20 Hz are conventionally referred to as "infrasound," sounds in this range can in fact be heard, but only when they are extremely intense (a sound of 97 dB SPL has 10 million times as much energy as a sound of 27 dB; see Table 1).

Complex sounds like those produced by wind turbines contain energy at multiple frequencies. The most complete descriptions of such sounds include dB levels for each of several frequency bands (eg, 22 to 45 Hz, 45 to 90 Hz, 90 to 180 Hz, . . . , 11,200 to 22,400 Hz). It is simpler, and appropriate in most circumstances, to specify overall sound intensity using meters that give full weight to the frequencies people hear well, and less weight to frequencies less than 500 Hz and higher than 5000 Hz. The resulting metric is "A-weighted" decibels or dBA. Levels in dBA correlate well with audibility; in a very quiet place, healthy young people can usually detect sounds less than 20 dBA.

Low-Frequency Sound and Infrasound

Low-frequency noise (LFN) is generally considered frequencies from 20 to 250 Hz, as described earlier in more detail in subsection "Low Frequency and Infrasonic Levels." The potential health implications of low-frequency sound from wind turbines have been investigated in a study of four large turbines and 44 smaller turbines in the Netherlands.[17] In close proximity to the turbines, infrasound levels were below audibility. The authors suggested that LFN could be an important aspect of wind turbine noise; however, they did not link measured or modeled noise levels with any health outcome measure, such as annoyance.

A literature review of infrasound and low-frequency sound concluded that low-frequency sound from wind turbines at residences did not exceed levels from other common noise sources, such as traffic.[44] The authors concluded that a "statistically significant association between noise levels and self-reported sleep disturbance was found in two of the three [epidemiology] studies."[(p.1)]. It has been suggested that LFN from wind turbines causes other and more serious health problems, but empirical support for these claims is lacking.[44]

Sounds with frequencies lower than 20 Hz (ie, infrasound) may be audible at very high levels. At even higher levels, subjects may experience symptoms from very low-frequency sounds—ear pressure (at levels as low as 127 dB SPL), ear pain (at levels higher than 145 dB), chest and abdominal movement, a choking sensation, coughing, and nausea (at levels higher than 150 dB).[80,81] The National Aeronautics and Space Administration considered that infrasound exposures lower than 140 dB SPL would be safe for astronauts; American Conference of Governmental Industrial Hygienists recommends a threshold limit value of 145 dB SPL for third-octave band levels between 1 and 80 Hz.[81] As noted earlier, infrasound from wind turbines has been measured at residential distances and noted to be many orders of magnitude below these levels.

Whenever wind turbine sounds are audible, some people may find the sounds annoying, as discussed elsewhere in this review. Some authors, however, have hypothesized that even inaudible sounds, especially at very low frequencies, could affect people by activating several types of receptors, including the following:

1. Outer hair cells of the cochlea[82];
2. Hair cells of the normal vestibular system,[83] especially the otolith organs[84];
3. Hair cells of the vestibular system after its fluid dynamics have been disrupted by infrasound[82];
4. Visceral graviceptors acting as vibration sensors.[83]

To evaluate these hypotheses, it is useful to review selected aspects of the anatomy and physiology of the inner ear (focusing on the differences between the cochlea and the vestibular organs), vibrotactile sensitivity to airborne sound, and the types of evidence that, while absent at present, could in theory support one or more of these hypotheses.

How the Inner Ear Works

The inner ear contains the cochlea (the organ of hearing) and five vestibular organs (three semicircular canals and two otolith organs, transmitting information about head position and movement). The cochlea and the vestibular organs have one important feature in common—they both use hair cells to convert sound or head movement into nerve impulses that can then be transmitted to the brain. Hair cells are mechanoreceptors that can elicit nerve impulses only when their stereocilia (or sensory hairs) are bent.

The anatomy of the cochlea ensures that its hair cells respond well to airborne sound and poorly to head movement, whereas the anatomy of the vestibular organs optimizes hair cell response to head movement and minimizes response to airborne sound. Specifically, the cochlear hair cells are not attached to the bony otic capsule, and the round window permits the cochlear fluids to move more freely when air-conducted sound causes the stapes to move back and forth in the oval window. Conversely, the vestibular hair cells are attached to the bony otic capsule, and the fluids surrounding them are not positioned between the two windows and thus cannot move as freely in response to air-conducted sound. At the most basic level, this makes it unlikely that inaudible sound from wind turbines can affect the vestibular system.

Responding to Airborne Sound

Airborne sound moves the eardrum and ossicles back and forth; the ossicular movement at the oval window then displaces inner ear fluid, causing a movement of membranes in the cochlea, with bending of the hair cell stereocilia. Nevertheless, this displacement of the cochlear hair cells depends on the fact that there are two windows separating the inner ear from the middle ear, with the cochlear hair cells positioned between them—whenever the oval window (the bony footplate of the stapes, constrained by a thin annular ligament) is pushed inward, the round window (a collagenous membrane lined by mucous membrane) moves outward, and vice versa. When the round window is experimentally sealed,[85] the cochlea's sensitivity to sound is reduced by 35 dB.

The vestibular hair cells are not positioned between the two cochlear windows, and therefore airborne sound-induced inner ear fluid movement does not efficiently reach them. Instead, the vestibular hair cells are attached to the bone of the skull so that they can respond faithfully to head movement (the cochlear hair cells are not directly attached to the skull). As one might expect, vestibular hair cells can respond to head vibration (bone-conducted sound), such as when a tuning fork is held to the mastoid. Very intense airborne sound can also make the head vibrate; people with severe conductive hearing loss can hear airborne sound in this way, but only when the sounds are made 50 to 60 dB more intense than those audible to normal people.

The cochlea contains two types of hair cells. It is often said that we hear with our inner hair cells (IHCs) because all the "type I" afferent neurons that carry sound-evoked impulses to the brain connect to the IHCs. The outer hair cells (OHCs) are important as "preamplifiers" that make it possible to hear very soft sounds; they are exquisitely tuned to specific frequencies, and when they move they create fluid currents that then displace the stereocilia of the IHCs.

Although more numerous than the IHCs, the OHCs receive only very scanty afferent innervation, from "type II" neurons, the function of which is unknown. Salt and Hullar[82] have pointed out that OHCs generate measurable electrical responses called cochlear microphonics to very low frequencies (eg, 5 Hz) at levels that are presumably inaudible to the animals and have hypothesized that the type II afferent fibers from the OHCs might carry this information to the brain. Nevertheless, it seems that no one has ever recorded action potentials from type II cochlear neurons, nor have physiological responses other than cochlear microphonics been recorded in response to inaudible sounds.[86,87] In other words, as Salt and Hullar[82] acknowledge, "The fact that some inner ear components (such as the OHC) may respond to [airborne] infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way."[(p.19)]

Responses of the Vestibular Organs

As previously noted, vestibular hair cells are efficiently coupled to the skull. The three semicircular canals in each ear are designed to respond to head rotations (roll, pitch, yaw, or any combination). When the head rotates, as in shaking the head to say "no," the fluid in the canals lags behind the skull and bends the hair cells. The otolith organs (utricle and saccule) contain calcium carbonate crystals (otoconia) that are denser than the inner ear fluid, and this allows even static head position to be detected; when the head is tilted, gravitational pull on the otoconia bends the hair cells. The otolith organs also respond to linear acceleration of the head, as when a car accelerates.

Many people complaining about wind turbines have reported dizziness, which can be a symptom of vestibular disorders; this has led to suggestions that wind turbine sound, especially inaudible infrasound, can stimulate the vestibular organs.[83,84] Pierpont[83] introduced a term "Wind Turbine Syndrome" based on a case series of 10 families who reported symptoms that they attributed to living near wind turbines. The author invited people to participate if they thought they had symptoms from living in the vicinity of wind turbines; this approach introduces substantial selection bias that can distort the results and their corresponding significance. Telephone interviews were conducted; no medical examination, diagnostic studies or review, and documentation of medical records were conducted as part of the case series. Noise measurements were not provided. Nonetheless, the author described a collection of nonspecific symptoms that were described as "Wind Turbine Syndrome." The case series, at the time of preparation of this review, has not been published in the peer-reviewed scientific literature. Although not medically recognized, advocates of this "disorder" suggest that wind turbines produce symptoms, such as headaches, memory loss, fatigue, dizziness, tachycardia, irritability, poor concentration, and anxiety.[88]

To support her hypotheses, Pierpont cited a report by Todd et al[89] that demonstrated human vestibular responses to bone-conducted sound at levels below those that can be heard. But as previously noted, this effect is not surprising because the vestibular system is designed to respond to head movement (including head vibration induced by direct contact with a vibrating source). The relevant issue is how the vestibular system responds to airborne sound, and here the evidence is clear. Vestibular responses to airborne sound require levels well above audible thresholds.[90,91] Indeed, clinical tests of vestibular function using airborne sound use levels in excess of 120 dB, which raise concerns of acoustic trauma.[92]

Salt and Hullar[82] acknowledge that a normal vestibular system is unlikely to respond to inaudible airborne sound—"Although the hair cells in other sensory structures such as the saccule may be tuned to infrasonic frequencies, auditory stimulus coupling to these structures is inefficient so that they are unlikely to be influenced by airborne infrasound."[(p.12)] They go on to hypothesize that infrasound may cause endolymphatic hydrops, a condition in which one of the inner ear fluid compartments is swollen and may disturb normal hair cell function. But here, too, they acknowledge the lack of evidence—" . . . it has never been tested whether stimuli in the infrasound range cause endolymphatic hydrops."[(p.19)] In previous research, Salt[93] was able to create temporary hydrops in animals using airborne sound, but only at levels (115 dB at 200 Hz) that are many orders of magnitude higher than levels that could exist at residential distances from wind turbines.

Human Vibrotactile Sensitivity to Airborne Sound

Very loud sound can cause head and body vibration. As previously noted, a person with absent middle ear function but an intact cochlea may hear sounds at 50 to 60 dB SPL. Completely deaf people can detect airborne sounds using the vibrotactile sense, but only at levels far above hearing threshold, for example, 128 dB SPL at 16 Hz.[94] Vibrotactile sensation depends on receptors in the skin and joints.

Pierpont[83] hypothesized that "visceral graviceptors,"[95,96] which contain somatosensory receptors, could detect airborne infrasound transmitted from the lungs to the diaphragm and then to the abdominal viscera. These receptors would seem to be well suited to detect body tilt or perhaps whole-body vibration, but there is no evidence that airborne sound could stimulate sensory receptors in the abdomen. Airborne sound is almost entirely reflected away from the body; when Takahashi et al[97] used airborne sound to produce chest or abdominal vibration that exceeded ambient body levels, levels had to exceed 100 dB at 20 to 50 Hz.

Further Studies of Note

The influence of preconception on mood and physical symptoms after exposure to LFN was examined by showing 54 university students one of two series of short videos that either promoted or dispelled the notion that sounds from wind turbines had health effects, then exposing subjects to 10 minutes of quiet period followed by infrasound (40 dB at 5 Hz) generated by computer software, and assessing mood and a series of physical symptoms.[71] In a double-blind protocol, participants first exposed to either a "high-expectancy" presentation included first-person accounts of symptoms attributed to wind turbines or a "low-expectancy" presentation showed experts stating scientific positions indicating that infrasound does not cause symptoms. Participants were then exposed to 10 minutes of infrasound and 10 minutes of sham infrasound. Physical symptoms were reported before and during each 10-minute exposure. The study showed that healthy volunteers, when given information designed to invoke either high or low expectations that exposure to infrasound causes symptom complaints, reported symptoms that were consistent with the level of expectation. These data demonstrate that the participants' expectations of the wind turbine sounds determined their patterns of self-reported symptoms, regardless of whether the exposure was to a true or sham wind turbine sound. The concept known as a "nocebo" response, essentially the opposite of a placebo response, will be discussed in more detail later in this report. A nocebo response refers to how a preconceived negative reaction can occur in anticipation of an event.[98]

A further study assessed whether positive or negative health information about infrasound generated by wind turbines affected participants' symptoms and health perceptions in response to wind farm sound.[72] Both physical symptoms and mood were evaluated after exposure to LFN among 60 university students first shown high-expectancy or low-expectancy short videos intended to promote or dispel the notion that wind turbines sounds impacted health. One set of videos presented information indicating that exposure to wind turbine sound, particularly infrasound, poses a health risk, whereas the other set presented information that compared wind turbine sound to subaudible sound created by natural phenomena such as ocean waves and the wind, emphasizing their positive effects on health. Students were continuously exposed during two 7-minute listening sessions to both infrasound (50.4 dB, 9 Hz) and audible wind farm sound (43 dB), which had been recorded 1 km from a wind farm, and assessed for mood and a series of physical symptoms. Both high-expectancy and low-expectancy groups were made aware that they were listening to the sound of a wind farm and were being exposed to sound containing both audible and subaudible components and that the sound was at the same level during both sessions. Participants exposed to wind farm sound experienced a placebo response elicited by positive preexposure expectations, with those participants who were given expectations that infrasound produced health benefits reporting positive health effects. They concluded that reports of symptoms or negative effects could be nullified if expectations could be framed positively.

University students exposed to recorded sounds from locations 100 m from a series of Swedish wind turbines for 10 minutes were assessed for parameters of annoyance.[99] Sound was played at a level of 40 dBAeq (the "eq" refers to the average level over the 10-minute exposure). After the initial exposure, students were exposed to an additional 3 minutes of noise while filling out questionnaires. Authors reported that ratings of annoyance, relative annoyance, and awareness of noise were different among the different wind turbine recordings played at equivalent noise levels. Various psychoacoustic parameters (sharpness, loudness, roughness, fluctuation strength, and modulation) were assessed and then grouped into profiles. Attributes such as "lapping," "swishing," and "whistling'' were more easily noticed and potentially annoying, whereas "low frequency" and "grinding" were associated with less intrusive and potentially less annoying sounds.

Adults exposed to sounds recorded from a 1.5 MV Korean wind turbine were assessed for the degree of noise annoyance.[100] Over a 40-minute period, subjects were exposed to a series of 25 random 30-second bursts of wind turbine noise, separated by at least 10 seconds of quiet between bursts. Following a 3-minute quiet period, this pattern was repeated. Participants reported their annoyance on a scale of 1 to 11. Authors found that the amplitude modulation of wind turbine noise had a statistically significant effect on the subjects' perception of noise annoyance.

The effect of psychological parameters on the perception of noise from wind turbines was also assessed in Italian adults from both urban and rural areas. Recorded sounds from different distances (150 m, 250 m, and 500 m) away from wind turbines were played while pictures of wind turbines were shown and subjects described their reaction to the pictures.[73] Pictures differed in color, the number of wind turbines, and distance from wind turbines. Pictures had a weak effect on individual reactions to the number of wind turbines; the color of the wind turbines influenced both visual and auditory individual reactions, although in different ways.

Epilepsy and Wind Turbines

Rapidly changing visual stimuli, such as flashing lights or oscillating pattern changes, can trigger seizures in susceptible persons, including some who never develop spontaneous seizures; stimuli that change at rates of 12 to 30 Hz are most likely to trigger seizures.[101] Rotating blades (of a ceiling fan, helicopter, or wind turbine) that interrupt light can produce a flicker, leading to a concern that wind turbines might cause seizures. Nevertheless, large wind turbines (2 MW or more) typically rotate at rates less than 1 Hz; with three blades, the frequency of light interruption would be less than 3 Hz, a rate that would pose negligible risk to developing a photoepileptic seizure.[102]

Smedley et al[103] applied a complex simulation model of seizure risk to wind turbines, assuming worst-case conditions—a cloudless day, an observer looking directly toward the sun with wind turbine blades directly between the observer and the sun, but with eyes closed (which scatters the light more broadly on the retina); they concluded that there would be a risk of seizures at distances up to nine times the turbine height, but only when blade frequency exceeds 3 Hz, which would be rare for large wind turbines. Smaller turbines, typically providing power for a single structure, often rotate at higher frequencies and might pose more risk of provoking seizures. At the time of preparation of this report, there has been no published report of a photoepileptic seizure being triggered by looking at a rotating wind turbine.

Sleep and Wind Turbines

Sleep disturbance is relatively common in the general population and has numerous causes, including illness, depression, stress, and the use of medications, among others. Noise is well known to be potentially disruptive to sleep. The key issue with respect to wind turbines is whether the noise is sufficiently loud to disrupt sleep. Numerous environmental studies of noise from aviation, rail, and highways have addressed sleep implications, many of which are summarized in the WHO's position paper on Nighttime Noise Guidelines (Fig. 7).[104] This consensus document is based on an expert analysis of environmental noise from sources other than wind turbines, including transportation, aviation, and railway noise. The WHO published the figure (Fig. 7) to indicate that significant sleep disturbance from environmental noise begins to occur at noise levels greater than 45 dBA. This figure is based on an analysis of pooled data from 24 different environmental noise studies, although no wind turbine–related noise studies were included in the analysis. Nonetheless, the studies provide substantial data on environmental noise exposure that can be contrasted with noise levels associated with wind turbine operations to enable one to draw reasonable inferences.

In contrast to the WHO position, an author in an editorial claimed that routine wind turbine operations that result in noise levels less than 45 dBA can have substantial effects on sleep, with corresponding adverse health effects.[105] Another author, however, challenged the basis of the assertion by pointing out that Hanning had ignored 17 reviews on the topic with alternative perspectives and different results.[106]

Sleep disturbance is a potential extra-auditory effect of noise, and research has shown a link between wind turbine noise and sleep disruption.[4,57,63,66,107] As with of the other variables reviewed, quantifying sleep quality is typically done with coarse measures. In fact, this reviewer identified no studies that used a multi-item validated sleep measure. Research studies typically rely on a single item (sometimes answered yes/no) to measure sleep quality. Such coarse measurement of sleep quality is unfortunate because impaired sleep is a plausible pathway by which wind turbine noise exposure may impact both psychological well-being and physical health.

Disturbed sleep can be associated with adverse health effects.[108] Awakening thresholds, however, depend on both physical and psychological factors. Signification is a psychological factor that refers to the meaning or attitude attached to a sound. Sound with high signification will awaken a sleeper at lower intensity than sound lacking signification.[108] As reviewed above, individuals often attach attitudes to wind turbine sound; as such, wind turbine sleep disruption may be impacted by psychological factors related to the sound source.

Shepherd et al[66] found a significant difference in perceived sleep quality between their wind farm and comparison groups, with the wind farm group reporting worse sleep quality. In the wind farm group, noise sensitivity was strongly correlated with sleep quality. In both the wind farm and comparison groups, sleep quality showed similar strong positive relationships with physical HRQL and psychological HRQL. Pedersen[63] found that sound-level exposure was associated with sleep interruption in two of three studies reviewed; however, the effect sizes associated with sound exposure were minimal.

Bakker et al[57] found that noise exposure was related to sleep disturbance in quiet areas ($d = 0.40$) but not for individuals in noisy areas ($d = 0.02$). Nevertheless, when extreme sound exposure groups were composed,[57] data showed that individuals living in high sound areas (greater than 45 dBA) had significantly greater sleep disruption than subjects in low sound areas (less than 30 dBA). Annoyance ratings were more strongly associated with sleep disruption.[57] Furthermore, when[57] structural equation models (SEMs) were applied, the direct association between sound level and sleep disruption was lost and annoyance seemed to mediate the effect of wind turbine sound on sleep disturbance. Across the reviewed studies it seems that sleep disruption was associated with sound-level exposure; however, the associations were weak and annoyance ratings were more strongly and consistently associated with self-reported sleep disruption.

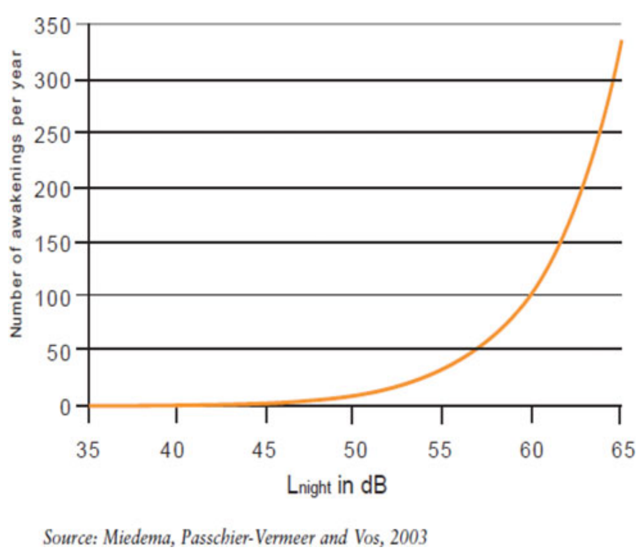

FIGURE 7. Worst-case prediction of noise-induced behavioral awakenings. Adapted from WHO[104] (Chapter 3); Miedema et al.[163]

Conclusions

Infrasound and low-frequency sound can be generated by the operation of wind turbines; however, neither low-frequency sound nor infrasound in the context of wind turbines or in experimental studies has been associated with adverse health effects.

Annoyance, Wind Turbines, and Potential Health Implications

The potential effect of noise on health may occur through both physiological (sleep disturbance) and psychological pathways. Psychological factors related to noise annoyance reported in association with wind turbine noise will be reviewed and analyzed. A critique of the methodological adequacy of the existing wind turbine research as it relates to psychological outcomes will be addressed.

As noted earlier, "annoyance" has been used as an outcome measure in environmental noise studies for many decades. Annoyance is assessed via a questionnaire. Because annoyance has been associated under certain circumstances with living in the vicinity of wind turbines, this section examines the significance of annoyance, risk factors for reporting annoyance in the context of wind turbines, and potential health implications.

For many years, it has been recognized that exposure to high noise levels can adversely affect health[109,110] and that environmental noise can adversely affect psychological and physical health.[111] Key to evaluating the health effects of noise exposure—like any hazard—is a thorough consideration of noise intensity and duration. When outcomes are broadened to include more subjective qualities like annoyance and QOL, additional psychological factors must be studied.

Noise-related annoyance is a subjective psychological condition that may result in anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion.[112] Annoyance is primarily identified using standardized self-report questionnaires. Well-established psychiatric conditions like major depressive disorder are also subjective states that are most often identified by self-report questionnaires. Despite its subjective nature, noise annoyance was included as a negative health outcome by the WHO in their recent review of disease burden related to noise exposure.[112] The inclusion of annoyance with conditions like cardiovascular disease reinforces its status as a legitimate primary health outcome for environmental noise research.

This section reviews the literature on the effect of wind turbines, including noise-related annoyance and its corresponding effect on health, QOL, and psychological well-being. "Quality of life" is a multidimensional concept that captures subjective aspects of an individual's experience of functioning, well-being, and satisfaction across the physical, mental, and social domains of life. The WHO defines QOL as "an individual's perception of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns. It is a broad ranging concept affected in complex ways by the person's physical health, psychological status, personal beliefs, social relationships and their relationship to salient features of their environment".[113(p1404)] Numerous well-validated QOL measures are available, with the SF-12 and SF-36[114] and the WHO Quality of Life—Short Form (WHOQLO-BREF[115]) being among the most commonly used. Quality of life measures have been widely adopted as primary outcomes for clinical trials and cost-effectiveness research.

Meta-analysis is a quantitative method for summarizing the relative strength of an effect or relationship as observed across multiple independent studies.[116] The increased application of meta-analysis has had a considerable effect on how literature reviews are approached. Currently, more than 20 behavioral science journals require that authors report measures of effect size along with tests of significance.[117] The use of effect size indicators enhances the comparability of findings across studies by changing the reported outcome statistics to a common metric. In behavioral health, the most frequently used effect size indicators are the Cohen d[118] and r the zero-order (univariate) correlation coefficient.[117] An additional advantage of reporting outcomes as effect size units is that benchmarks exist for judging the magnitude of these (significant) differences. Studies reviewed below report an array of statistical analyses (the t test, analysis of variances, odds ratios, and point-biserial and biserial correlations), some of which are not suitable for conversion into the Cohen d; thus, following the recommendations of McGrath and Meyer,[117] r will be used as the common effect size measure for evaluating studies. As reference points, r between 0.10 and 0.23 represents small effects, r between 0.24 and 0.36 represents medium effects, and r of 0.37 and greater represent large effects.[117] Although these values offer useful guidelines for comparing findings, it is important to realize that, in health-related research, very small effects with $r < 0.10$ can be of great importance.[119]

Noise Sensitivity

Noise sensitivity is a stable and normally distributed psychological trait,[120] but predicting who will be annoyed by sound is not a straightforward process.[121] Noise sensitivity has been raised as a major risk factor for reporting annoyance in the context of environmental noise.[156] Noise sensitivity is a psychological trait that affects how a person reacts to sound. Despite lacking a standard definition, people can usually reliably rate themselves as low (noise tolerant), average, or high on noise sensitivity questionnaires; those who rate themselves as high are by definition noise sensitive.

Noise-sensitive individuals react to environmental sound more easily, evaluate it more negatively, and experience stronger emotional reactions than noise tolerant people.[122–124,146,153–156,159–161] Noise sensitivity is not related to objectively measured auditory thresholds,[125] intensity discrimination, auditory reaction time, or power-function exponents for loudness.[120] Noise sensitivity reflects a psychophysiological process with neurocognitive and psychological features. Noise-sensitive individuals have noise "annoyance thresholds" approximately 10 dB lower than noise tolerant individuals.[123] Noise sensitivity has been described as increasing a person's risk for experiencing annoyance when exposed to sound at low and moderate levels.[4,157]

Noise-Related Annoyance

Noise sensitivity and noise-related annoyance are moderately correlated ($r = 0.32$[120]) but not isomorphic. The WHO[112] defines noise annoyance as a subjective experience that may include anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation, or exhaustion. A survey of an international group of noise researchers indicated that noise-related annoyance is multifaceted and includes both behavioral and emotional features.[126] This finding is consistent with Job's[122] definition of noise annoyance as a state associated with a range of reactions, including frustration, anger, dysphoria, exhaustion, withdrawal, and helplessness.

Annoyance and Wind Turbine Sounds

As noted elsewhere in this review, Pedersen and colleagues[58,61,62,65] conducted the world's largest epidemiological studies of people living in the vicinity of wind turbines. These studies have been discussed in detail in the epidemiological studies section of this review. Other authors have also addressed annoyance in the context of living near wind turbines.[57,61,125,127,128] Pedersen[63] later compared findings from the three cross-sectional epidemiological studies to identify common outcomes. Across all three studies, SPLs were associated with annoyance outside (r between 0.05 and 0.09) and inside of the people's homes (r between 0.04 and 0.05). These effect sizes were all less than the small effect boundary of 0.10, meaning that sound levels played a minor role in annoyance. The percentages of people reporting annoyance with wind turbine noise ranged from 7% to 14% for indoor exposure and 18% to 33% for outside exposure.[58,61] These rates are similar to those reported for exposure to other forms of environmental noise.[129]

The dynamic nature of wind turbine sound may make it more annoying than other sources of community noise according to Pedersen et al.[58] They compared self-reported annoyance from other environmental noise exposure studies (aircraft, railways, road traffic, industry, and shunting yards) with annoyance from wind turbine sound. Proportionally, more subjects were annoyed with wind turbine sound at levels lower than 50 dB than with all other sources of noise exposure, except for shunting yards. Pedersen and Waye[107,128] reported that the sound characteristics of swishing ($r = 0.70$) and whistling ($r = 0.62$) were highly correlated with annoyance to wind turbine sound. Others have reported similar findings. One author has suggested that wind turbine sound may have acoustic qualities that may make it more annoying at certain noise levels.[80] Other theories for symptoms described in association with living near wind turbines have also been proposed.[139]

Annoyance associated with wind turbine sounds tends to show a linear association. Sound levels, however, explain only between 9% ($r = 0.31$) and 13% ($r = 0.36$) of the variance in annoyance ratings.[57,61] Therefore, SPLs seem to play a significant, albeit limited, role in the experience of annoyance associated with wind turbines, a conclusion similar to that reached by Knopper and Ollson.[4]

Nonacoustical Factors Associated With Annoyance

Although noise levels and noise sensitivity affect the risk of a person reporting annoyance, nonacoustic factors also play a role, including the visual effect of the turbines, whether a person derives economic benefit from the turbines and the type of terrain where one lives.[4] Pedersen and Waye[61] assessed the effect of visual/perceptual factors on wind turbine–related annoyance; all of the variables described above were significantly related to self-reported annoyance after controlling for SPLs. Nevertheless, when these variables were evaluated simultaneously, only attitude to the visual effect of the turbines remained significantly related to annoyance ($r = 0.41$, which can be interpreted as a large effect) beyond sound exposure. Pedersen and Waye[128] also found visual effect to be a significant factor in addition to sound exposure for self-reported annoyance to wind turbine sounds. Pedersen et al[58] explored the effect of visual attitude on wind turbine sound-related annoyance. Logistic regression showed that sound levels, noise sensitivity, attitudes toward wind turbines, and visual effect were all significant independent predictors of annoyance. Nevertheless, visual attitudes showed an effect size of $r = 0.27$ (medium effect), whereas noise sensitivity had an r of 0.09. Other authors have also found the visual effect of wind turbines to be related to annoyance ratings.[130] Results from multiple studies support the conclusion that visual effect contributes to wind turbine annoyance,[4] with this review finding visual effect to have an effect size in the medium to large range. Nevertheless, given that noise sensitivity and visual attitude are consistently correlated ($r = 0.19$ and $r = 0.26$, respectively),[58,61] it is possible that visual effect enhances annoyance through multisensory (visual and auditory) activation of the noise-sensitivity trait.

Economic Benefit, Wind Turbines, and Annoyance

Some studies have indicated that people who derive economic benefit from wind turbines are less likely to report annoyance. Pedersen et al[58] found that people who benefited economically (n = 103) from wind turbines reported significantly less annoyance despite being exposed to relatively high levels of wind turbine noise. The annoyance mitigating effect of economic benefit was replicated in Bakker et al.[57] The mitigation effect of economic benefit seems to be within the small effect size range ($r = 0.15$).[57] In addition, because receiving economic benefit represents a personal choice to have wind turbines on their property in exchange for compensation, the involvement of subject selection factors (ie, noise tolerance) requires additional study.

Annoyance, Quality of Life, Well-being, and Psychological Distress

The largest cross-sectional epidemiological study of wind turbine noise on QOL was conducted in northern Poland.[67] Surveys were completed by 1277 adults (703 women and 574 men), aged 18 to 94 years, representing a 10% two-stage random sample of the selected communities. Although the response rate was not reported, participants were sequentially enrolled until a 10% sample was achieved, and the proportion of individuals invited to participate but unable or refusing to participate was estimated at 30% (B. Mroczek, personal communication). Proximity of residence was the exposure variable, with 220 (17.2%) respondents within 700 m, 279 (21.9%) between 700 and 1000 m, 221 (17.3%) between 1000 and 1500 m, and 424 (33.2%) residing more than 1500 m from the nearest wind turbine. Several indicators of QOL, measured using the SF-36, were analyzed by proximity to wind turbines. The SF-36 consists of 36 questions divided into the following subscales: physical functioning, role-functioning physical, bodily pain, general health, vitality, social functioning, role-functioning emotional, and mental health. An additional question concerning health change was included, as well as the Visual Analogue Scale for health assessment. It is unclear whether age, sex, education, and occupation were controlled. The authors report that within all subscales, those living closest to wind farms reported the best QOL, and those living farther than 1500 m scored the worst. They concluded that living in close proximity to wind farms does not result in worsening of the QOL.[67] The authors recommend that subsequent research evaluate the reasons for the higher QOL and health indicators associated with living in closer proximity to wind farms. They speculated that these might include economic factors such as opportunities for employment with or renting land to the wind farm companies.

Individuals living closer to wind farms reported higher levels of mental health ($r = 0.11$), physical role functioning ($r = 0.07$), and vitality ($r = 0.10$) than did those living farther away.[67] Nevertheless, the implications of the study[67] are unclear, as the authors did not estimate sound-level exposure or obtain noise annoyance ratings from their subjects. Overall, with the exception of the study by Mroczek et al,[67] noise annoyance demonstrated a consistent small to medium effect on QOL and psychological well-being.

A study a year earlier of 39 individuals in New Zealand came to different conclusions than the Polish study.[131] Survey results from 39 residents located within 2 km of a wind turbine in the South Makara Valley in New Zealand were compared with 139 geographically and socioeconomically matched individuals who resided at least 8 km from any wind farm. The response rates for both the proximal and more distant study groups were poor, that is, 34% and 32%, respectively, although efforts were made to blind respondents to the study hypotheses. No other indicator of exposure to wind turbines was included beyond the selection of individuals from within 2 km or beyond 8 km of a wind turbine, so actual or calculated wind turbine noise exposures were not available. Subjective HRQOL scales were used to describe and compare the self-reported physical, psychological, and social well-being for each group. Health-related quality of life measures are believed to provide an alternative approach to direct health assessment in that decrements in well-being are assumed to be sensitive to and reflect possible underlying health effects. The authors reported statistically significant differences between the groups in some HRQOL domain scores, with residents living within 2 km of a turbine installation reporting lower mean physical HRQOL domain score (including lower component scores for sleep quality and self-reported energy levels) and lower mean environmental QOL scores (including lower component scores for considering one's environment to be less healthy and being less satisfied with the conditions of their living space). The wind farm group scored significantly lower on physical HRQL ($r = 0.21$), environmental QOL ($r = 0.19$), and overall HRQL ($r = 0.10$) relative to the comparison group. Although the psychological QOL ratings were not significantly different ($P = 0.06$), the wind farm group also scored lower on this measure ($r = 0.16$). In the wind farm group, noise sensitivity was strongly correlated with noise annoyance ($r = 0.44$), psychological HRQL ($r = 0.40$), and social HRQOL ($r = 0.35$). These correlations approach or exceed the large effect size boundary ($r > 0.37$ suggested by Cohen).

There were no differences seen for social or psychological HRQOL domain scores. The turbine group also reported lower amenity scores, which are based on responses to two general questions—"I am satisfied with my neighborhood/living environment," and "My neighborhood/living environment makes it difficult for me to relax at home." No differences were reported between groups for traffic or neighborhood noise annoyance. Lack of actual wind turbine and other noise source measurements, combined with the low response rate (both noted by the authors as limitations), limits the inferential value of this study because it might pertain to wind turbine emissions.

Across three studies, Pedersen[63] found that outdoor annoyance with turbine sound was associated with tension and stress ($r = 0.05$ to 0.06) and irritability ($r = 0.05$ to 0.08), qualities associated with psychological distress. Bakker et al[57] also found that psychological distress was significantly related to wind turbine sound ($r = 0.16$), reported outside annoyance ($r = 0.18$) and inside annoyance ($r = 0.24$). Taylor et al[69] found that subjects living in areas with a low probability of hearing turbine noise reported significantly higher levels of positive affect than those living in moderate or high noise areas ($r = 0.24$), suggesting greater well-being for the low noise group.

Personality Factors and Wind Turbine Sound

Personality psychologists use five bipolar dimensions (neuroticism, extraversion-introversion, openness, agreeableness, and conscientiousness) to organize personality traits.[132] Two of these dimensions, neuroticism and extraversion-introversion, have been studied in relation to noise sensitivity and annoyance. Neuroticism is characterized by negative emotional reactions, sensitivity to harmful cues in the environment, and a tendency to evaluate situations as threatening.[133] Introversion (the opposite pole of extraversion) is characterized by social avoidance, timidity, and inhibition.[133] A strong negative correlation has been shown between noise sensitivity (self-ratings) and self-rated extraversion,[125] suggesting that introverts are more noise sensitive. Introverts experience a greater disruption in vigilance when exposed to low-intensity noise than do extroverts.[134] Extroverts and introverts differ in terms of stimulation thresholds with introverts being more easily overstimulated than extroverts.[135] Despite these studies, the potential link between broad personality domains and noise annoyance remains unclear.

Taylor et al[69] explored the role of neuroticism, attitude toward wind turbines, negative oriented personality (NOP) traits (negative affectivity, frustration intolerance), and self-reported nonspecific somatic symptoms (NSS) in reaction to wind turbine noise. Despite one of the few peer-reviewed studies of personality and noise sensitivity, it only achieved a 10% response rate, which raises questions as to the representativeness of the findings. Nonetheless, the study sample reported a moderately positive attitude toward wind turbines in general and seemed representative of the local community. In the study by Taylor et al,[69] zero-order correlations showed that estimated sound levels were significantly related to perceived turbine noise ($r = 0.33$) and reduced positive affect ($r = -0.32$) but not to nonspecific symptoms ($r = 0.002$), whereas neuroticism and NOP traits were significantly related to NSS (r of 0.44 and 0.34, respectively). Multivariate analysis suggested that high NOP traits moderated the relationship between perceived noise and the report of NSS; that is, subjects with higher NOP traits reported significantly more NSS than did subjects low in NOP across the range of perceived loudness of noise.

Nocebo Response

The nocebo response refers to new or worsening symptoms produced by negative expectations.[98,136] When negatively worded pretreatment information ("could lead to a slight increase in pain") was given to a group of chronic back pain patients, they reported significantly more pain ($r = 0.38$) and had worse physical performance ($r = 0.36$).[98] These effect sizes are within the moderate to large ranges and reflect a meaningful adverse effect for the negative information contributing to the nocebo response. The effect of providing negative information regarding wind turbines prior to exposure to infrasound has been experimentally explored. Crichton et al[137] exposed college students to sham and true infrasound under high-expectancy (ie, adverse health effects from wind turbines) and low-expectancy (ie, no adverse health effects) conditions. The high-expectancy group received unfavorable information from TV and Internet accounts of symptoms associated with wind farm noise, whereas the low-expectancy group heard experts stating that wind farms would not cause symptoms. Symptoms were assessed pre- and postexposure to actual and sham infrasound. The high-expectancy group reported significantly more symptoms ($r = 0.37$) and greater symptom intensity ($r = 0.37$) following both sham and true infrasound exposure ($r = 0.65$ and 0.48, respectively). The effect sizes were similar to those found in medical research on the nocebo response. These findings demonstrate that exposing individuals to negative information can increase symptom reporting immediately following exposure. The inclusion of information from TV and the Internet suggests that similar reactions may occur in real-world settings.

A study by Deignan et al[138] analyzed newspaper coverage of wind turbines in Canada and found that media coverage might contribute to nocebo responses. Newspaper coverage contained fright factor words like "dread," "poorly understood by science," "inequitable," and "inescapable exposure"; the use of "dread" and "poorly understood by science" had increased from 2007 to 2011. These results document the use of fright factor words in the popular coverage of wind turbine debates; exposure to information containing these words may contribute to nocebo reactions in some people.

Wind turbines, similar to multiple technologies, such as power lines, cell phone towers, and WiFi signals, among others, have been associated with clusters of unexplained symptoms. Research suggests that people are increasingly worried about the effect of modern life (in particular emerging technologies) on their health (modern health worries [MHW]).[140]) Modern Health Worries are moderately correlated with negative affect ($r = 0.23$) and, like the nocebo response, are considered psychogenic in origin. The expansion of wind turbine energy has been accompanied by substantial positive and negative publicity that may contribute to MHW and nocebo responses among some people exposed to this information. Health concerns have also been raised about the potential of electromagnetic fields associated with wind turbine operations; however, a recent study indicated that magnetic fields in the vicinity of wind turbines were lower than those produced by common household items.[140]

Chapman et al[52] explored the pattern of formal complaints (health and noise) made in relation to 51 wind farms in Australia from 1993 to 2012. The authors suggest that their study is a test of the psychogenic (nocebo or MHW) hypothesis. The findings showed that very few complaints were formally lodged; only 129 individuals in Australia formally or publically complained during the time period studied, and the majority of wind farms had no complaint made against them. The authors found that complaints increased around 2009 when "wind turbine syndrome" was introduced. On the basis of these findings, the authors conclude that nocebo effects likely play an important role in wind farm health complaints. But the authors do report that the vast majority of complaints (16 out of 18) were filed by individuals living near large wind farms ($r = 0.32$). So while few individuals complain, those who do almost exclusively live near large wind farms. Nevertheless, it is important to note that filing a formal or public complaint is a complex sociopolitical action, not a health-related outcome. Furthermore, analysis of data provided in Table 2 of the Chapman[54] study shows that the strongest predictor of a formal complaint was the presence of an opposition group in the area of the wind farm. A review of Table 2 shows that opposition groups were present in 15 of the 18 sites that filled complaints, whereas there was only one opposition group in the 33 areas that did not file a complaint ($r = 0.82$). Therefore, the relevance of this study for understanding health effects of wind turbines is limited. Chapman has also addressed the multitude of reasons why some Australian home owners may have left their homes and attributed the decision to wind turbines.[54] Gross[140] provides a community justice model designed to counter the potential for nocebo or psychogenic response to wind farm development. This method was pilot tested in one community and showed the potential to increase the sense of fairness for diverse community members. No empirical data were gathered during the pilot study so the effect of method cannot be formally evaluated.

Conclusions

Annoyance is a recognized health outcome measure that has been used in studies of environmental noise for many decades. Noise levels have been shown to account for only a modest portion of self-reported annoyance in the context of wind turbines ($r = 0.35$).[4] Noise sensitivity, a stable psychological trait, contributes equally to exposure in explaining annoyance levels ($r = 0.37$). Annoyance associated with wind turbine noise shows a consistent small to medium adverse effect on self-rated QOL and psychological well-being. Given the coarseness of measures used in many studies, the magnitude of these findings are likely attenuated and underestimate the effect of annoyance on QOL. Visual effect increases annoyance beyond sound exposure and noise sensitivity, but at present there is insufficient research to conclude that visual effect operates separately from noise sensitivity because the two variables are correlated. Wind turbine development is subject to the same global psychogenic health worries and nocebo reactions as other modern technologies.[139]

Economic benefit mitigates the effect of wind turbine sound; however, research is needed to clarify the potential confounding role of (self) selection in this finding. The most powerful multivariate model reviewed accounted for approximately 50% ($r = 0.69$) of the variance in reported annoyance, leaving 50% unexplained. Clearly other relevant factors likely remain unidentified. Nevertheless, it is not unusual for there to be a significant percentage of unexplained variance in biomedical or social science research. For example, a meta-analysis of postoperative pain (a subjective experience), covering 48 studies and 23,037 subjects, found that only 54% ($r =$ 0.73) of the variance in pain ratings could be explained by the variables included in the studies.[144] Wind turbine development is subject to the same global psychogenic health worries and nocebo reactions as other modern technologies. Therefore, communities, government agency, and companies would be well advised to adopt an open, transparent, and engaging process when debating the potential effect of wind turbine sites. The vast majority of findings reviewed in this section were correlational and, therefore, do not imply causality, and that other as of yet unidentified (unmeasured) factors may be associated with or responsible for these findings.

DISCUSSION

Despite the limitations of available research related to wind turbines and health, inferences can be drawn from this information, if used in concert with available scientific evidence from other environmental noise studies, many of which have been reviewed and assessed for public policy in the WHO's Nighttime Noise Guidelines.[104] A substantial database on environmental noise studies related to transportation, aviation, and rail has been published.[147] Many of these studies have been used to develop worldwide regulatory noise guidelines, such as those of the WHO,[104] which have proposed nighttime noise levels primarily focused on preventing sleep disturbance.

Because sound and its components are the potential health hazards associated with living near wind turbines, an assessment of other environmental noise studies can offer a valuable perspective in assessing health risks for people living near wind turbines. For example, one would not expect adverse health effects to occur at lower noise levels if the same effects do not occur at higher noise levels. In the studies of other environmental noise sources, noise levels have been considerably higher than those associated with wind turbines. Noise differences as broad as 15 dBA (eg, 55 dBA in highways vs 40 dBA from wind turbines) have been regularly reported.[147] In settings where anthropogenic changes are perceived, indirect effects such as annoyance have been reported, and these must also be considered in the evaluation of health effects.

We now attempt to address three fundamental questions posed at the beginning of this review related to potential health implications of wind turbines.

Is there available scientific evidence to conclude that wind turbines adversely affect human health? If so, what are the circumstances associated with such effects and how might they be prevented?

The epidemiological and experimental literature provides no convincing or consistent evidence that wind turbine noise is associated with any well-defined disease outcome. What is suggested by this literature, however, is that varying proportions of people residing near wind turbine facilities report annoyance with the turbines or turbine noise. It has been suggested by some authors of these studies that this annoyance may contribute to sleep disruption and/or stress and, therefore, lead to other health consequences. This self-reported annoyance, however, has not been reported consistently and, when observed, arises from cross-sectional surveys that inherently cannot discern whether the wind turbine noise emissions play any direct causal role. Beyond these methodological limitations, such results have been associated with other mediating factors (including personality and attitudinal characteristics), reverse causation (ie, disturbed sleep or the presence of a headache increases the perception of and association with wind turbine noise), and personal incentives (whether economic benefit is available for living near the turbines).

There are no available cohort or longitudinal studies that can more definitively address the question about causal links between wind turbine operations and adverse health effects. Nevertheless, results from cross-sectional and experimental studies, as well as studies of other environmental noise sources, can provide valuable information in assessing risk. On the basis of the published cross-sectional epidemiological studies, "annoyance" is the main outcome measure that has been raised in the context of living in the vicinity of wind turbines. Whether annoyance is an adverse health effect, however, is disputable. "Annoyance" is not listed in the International Classification of Diseases (10th edition), although it has been suggested by some that annoyance may lead to stress and to other health consequences, such as sleep disturbance. This proposed mechanism, however, has not been demonstrated in studies using methods capable of elucidating such pathways.

The authors of this review are aware of the Internet sites and non–peer-reviewed reports, in which some people have described symptoms that they attribute to living near wind turbines. The quality of this information, however, is severely limited such that reasonable assessments cannot be made about direct causal links between the wind turbines and symptoms reported. For example, inviting only people who feel they have symptoms because of wind turbines to participate in surveys and asking people to remember events in the past in the context of a current concern (ie, postturbine installation) introduce selection and recall biases, respectively. Such major biases compromise the reliability of the information as used in any rigorous causality assessment. Nonetheless, consistent associations have been reported between annoyance, sleep disturbance, and altered QOL among some people living near wind turbines. It is not possible to properly evaluate causal links of these claims in the absence of a thorough medical assessment, proper noise studies, and a valid study approach. The symptoms reported tend to be nonspecific and associated with various other illnesses. Personality factors, including self-assessed noise sensitivity, attitudes toward wind energy, and nocebo-like reactions, may play a role in the reporting of these symptoms. In the absence of thorough medical evaluations that include a characterization of the noise exposure and a diagnostic medical evaluation, confirmation that the symptoms are due to living near wind turbines cannot be made with any reliability. In fact, the use of a proposed case definition that seemed in a journal not indexed by PubMed can lead to misleading and incorrect assessments of people's health, if performed in the absence of a thorough diagnostic evaluation.[143] We recommend that people who suspect that they have symptoms from living near wind turbines undergo a thorough medical evaluation to identify all potential causes of and contributors to the symptoms. Attributing symptoms to living near wind turbines in the absence of a comprehensive medical evaluation is not medically appropriate. It is in the person's best interest to be properly evaluated to ensure that recognized and treatable illnesses are recognized.

Available scientific evidence does not provide support for any bona fide–specific illness arising out of living in the vicinity of wind turbines. Nonetheless, it seems that an array of factors contribute to some proportion of those living in proximity to wind turbines, reporting some degree of annoyance. The effect of prolonged annoyance—regardless of its source or causes—may have other health consequences, such as increasing stress; however, this cannot be demonstrated with the existing scientific literature on annoyance associated with wind turbine noise or visibility.

Is there available scientific evidence to conclude that psychological stress, annoyance, and sleep disturbance can occur as a result of living in proximity to wind turbines? Do these effects lead to adverse health effects? If so, what are the circumstances associated with such effects and how might they be prevented?

Available research is not suitable for assessing causality because the major epidemiological studies conducted to date have been cross-sectional, data from which do not allow the evaluation of the temporal relationship between any observed correlated factors.

Cross-sectional studies, despite their inherent limitations in assessing causal links, however, have consistently shown that some people living near wind turbines are more likely to report annoyance than those living farther away. These same studies have also shown that a person's likelihood of reporting annoyance is strongly related to their attitudes toward wind turbines, the visual aspect of the turbines, and whether they obtain economic benefit from the turbines. Our review suggests that these other risk factors play a more significant role than noise from wind turbines in people reporting annoyance.

The effect of annoyance on a person's health is likely to vary considerably, based on various factors. To minimize these reactions, solutions may include informative discussions with area residents before developing plans for a wind farm along with open communications of plans and a trusted approach to responding to questions and resolving noise-related complaints.

Is there evidence to suggest that specific aspects of wind turbine sound such as infrasound and low-frequency sound have unique potential health effects not associated with other sources of environmental noise?

Both infrasound and low-frequency sound have been raised as possibly unique health hazards associated with wind turbine operations. There is no scientific evidence, however, including results from field measurements of wind turbine–related noise and experimental studies in which people have been purposely exposed to infrasound, to support this hypothesis. Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines, but that the levels at customary distances to homes are well below audibility thresholds, even at residences where people have reported symptoms that they attribute to wind turbines. These levels of infrasound—as close as 300 m from the turbines—are not audible. Moreover, experimental studies of people exposed to much higher levels of infrasound than levels measured near wind turbines have not indicated adverse health effects. Because infrasound is associated more with vibratory effects than high-frequency sound, it has been suggested that the vibration from infrasound may be contributing to certain physical sensations described by some people living near wind turbines. These sensations are difficult to reconcile in light of field studies that indicated that infrasound at distances more than 300 m for a wind turbine meet international standards for preventing rattling and other potential vibratory effects.[14]

Areas for Further Inquiry

In light of the limitations of available studies for drawing definitive conclusions and the need to address health-related concerns associated with wind turbines raised by some nearby residents, each author discussed potential areas of further inquiry to address current data gaps. These recommendations primarily address exposure characterization, health endpoints, and the type of epidemiological study most likely to lead to informative results regarding potential health effects associated with living near wind turbines.

Noise From Wind Turbines

As with any potential occupational or environmental hazard, further efforts at exposure characterization, that is, noise and its components such as infrasound and low-frequency sound, would be valuable. Ideally, uniform equipment and standardized methods of measurement can be used to enable comparison with results from published studies and evaluate adherence to public policy guidelines.

Efforts directed at evaluating models used to predict noise levels from wind turbines—in contrast to actual measured noise levels—would be valuable and may be helpful in informing and reassuring residents involved in public discussions related to the development of wind energy projects. Efforts at fine tuning noise models for accuracy to real-world situations can be reassuring to public health officials charged with evaluating potential health effects of noise. The development and the use of reliable and portable noise measuring devices to address components of noise near residences and evaluating symptoms and compliance with noise guidelines would be valuable.

Epidemiology

Prospective cohort studies would be most informative for identifying potential health effects of exposure to wind turbine noise before and after wind turbines are installed and operating. Ideally, substantially large populations would be evaluated for baseline health status, and subsequently part of the population would become exposed to wind turbines and part would remain unexposed, as in an area where large wind turbine farms are proposed or planned. The value of such studies is in the avoidance of several forms of bias such as recall bias, where study participants might, relying on recall, under- or overreport risk factors or diseases that occurred sometime in the past. As has been noted by several authors, the level of attention given the topic of wind turbines and possible health effects in the news and the Internet makes it difficult to study any population truly "blinded" to the hypotheses being evaluated. The main advantage of prospective cohort studies with a pre- and post–wind turbine component is the direct ability to compare changes in disease and health status among individuals subsequently exposed to wind turbine noise with those among similar groups of people not exposed. These conditions are not readily approximated by any other study approach. A similar but more complex approach could include populations about to become exposed to other anthropogenic stimuli, such as highways, railroads, commercial centers, or other power generation sources.

We note that additional cross-sectional studies may not be capable of contributing meaningfully and in fact might reinforce biases already seen in many cross-sectional studies and surveys.

Sound and Its Components

Several types of efforts can be undertaken to test hypotheses proposed about inaudible sound being a risk for causing adverse health effects. It would be simple, at least conceptually, to expose blinded subjects to inaudible sounds, especially in the infrasound range, to determine whether they could detect the sounds or whether they developed any unpleasant symptoms. Ideally, these studies would use infrasound levels that are close to hearing thresholds and comparable with real-world wind turbine levels at residential distances. Crichton et al[137,149] have begun such studies, finding that subjects could not detect any difference between infrasound and sham "exposures." The infrasound stimulus used, however, was only 40 dB at 5 Hz, more than 60 dB lower than hearing threshold and lower than levels measured at some residences near wind turbines.

The possibility of adverse effects from inaudible sound could also be tested in humans or animals in long-term studies. To date, there seem to be no reports of adverse effects in people exposed to wind turbine noise that they could never hear (such reports would require careful controls), nor are any relevant animal studies known to the authors of this review.

Controlled human exposure studies have been used to gain insight into the effects of exposure to LFN from wind turbines. Human volunteers are exposed for a short amount of time under defined conditions, sometimes following various forms of preconditioning, and different response metrics evaluated. Most of these studies addressed wind turbine noise annoyance but no direct health indicator; however, one study addressed visual reaction to the color of wind turbines in pictures,[73] and another evaluated physical symptoms in response to wind turbine noise.[137,149]

Efforts to document a potential effect of infrasound on health have been unsuccessful, including searches for responses to sound from cochlear type II afferent neurons or responses to inaudible airborne sound from the vestibular system. But in other cases, the relevant experiments (can inaudible sound cause endolymphatic hydrops?) seem not to have been conducted to date. This seemingly improbable hypothesis, however, could be tested in guinea pigs, which reliably develops endolymphatic hydrops in response to other experimental interventions.

Psychological Factors

This review has demonstrated that a complex combination of noise and personal factors contributes to some people reporting annoyance in the context of living near wind turbines. Further efforts at characterizing and understanding these issues can be directed to improvements in measurement of sound perception, data analysis, and conceptualization.

We suggest improvements in the quality and standardization of measurement for important constructs like noise sensitivity and noise annoyance across studies. We also suggest eliminating the use of single-item "measures" for primary outcomes.

Data analysis should ideally include effect size measures in all studies to supplement the significance testing (some significant differences are small when sample sizes are large). This will help improve the comparability of findings across studies.

Integrate noise sensitivity, noise annoyance, and QOL into a broader more comprehensive theory of personality or psychological functioning, such as the widely accepted five-factor model of personality.

SUMMARY

1. Measurements of low-frequency sound, infrasound, tonal sound emission, and amplitude-modulated sound show that infrasound is emitted by wind turbines. The levels of infrasound at customary distances to homes are typically well below audibility thresholds.
2. No cohort or case–control studies were located in this updated review of the peer-reviewed literature. Nevertheless, among the cross-sectional studies of better quality, no clear or consistent association is seen between wind turbine noise and any reported disease or other indicator of harm to human health.
3. Components of wind turbine sound, including infrasound and low-frequency sound, have not been shown to present unique health risks to people living near wind turbines.
4. Annoyance associated with living near wind turbines is a complex phenomenon related to personal factors. Noise from turbines plays a minor role in comparison with other factors in leading people to report annoyance in the context of wind turbines.

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Exhibit A7-6

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FULL-LENGTH ORIGINAL RESEARCH

Potential of wind turbines to elicit seizures under various meteorological conditions

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Summary

Purpose: **To determine the potential risk of epileptic seizures from wind turbine shadow flicker under various meteorologic conditions.**

Methods: **We extend a previous model to include attenuation of sunlight by the atmosphere using the libradtran radiative transfer code.**

Results: **Under conditions in which observers look toward the horizon with their eyes open we find that there is risk when the observer is closer than 1.2 times the total turbine height when on land, and 2.8 times the total turbine height in marine environments, the risk limited by the size of the image of the sun's disc on the retina. When looking at the ground, where the shadow of the blade is cast, observers are at risk only when at a distance <36 times the blade width, the risk limited by image contrast. If the observer views the horizon and closes their eyes, however, the stimulus size and contrast ratio are epileptogenic for solar elevation angles down to approximately 5°.**

Discussion: **Large turbines rotate at a rate below that at which the flicker is likely to present a risk, although there is a risk from smaller turbines that interrupt sunlight more than three times per second. For the scenarios considered, we find the risk is negligible at a distance more than about nine times the maximum height reached by the turbine blade, a distance similar to that in guidance from the United Kingdom planning authorities.**

KEY WORDS: **Photosensitive epilepsy, Flicker, Wind turbines, Atmospheric scattering of light.**

The shadow from the blades of certain wind turbines can result in changes in retinal illumination at a rate >3 Hz. Flicker at such frequencies is known to cause epileptic seizures in susceptible people (Binnie et al., 2002). The risk is known to depend upon (1) the flicker frequency; (2) whether one or both eyes are stimulated; (3) the area of the retina receiving stimulation; (4) whether the central or peripheral retina is stimulated; (5) the amount of the change in light intensity (modulation depth); (6) the nature of its variation over time (mark/space fraction); and (7) the spectral composition of the light. A simple model that takes into account these parameters has been published (Harding et al., 2008), but the model fails to consider the atmospheric effects that reduce the shadow contrast. In the following article, we extend the earlier model of Harding et al. to include estimation of the effects of atmospheric scattering. The current view used by United Kingdom planning authorities is simply that "Flicker effects have been proven to occur only within ten rotor diameters of a turbine" (Office of the Deputy Prime Minister, 2004). Therefore, if the turbine has 80-m diameter blades, the potential shadow flicker effect could be felt up to 800 m from a turbine.

The depth or darkness of the shadow of a turbine blade will depend on how much of the light comes directly from the sun and how much comes from elsewhere in the sky as a result of diffuse radiation. This in turn depends on the solar elevation (itself a function of latitude, time of day, and season), and on the amount of aerosols and optically thin clouds in the atmosphere. If the optical depth of cloud is sufficient to completely block the direct beam, then there is no shadow. The greatest contrast will be found when the atmosphere is clean and cloud free, when the scattering that leads to diffuse radiation is strongly wavelength dependent.

Although there is a little evidence that long wavelengths may be more epileptogenic (Parra et al., 2007), the basis for this is currently uncertain, and insufficient to suggest an action spectrum different from that for photopic vision. The variation in photopic luminance (V_λ) will, therefore, be considered.

Method

To determine the risk of seizures from wind turbines in persons with photosensitive epilepsy we have modeled the light–dark contrasts of turbine shadows for worst case

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conditions, that is, for a completely cloud-free atmosphere with the turbine blades rotating in a vertical plane and directly facing the observer on a line between the observer and the position of the sun in the sky. The observer is assumed to be looking straight ahead, so that we consider the radiation falling on a vertical plane at the location of the observer's eye (Fig. 1). We consider the mark/space fraction of the flicker to be within the epileptogenic range for reasons outlined by Harding et al. (2008).

For each meteorologic case, a determination of the diffuse radiance distribution in the sky, the intensity of the direct beam, together with the surface reflectivity (albedo) is required. To this end the libradtran radiative transfer code has been used (Mayer & Kylling, 2005). The model has been developed over several years and verified in a variety of measurement campaigns and, therefore, can be considered robust and reliable.

In the first instance we model the solar radiation for four possible atmospheric and ground conditions: a marine aerosol with a visibility of 30 km over a water surface, a rural aerosol also with a visibility of 30 km, an urban aerosol with a visibility of 10 km, and haze with a visibility of only 5 km. For all the nonmarine model runs, a grass surface was assumed. Although many of the larger turbines are located in open areas, the smaller turbines that have a higher and more epileptogenic flicker frequency are often located on roof tops. Roof surfaces exhibit a range of albedos; for simplicity we take the combined effect to be broadly similar to that of grass. The aerosol characteristics were taken from Shettle (1989) and the albedo for grass from Feister and Grewe (1995). The equivalent value for water, however,

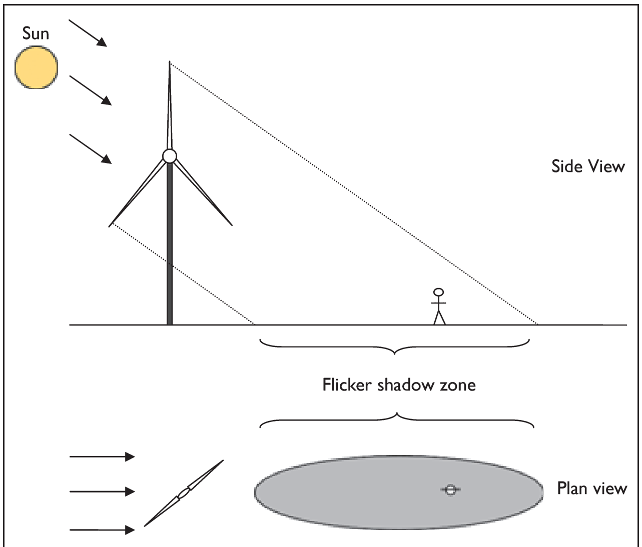

Figure 1.
Generalized geometry for turbine flicker, showing an observer in the shadow area. Note the main analysis assumes the observer and turbine blades are directly facing each other.
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was simply set at 0.035, due to the complications inherent in assigning a single Lambertian value for the range of sea states that could occur.

In many environments, especially urban areas, the presence of buildings, trees, and other obstructions close to the observer, as well as clouds close to the horizon, prevents the sun being viewed close to the horizon. Therefore, the lowest solar elevation angle modeled was chosen as 2°. Similarly for an observer looking directly ahead, once the sun is out of their field of view, the primary stimulus no longer has any potential to cause epileptic seizures; consequently, the upper limit is chosen as 40°. The model has been run at intervals between these two limits.

The output radiance distributions, calculated for wavelengths of 380–760 nm at 10 nm intervals, have been weighted with the CIE 1924 photopic action spectrum (Wyszecki & Stiles, 1982) to represent the sunlight as detected by the human eye. These values have then been converted to irradiances incident on a vertical surface, representing the observer's eye.

To incorporate the effect of a turbine blade upon these received irradiances, we make the assumption that the radiance in the vicinity of the solar disc is rotationally symmetric; this simplifies subsequent analysis, as only the angular width of the blade need be considered, with the relative position of the turbine axis with respect to the sun being removed. The contrast function then results from the blade obscuring the sky and occasionally the sun behind it.

Still considering the observer to be looking toward the horizon with the turbine in the foreground, we also include the cortical magnification factor (Drasdo, 1977)—an expression of the relative density of neurons on the visual cortex and hence the relative contributions of each part of the stimulus—to determine the perceived relative intensities of the direct and diffuse contributions (see Harding et al., 2008).

Then to find the contrast ratio, that is, the extremum value of the time varying contrast function, we additionally consider the area of the sun's disc that is obscured by a blade. As the observer becomes more distant from the turbine blade, the blade will obscure a smaller fraction of the direct beam/sun's disc. At a certain distance the fraction of the direct beam obscured as each blade passes in front of the sun will decrease to the point that the contrast is insufficient to induce seizures. The threshold Michelson contrast has been estimated as 5–10%, depending on the dataset used (Harding & Fylan, 1999; or Wilkins et al., 1980), which equates to a Weber contrast of 10–18%. In this case we define contrast in terms of the Weber fraction, as appropriate when the mark/space ratio is low, and we choose the more risk-averse figure of 10%. This contrast threshold distance is defined by the area of the sun obscured by the blade (the threshold obscuration area) and is, therefore, a function of the relative contributions of the diffuse and direct components and, in turn, the state of the atmosphere and the solar elevation.

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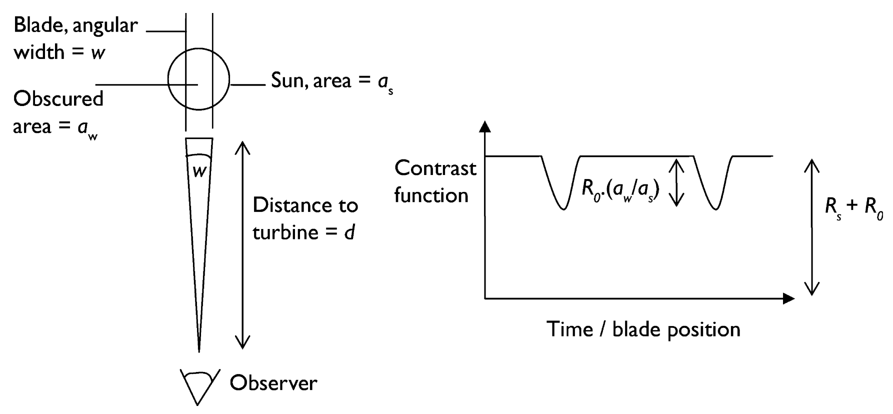

Figure 2.
Geometry showing symbols used in calculation of threshold distance.
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To calculate the threshold obscuration area, we set the reduction in direct beam intensity due to blade obscuration equal to the maximum intensity multiplied by the epileptogenic contrast threshold (see Fig. 2 for geometry). The maximum intensity occurs when the sun is unobscured, and is given by the sum of the direct and sky contributions. The intensity is reduced most when the blade lies symmetrically over the sun, obscuring a fraction a_w/a_s of the direct beam, where a_w is the threshold obscuration area and a_s is the area of the solar disc. Rearranging, the threshold area can then be expressed as follows:

$$a_w = \frac{a_s(R_s + R_0)\,C_w}{R_0}$$

Here C_w is the epileptogenic contrast threshold, R_s is the relative contribution from the sky, and R_0 is the relative contribution of the sun's direct beam.

The blade is assumed to be delimited by parallel edges in the region of interest and lying symmetrically over the sun's disc at the time of minimum contrast ratio. Simple geometry then enables the threshold area to be expressed as an angular blade width.

Finally, the threshold width in each meteorologic situation can be converted to find the threshold distance in units of blade width—this is the distance beyond which the flicker from the turbine blade is no longer epileptogenic to an observer because the contrast ratio would fall below 10%. It is, as follows:

$$d = 0.5\cot(w/2),$$

where w is the threshold angular blade width.

Results and Discussion

As the aerosol loading of the atmosphere and the solar elevation angle change, the relative contributions of the diffuse and direct components will alter. In turn, as turbine blades pass in front of the sun, the fraction of the solar disc that results in a threshold contrast ratio will vary. When applying the analysis in the preceding section to the cases modeled, we obtain the distances at which this threshold is reached. These are shown in Fig. 3.

It is clear that as the amount of aerosol in the atmosphere decreases, the direct beam contribution rises and so the threshold distance increases. Furthermore, when the sun approaches the horizon for the high visibility (low aerosol) cases the threshold distance increases to over 1,000 times the blade width. From atmospheric radiative considerations alone for each level of aerosol loading, it would be expected that as the solar elevation angle increases, a corresponding increase in the threshold distance would also be seen. However, the direct beam contribution in fact decreases with increasing solar elevation angle due to the cortical magnification factor. It is competition between these two aspects that results in a peak at 15–20° for the two highest aerosol cases and at 5° for the low aerosol cases: At lower solar elevation angles the direct beam is reduced by aerosol interactions, and at higher elevations its contribution falls due to the decreasing cortical magnification factor. Furthermore, it can be seen that the differing albedos of grass and

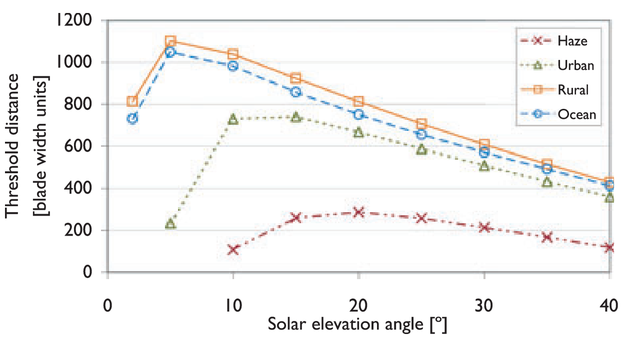

Figure 3.
Threshold distances corresponding to a threshold contrast ratio of 10%, as a function of solar elevation angle for sample aerosol loadings, as described in the text.
Epilepsia © ILAE

water and the different aerosol properties in the two cases, increase the observed diffuse radiation component for marine environments, and in turn the threshold distances. It will also be noted that there is a lower limit reached for high aerosols—where even when the blade obscures the entire sun the contrast threshold is not achieved.

Taking the maximum threshold distance allows two example turbines to be considered. Wind turbines are commonly either for large-scale power generation as stand-alone structures, or for microgeneration, being sited on or close to the structure requiring electricity. A typical large 2MW turbine has a blade width of approximately 2 m (although very close to the rotation axis it may be more than this, and will taper toward the point). The contrast ratio threshold distance for a clear, low aerosol day would then be ~2 km. For a small turbine the equivalent distance is an order of magnitude less at 200 m, assuming a blade width of 20 cm.

It should be noted, however, that this does not imply that there is a risk of seizures wherever the turbine can be seen. For there to be a risk, the observer still must be within the shadow zone. For the 2MW turbine example (total height of 120 m), the furthest part of the shadow falls 1,380 m from the turbine when the sun is 5° above the horizon—less than the threshold distance in the previous paragraph. Therefore, in this example the locations on the ground that present a risk of seizures are determined by the extent of the shadow and not the contrast ratio threshold. This point suggests that there are a number of other factors that ought to be considered. We will discuss these below.

The most pertinent is a direct consideration of the cortical magnification factor. From Drasdo (1977) and Binnie et al. (2002), the proportion of patients at risk from a stimulus subtending a half-angle ϕ can be given as follows:

$$p = -0.184 + 2.1(1 - \exp(-0.0574\phi))$$

Solving for p = 0, shows that when the stimulus subtends a half-angle <1.6°, no patients are at risk. In our case the dominant stimulus is the solar disc, which subtends a total angle of 0.53°, implying that although the contrast ratio would appear to be sufficient to cause seizures, the size of the solar disc stimulus prevents the flicker from being epileptogenic.

Yet the analysis thus far only includes radiative transfer in the atmosphere. A further consideration is scattering of the external stimulus within the eye, before the image reaches the retina. Following Vos et al. (1976), the intensity profile of an external point source falling on the fovea can be expressed as a power law for angles >1′. In general 50% of the source intensity falls within 2′ and 3′, and 90% within 1°.

We take the edge of the sun's image to be the radius at which the solar entopic stray light is 10% of the steady diffuse background, the same limit used by de Wit and Coppens (2003). (Entopic scatter of the circumsolar radiation itself has not been included, although it is noted it would increase the calculated values slightly—the direct beam contribution will always be much larger.) To determine this radius, the ratio of the direct beam irradiance to the circumsolar value was calculated and multiplied by 0.1. The apparent radius of the solar disc was then found from the tables provided in Vos et al. (1976). This is plotted in Fig. 4, alongside the epileptogenic threshold radius of 1.6°. It is clear that for most combinations of solar elevation angle and aerosol loading, the minimum epileptogenic stimulus size is not reached. Moreover, even with the lowest aerosol loadings this threshold is not reached when the sun is <20° above the horizon. For land-based turbines the equivalent solar elevation angle is 40°—the upper limit of our analysis. The implications of this result are as follows: considering the contrast ratio threshold alone would lead to the conclusion that wind turbines can cause seizures up to 2 km distant; including the apparent stimulus size limits the solar elevation angle to 40° on land, and hence the maximum "at risk" distance is reduced to 1.2 times (cot 40°) the total turbine height (hub height plus blade length). For marine environments the "at risk" distance is 2.8 (cot 20°) times the total turbine height. In each case the total turbine height includes the height of any structure that the turbine might be situated on, for example. a building.

The weather conditions modeled so far have neglected the presence of clouds or other nonhorizontally homogenous components. The minimum stimulus size required for patients to be "at risk," however, allows us to consider a more general meteorologic situation with a bright patch in the sky of angular width 1.6°. Assuming the other epileptogenic conditions are met, this defines an angular blade width that would be required to cover and uncover the stimulus. The threshold distance in this case is equal to 35.8 multiples

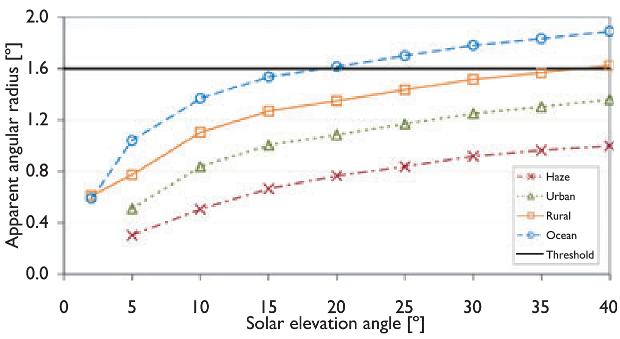

Figure 4.
Apparent solar angular radius due to entopic (intraocular) scattering. The perceived edge is defined as the radius from the center of the retinal image of the sun at which intraocular scattering has reduced the sun's image intensity to 10% of the diffuse background intensity.
Epilepsia © ILAE

of the blade width. For the large turbine example this would be approximately 70 m from the blades, and for a small turbine, approximately 7 m.

Up until this point we have assumed that the observer is directly facing the turbine looking toward the horizon. This would seem to be a reasonable first assumption; it also simplified calculations and caused the sun to be within the observer's field of view. That said, except during high aerosol loadings of the atmosphere, it is the body's natural response to look away from the sun, or to partially close the eyelids (Sliney, 2005). Indeed it is widely recommended not to view the sun directly because of the risk of retinal damage. Without the solar disc in the observer's field of view though, the analysis described in the preceding text does not hold.

There are some other possible scenarios in which turbine flicker of the direct solar beam could be epileptogenic. First where the observer stands in the shadow zone, but views the ground, and second, an observer viewing the turbine blades against the sky. The analysis was similar to that for the main case, but the threshold distances were found to be about two orders of magnitude smaller, with a maximum of 36 times the blade diameter for the marine case. The rural, urban, and haze aerosols all had lower threshold distances. This corresponds to a distance at which the general public would normally be excluded on other safety grounds, and may be less than the distance from the blades to the ground.

If rather than looking down, an observer chooses to close their eyes, but remains with their gaze directed ahead, the threshold distance is as in Fig. 5. The effect of the eyelids is to reduce the transmission of the incoming radiation (in the present study this is assumed to be wavelength independent), and to scatter radiation from all directions equally. The diffuse contribution is, therefore, the mean irradiance within a 40° field of view, and does not include any weighting by the cortical magnification factor because the entire retina is then equally stimulated. From Fig. 5 we see that the contrast ratio threshold distance now increases with increasing solar elevation angle. For the lowest aerosol loadings this is from <600 at 5° to almost 1,100 at 40°. As discussed earlier for the main "eyes open" case, the limiting factor for marine and rural aerosols for these solar elevations is then the distance from the turbine that a shadow falls, rather than the contrast ratio threshold distance. For the 2MW turbine example with solar elevations of 5° and lower, we find that the contrast ratio threshold distance is the limiting factor. For example a 120 m total tower height, with blades 2 m wide, the contrast ratio threshold distance at 5° is 1,070 m on land—approximately nine times the total turbine height. The shadow, however, would extend to 1,370 m. As the sun drops lower, the contrast ratio threshold will fall and the blades' shadow will be cast outside this limit, therefore, not creating a risk of seizure. This worst case scenario is in line with the rule of thumb used by United Kingdom planning authorities to determine the "at risk" region—10 times the total turbine height (Harding et al., 2008).

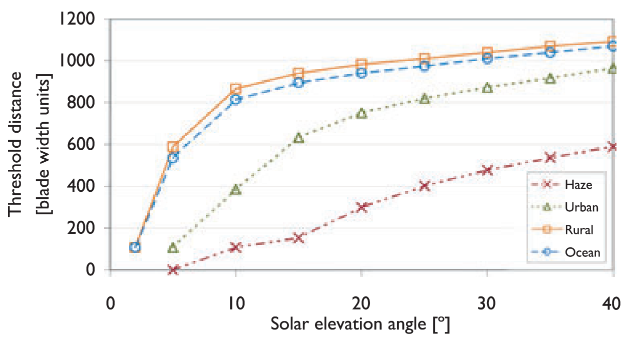

Figure 5.
Threshold distances as a function of solar elevation angle for sample aerosol loadings and an observer with closed eyelids.
Epilepsia © ILAE

The final contributing aspect to epileptogenic flicker is its frequency. Modern turbines are designed to have a constant tip speed ratio:

$$\lambda = \frac{4\pi}{n},$$

where n is the number of blades. The most efficient three-bladed turbines may have tip speed ratios of 6–7. The frequency at which the blades pass in front of a point on the sky can then be expressed as:

$$v = \lambda u \cdot \frac{n}{2\pi l} = \frac{2u}{l},$$

where u is the wind speed, and l is the blade length. This is in accordance with the fact that microgeneration turbines rotate faster than their larger counterparts. However, for the 2MW example, with 40 m blades, a wind speed of 20 m/s is required before the flicker frequency reaches 1 Hz, which is close to the typical storm protection shutdown speed of 25 m/s (BWEA 2005). Turbines of this size, therefore, rotate slower than 3 Hz, the lower frequency threshold at which seizures are a potential risk. For smaller turbines the flicker frequency is expected to be a factor of 10 or more higher, and, therefore, would have the potential to affect a larger proportion of people with epilepsy. For typical mean wind speeds of 5 m/s and a blade length of 2 m, the flicker frequency would be 5 Hz, although helical designs rotate at higher speeds and have shadows that move against one another, increasing the rate of shadow flicker.

Conclusions

This study has used a robust and accurate radiative transfer model to predict the radiance distribution and direct solar beam intensity for a range of clear sky atmospheric conditions. It is found that for a low aerosol loading of the atmosphere the epileptogenic contrast threshold of 10% is met for all locations where the turbine blade shadow would be reasonably expected to fall. However, with the eyes open, the apparent angular radius of the stimulus falls below the limit where any patients would be at risk (1.6°) for solar elevation angles of 40° or less (on land) and 20° or less (marine environments). Therefore, we envisage no epileptogenic risk to observers looking toward the horizon except when standing closer than 1.2 times the total turbine height on land, or situated closer than 2.8 times the total turbine height in marine environments.

Furthermore, considering the tendency of patients to look away from the sun as a natural reaction, but for those who find themselves in the shadow zone, we find that for an observer viewing the ground the contrast is almost always insufficient to be epileptogenic. If, alternatively, the observer maintains their gaze, but closes their eyes, then both the contrast ratio threshold distance and stimulus size conditions are sufficient down to a solar elevation angle of 5°, for the example discussed. In other words, when solar elevation is greater than 5°, there is epileptogenic potential where the blade's shadow falls. Below this angle the contrast ratio threshold limits the ''at risk'' region to <535 times the blade width on land. For the large turbine example used this corresponds to nine times the total tower height. It is noted that eye closure is a natural immediate protective action when exposed to flicker, and so has the unfortunate consequence of exacerbating its adverse effect in this context. A more effective strategy would be to cover one eye with the palm of a hand as monocular stimulation is known to be generally far less epileptogenic (Harding & Jeavons, 1995), or for the observer to simply avert their gaze toward the ground.

Finally we find that if flicker of sufficient contrast and stimulus size were produced by turbines, the larger turbines are unlikely to rotate fast enough to induce seizures. However, the rotation frequency increases inversely with the blade length, making small microgeneration turbines more likely to induce seizures, should the combined intensity and stimulus size conditions be met.

Acknowledgments

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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Update of UK Shadow Flicker Evidence Base

Department of Energy and Climate Change

Update of UK Shadow Flicker Evidence Base

Final Report

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Appendix 3 LPA Questionnaire (England)

Appendix 4 LPA Questionnaire (Scotland)

Appendix 5 LPA Questionnaire (Wales)

Appendix 6 LPA Questionnaire (Northern Ireland)

EXECUTIVE SUMMARY

The term ‘shadow flicker’ refers to the flickering effect caused when rotating wind turbine blades periodically cast shadows over neighbouring properties as they turn, through constrained openings such as windows. The magnitude of the shadow flicker varies both spatially and temporally and depends on a number of environmental conditions coinciding at any particular point in time, including, the position and height of the sun, wind speed, direction, cloudiness, and position of the turbine to a sensitive receptor.

Planning guidance in the UK requires developers to investigate the impact of shadow flicker, but does not specify methodologies.

To enable the Department of Energy and Climate Change to advance current understanding of the shadow flicker effect, this report details the findings of an investigation into the phenomenon of shadow flicker. This report presents an update of the evidence base which has been produced by carrying out a thorough review of international guidance on shadow flicker, an academic literature review and by investigating current assessment methodologies employed by developers and case study evidence. Consultation (by means of a questionnaire) was carried out with stakeholders in the UK onshore wind farm industry including developers, consultants and Local Planning Authorities (LPAs). This exercise was used to gauge their opinion and operational experience with shadow flicker, current guidance and the mitigation strategies that can and have been implemented.

All of the data collated was analysed and a number of conclusions were drawn. The current recommendation in Companion Guide to PPS22 (2004) to assess shadow flicker impacts within 130 degrees either side of north is considered acceptable, as is the 10 rotor diameter distance from the nearest property. It is acknowledged that this is a ‘one size fits all’ approach that may not be suitable depending on the latitude of the site.

It has become clear that there is no standard methodology that all developers employ when introducing environmental and site specific data into shadow flicker assessments. The three key computer models used by the industry are WindPro, WindFarm and Windfarmer. It has been shown that the outputs of these packages do not have significant differences between them. All computer model assessment methods use a ‘worst case scenario’ approach and don’t consider ‘realistic’ factors such as wind speed and cloud cover which can reduce the duration of the shadow flicker impact.

On health effects and nuisance of the shadow flicker effect, it is considered that the frequency of the flickering caused by the wind turbine rotation is such that it should not cause a significant risk to health. Mitigation measures which have been employed to operational wind farms such as turbine shut down strategies, have proved very successful, to the extent that shadow flicker can not be considered to be a major issue in the UK.

1 INTRODUCTION

The term ‘shadow flicker’ refers to the flickering effect caused when rotating wind turbine blades periodically cast a shadow over neighbouring properties as they turn, through constrained openings such as windows. The magnitude of the shadow flicker effect varies both spatially and temporally, and depends on a number of environmental conditions coinciding at any particular point in time, including, the position and height of the sun, wind speed and direction, cloudiness, and proximity of the turbine to a sensitive receptor.

Planning guidance in the UK (Companion Guide to PPS22, PAN45, Best Practice Guidance to PPS18 and the Welsh Planning Guidelines) requires developers to investigate the impact of shadow flicker, but does not specify methodologies.

To enable DECC to advance current understanding of the shadow flicker effect; this report details the findings of an investigation into the phenomenon of shadow flicker. In this report, Parsons Brinckerhoff (PB) update the evidence base by providing a review of planning guidance on shadow flicker from across the world, academic literature on the subject of shadow flicker, and has investigated assessment methodologies and case study evidence. Parsons Brinckerhoff has also consulted with stakeholders in the industry – both developers and local planning authorities (LPAs) through a questionnaire to gauge their opinion and operational experience with regard to shadow flicker, current guidance and the mitigation strategies that can be implemented.

Following this introduction (**Section 1**), the report is structured in six key sections:

- **Section 2** provides a review of guidance on shadow flicker from countries across the world.
- **Section 3** is an academic literature review, investigating the current understanding of the phenomenon.
- **Section 4** examines software models which are available to allow the assessment of shadow flicker on proposed developments.
- **Section 5** includes information from the respondents to the questionnaires which were sent to developers and planning authorities.
- **Section 6** collates information from the preceding four sections and provides a discussion of ten key themes and issues that were identified during the study.
- **Section 7** provides conclusions.

This report focuses solely on shadow flicker effect caused by large scale onshore (approximately 500kW upwards) wind turbines and does not consider the distinct shadow flicker conditions and impacts that are related to shadow flicker from small and micro scale (also known as ‘domestic’ scale, 0.3-10 kW) wind turbines.

Another distinct phenomenon that is often confused with ‘shadow flicker effect’ is that of ‘strobe effect’. Strobe effect refers to the flashing of reflected light which can be visible from some distance. This phenomenon has largely been ameliorated by the development of an industry standard (light grey semi-matt) for the colour and surface finish of turbine blades, as proposed by the ETSU (1999) study and the Companion Guide to PPS22 (2004). As a point of clarity, PB has disregarded the ‘strobe effect’ phenomenon from this study.

Throughout this report, we have included relevant quotations taken from our questionnaire responses. Whilst these are used in context, these quotations do not necessarily represent the views of Parsons Brinckerhoff or DECC and are the opinions of the questionnaire respondent. Please bear this in mind when reading the report.

2 CURRENT GUIDANCE

2.1 Introduction

This section reviews available guidance and policy literature relating to the shadow flicker phenomenon. This section is split into:

- Section 2.2 – United Kingdom Guidance
- Section 2.3 – International Guidance
- Section 2.4 – Non-governmental Organisation Guidance

For each country, relevant shadow flicker literature is detailed. For each guidance / policy document, the following information is included:

- Publication details – eg. report title, institution / author name, date, etc;
- A short synopsis detailing the salient issues raised and mitigation measures proposed;
- Extracts of the relevant text from the original document.

For the international guidance, the following European countries with an installed onshore wind energy capacity of greater than 100 megawatts (EWEA, 2010) were short listed and each country's national wind energy association was contacted for information on country specific shadow flicker guidance or regulatory policy.

Austria	Finland	Italy
Belgium	France	Netherlands
Bulgaria	Germany	Poland
Czech Republic	Greece	Portugal
Denmark	Hungary	Spain
Estonia	Ireland	Sweden

2.2 United Kingdom Guidance

2.2.1 England

2.2.1.1 Planning for Renewable Energy – A Companion Guide to PPS22 Office of the Deputy Prime Minister (2004)

Synopsis

Companion Guide to PPS22 makes the following statements:

- Shadow flicker only occurs inside buildings where the flicker appears through a narrow window opening;
- Only properties within 130 degrees either side of north of the turbines can be affected at UK latitudes;
- Shadow flicker has been proven to occur only within ten rotor diameters of a turbine position;
- Less than 5% of photo-sensitive epileptics are sensitive to the lowest frequencies of 2.5-3 Hz; the remainder being sensitive to higher frequencies; and
- A fast-moving three-bladed wind turbine will give rise to the highest levels of flicker frequency of well below 2 Hz. The new generation of wind turbines is known to operate at levels below 1 Hz.

Relevant *text*

"It [shadow flicker] only occurs inside buildings where the flicker appears through a narrow window opening. The seasonal duration of this effect can be calculated from the geometry of the machine and the latitude of the site. Although problems caused by shadow flicker are rare, for sites where existing development may be subject to this problem, applicants for planning permission for wind turbine installations should provide an analysis to quantify the effect. A single window in a single building is likely to be affected for a few minutes at certain times of the day during short periods of the year. The likelihood of this occurring and the duration of such an effect depends upon:

- *the direction of the residence relative to the turbine(s);*
- *the distance from the turbine(s);*
- *the turbine hub-height and rotor diameter;*
- *the time of year;*
- *the proportion of day-light hours in which the turbines operate;*
- *the frequency of bright sunshine and cloudless skies (particularly at low elevations above the horizon); and,*
- *the prevailing wind direction."* (Page 176)

"Only properties within 130 degrees either side of north, relative to the turbines can be affected at these latitudes in the UK – turbines do not cast long shadows on their southern side." (Page 177)

"The further the observer is from the turbine the less pronounced the effect will be. There are several reasons for this:

- *there are fewer times when the sun is low enough to cast a long shadow;*
- *when the sun is low it is more likely to be obscured by either cloud on the horizon or intervening buildings and vegetation; and,*
- *the centre of the rotor's shadow passes more quickly over the land reducing the duration of the effect."* (Page 177)

"At distance, the blades do not cover the sun but only partly mask it, substantially weakening the shadow. This effect occurs first with the shadow from the blade tip, the tips being thinner in section than the rest of the blade. The shadows from the tips extend the furthest and so only a very weak effect is observed at distance from the turbines." (Page 177)

"Shadow flicker can be mitigated by siting wind turbines at sufficient distance from residences likely to be affected. Flicker effects have been proven to occur only within ten rotor diameters of a turbine. Therefore if the turbine has 80 m diameter blades, the potential shadow flicker effect could be felt up to 800 m from a turbine." (Page 177)

"Around 0.5 % of the population is epileptic and of these around 5 % are photo-sensitive. Of photo-sensitive epileptics less than 5 % are sensitive to lowest frequencies of 2.5 – 3 Hz, the remainder are sensitive only to higher frequencies. The flicker caused by wind turbines is equal to the blade passing frequency. A fast-moving three-bladed machine will give rise to the highest levels of flicker frequency. These levels are well below 2 Hz. The new generation of wind turbines is known to operate at levels below 1 Hz." (Page 177)

2.2.1.2 Onshore Wind Energy Planning Conditions Guidance Note, Renewables Advisory Board and BERR (2007)

Synopsis

This document provides guidance to Local Planning Authorities and other stakeholders on preparing planning conditions for onshore wind energy developments.

The document states that only dwellings within 130 degrees either side of north relative to a turbine can be affected and the shadow can be experienced only within 10 rotor diameters of the wind farm.

Shadow flicker is more likely to be relevant when considering potential effects on residential amenity than on health effects.

It is worth noting that this document states that where wind turbines lie within the geographical range which may be affected by shadow flicker, it will not be possible to determine whether or not shadow flicker effects will actually be felt until an assessment has been made of window widths, the uses of the rooms with potentially affected windows and the effects of intervening topography and other vegetation. Therefore, the document proposes that local ameliorating factors are taken into account when preparing a shadow flicker report.

If shadow flicker is determined to have a potentially significant impact, then a Local Planning Authority may wish to impose the following planning condition:

> *"The operation of the turbines shall take place in accordance with the approved shadow flicker mitigation protocol unless the Local Planning Authority gives its prior written consent to any variation."*

Relevant *text*

> *"When blades rotate and the shadow passes a narrow window then a person within that room may perceive that the shadow appears to flick on and off; this effect is known as shadow flicker. It occurs only within buildings where the shadow appears through a narrow window opening. Only dwellings within 130 degrees either side of north relative to a turbine can be affected and the shadow can be experienced only within 10 rotor diameters of the wind farm."* (Page 22)

> *"The operating frequency of a wind turbine will be relevant in determining whether or not shadow flicker can cause health effects in human beings. The National Society for Epilepsy advises that only 3.5 % of the 1 in 200 people in the UK who have epilepsy suffer from photosensitive epilepsy. The frequency at which photosensitive epilepsy may be triggered varies from person to person but generally it is between 2.5 and 30 flashes per second (hertz). Most commercial wind turbines in the UK rotate much more slowly than this, at between 0.3 and 1.0 hertz. Therefore, health effects arising from shadow flicker will not have the potential to occur unless the operating frequency of a particular turbine is between 2.5 and 30 hertz and all other pre-conditions for shadow flicker effects to occur exist."* (Page 22)

> *"Shadow flicker is therefore more likely to be relevant in considering the potential effects on residential amenity. Where wind turbines lie within the geographical range which may be affected by shadow flicker it will not be possible to determine whether or not shadow flicker effects will actually be felt until an assessment has been made of window widths, the uses of the rooms with potentially affected windows and the effects of intervening*

topography and other vegetation. Where it has been predicted that shadow flicker effects may occur in theory, a local planning authority may consider it appropriate to impose a planning condition to provide that wind turbines should operate in accordance with a shadow flicker mitigation scheme which shall be submitted to and approved by the Local Planning Authority prior to the operation of any wind turbine unless a survey carried out on behalf of the developer in accordance with a methodology approved in advance by the local planning authority confirms that shadow flicker effects would not be experienced within habitable rooms within any dwelling." (Page 22)

"Sample Condition: The operation of the turbines shall take place in accordance with the approved shadow flicker mitigation protocol unless the Local Planning Authority gives its prior written consent to any variation." (Page 22)

2.2.2 Northern Ireland

In Northern Ireland, wind farm planning decisions are overseen by the National Planning Service rather than local councils.

2.2.2.1 Best Practice Guidance to Planning Policy Statement 18 'Renewable Energy', Northern Ireland Department of the Environment (2009)

Synopsis

Best Practice Guidance to Planning Policy Statement 18 makes the following statements:

- Shadow flicker only occurs inside buildings where the flicker appears through a narrow window opening;
- Only properties within 130 degrees either side of north of the turbines can be affected at UK latitudes;
- The potential for shadow flicker at distances greater than ten rotor diameters from a turbine position is very low;

The document also recommends that shadow flicker at offices and dwellings within 500 m of a turbine position should not exceed 30 hours per year or 30 minutes per day, quoting a survey undertaken by Predac, a European Union sponsored organisation that promotes best practice in energy use and supply.

In addition, the guidance proposes that developers should quantify the shadow flicker effect, and implement measures to ameliorate the impact, such as by turning off a particular turbine at certain times.

Relevant *text*

"It [shadow flicker] only occurs inside buildings where the flicker appears through a narrow window opening. A single window in a single building is likely to be affected for a few minutes at certain times of the day during short periods of the year. The likelihood of this occurring and the duration of such an effect depends upon:

- *the direction of the residence relative to the turbine(s);*
- *the distance from the turbine(s);*
- *the turbine hub-height and rotor diameter;*
- *the time of year;*
- *the proportion of day-light hours in which the turbines operate;*
- *the frequency of bright sunshine and cloudless skies (particularly at low elevations above the horizon); and,*
- *the prevailing wind direction."* (Page 28)

"Shadow flicker generally only occurs in relative proximity to sites and has only been recorded occasionally at one site in the UK. Only properties within 130 degrees either side of north, relative to the turbines can be affected at these latitudes in the UK – turbines do not cast long shadows on their southern side." (Page 28)

"The further the observer is from the turbine the less pronounced the effect will be. There are several reasons for this:

- *there are fewer times when the sun is low enough to cast a long shadow;*
- *when the sun is low it is more likely to be obscured by either cloud on the horizon or intervening buildings and vegetation; and,*
- *the centre of the rotor's shadow passes more quickly over the land reducing the duration of the effect."* (Page 28)

"At distance, the blades do not cover the sun but only partly mask it, substantially weakening the shadow. This effect occurs first with the shadow from the blade tip, the tips being thinner in section than the rest of the blade. The shadows from the tips extend the furthest and so only a very weak effect is observed at distance from the turbines." (Page 28)

"Problems caused by shadow flicker are rare. At distances greater than 10 rotor diameters from a turbine, the potential for shadow flicker is very low. The seasonal duration of this effect can be calculated from the geometry of the machine and the latitude of the site. Where shadow flicker could be a problem, developers should provide calculations to quantify the effect and where appropriate take measures to prevent or ameliorate the potential effect, such as by turning off a particular turbine at certain times." (Page 29)

"Careful site selection, design and planning, and good use of relevant software, can help avoid the possibility of shadow flicker in the first instance. It is recommended that shadow flicker at neighbouring offices and dwellings within 500m should not exceed 30 hours per year or 30 minutes per day3." (Page 29)

2.2.3 Wales

In Wales, planning policy and guidance is prepared by the Welsh Assembly Government.

2.2.3.1 Practice Guidance – Planning Implications of Renewable and Low Carbon Energy, Planning Division – Welsh Assembly Government (2010)

Synopsis

This Welsh guidance document proposes the following mitigation strategies for shadow flicker: careful site design; turbine shut down; installation of blinds and landscaping (tree / shrub planting) at affected residential properties.

Relevant *text*

"Shadow flicker can occur when the sun passes behind the rotors of a wind turbine, which casts a shadow over neighbouring properties that flicks on and off as the blades rotate. However, this only occurs under particular circumstances and lasts only for a few hours per day. Shadow flicker can cause a disturbance for affected residents of nearby properties and can have potentially harmful impacts on sufferers of photo-sensitive epilepsy. These potential impacts can be mitigated by micrositing turbines as far as practically possible from residential properties and through the use of technological fixes such as the shutting down of turbines during periods of predicted shadow flicker. The use

of blinds at residential properties or tree/shrub planting to screen shadow flicker can also help minimise potential impacts." (Page 25)

Generating Your Own Energy. Wind: A Planning Guide for Householders, Communities and Businesses.
Welsh Assembly Government (2010)

Synopsis

This guidance document proposes two mitigation strategies - careful site design and introducing vegetation screening,

Relevant text

"Site and position the turbine to avoid shadow flicker (where possible)." (Page 6)

"Screen shadow flicker impacts using planting." (Page 6)

2.2.4 Scotland

2.2.4.1 Planning Advice Note (PAN) 45: Renewable Energy Technologies Scottish Executive (2002)

Synopsis

Scottish guidance on shadow flicker is given in PAN45. The following statements are made:

- Shadow flicker only occurs inside buildings where the flicker appears through a narrow window opening;
- A general rule of ten rotor diameters should be used for separation distance from a turbine position to a dwelling.

Relevant text

"It [shadow flicker] occurs only within buildings where the flicker appears through a narrow window opening. The seasonal duration of this effect can be calculated from the geometry of the machine and the latitude of the potential site. Where this could be a problem, developers should provide calculations to quantify the effect. In most cases however, where separation is provided between wind turbines and nearby dwellings (as a general rule 10 rotor diameters), "shadow flicker" should not be a problem." (Paragraph 64)

2.3 International Guidance

2.3.1 Spain

PB contacted the Spanish Wind Energy Association to obtain information on shadow flicker guidance. A translation of the response received is below:

"In Spain, shadow flicker is not included in the planning requirements at present. As wind farms in Spain tend to be located very far away from any populated settlement, no complaints have been registered and no standard practice has been implemented."

2.3.2 Ireland

2.3.2.1 Planning Guidelines
Department of Environment, Heritage and Local Government (Undated)

Synopsis

The Irish Planning Guidelines document makes the following statements:

- It is recommended that shadow flicker at offices and dwellings within 500 m of a turbine should not exceed 30 hours per year or 30 minutes per day;
- At distances greater than 10 rotor diameters from a turbine, the potential for shadow flicker is very low;
- Careful site design and turbine shut down are proposed as mitigation measures.

Relevant text

"*Shadow flicker only occurs in certain specific combined circumstances, such as when:*
The sun is shining and is at a low angle (after dawn and before sunset), and
The turbine is directly between the sun and the affected property, and
There is enough wind energy to ensure that the turbine blades are moving." (Page 33)

"Careful site selection, design and planning, and good use of relevant software can help avoid the possibility of shadow flicker in the first instance. It is recommended that shadow flicker at neighbouring offices and dwellings within 500m should not exceed 30 hours per year or 30 minutes per day [Predac]" (Page 33)*

"At distances greater than 10 rotor diameters from a turbine, the potential for shadow flicker is very low. Where shadow flicker could be a problem, developers should provide calculations to quantify the effect and where appropriate take measures to prevent or ameliorate the potential effect, such as by turning off a particular turbine at certain times." (Page 33)

*The shadow flicker recommendations are based on the survey by Predac, a European Union sponsored organisation promoting best practice at energy use and supply which draws on experience from Belgium, Denmark, France, the Netherlands and Germany.

2.3.2.2 Best Practice Guidelines for the Irish Wind Energy Industry
Irish Wind Energy Association and Sustainable Energy Ireland (2008)

Synopsis

This document suggests that it is reasonable to take into account ambient environmental conditions (such as wind direction and general climate) to modify the astronomical worst case scenario calculations.

Two mitigation options are recommended – turbine shut down and provision of screening measures.

In addition, the document states that the '10 x rotor diameter' rule is normally sufficient for EIA purposes.

Relevant text

"Calculations for shadow flicker modelling generally assume 100% sunshine conditions. It is reasonable in Ireland's climate to modify these figures. Some attention can also be given to the wind rose. If winds rarely come from the sectors which would give rise to the greatest shadow flicker effects on a dwelling, this can be taken into account." (Page 24)

"Where shadow flicker is anticipated to lead to potential problems, measures can be implemented to mitigate these effects. Wind turbine control software is available, which can turn the relevant turbine off at these times. The developer may wish to consider the economic impact of use of this mechanism. Other mitigation measures could include the provision of screening measures, where this is acceptable to the relevant householder." (Page 24)

"The assessment of potentially sensitive locations or receptors within a distance of ten rotor diameters from proposed turbine locations will normally be suitable for EIA purposes. A guideline of not more than 30 hours of shadow flicker per year is suggested for dwellings." (Page 25)

2.3.3 Germany

2.3.3.1 Notes on the Identification and Evaluation of the Optical Emissions of Wind Turbines, States Committee for Pollution Control – Nordrhein-Westfalen (2002)

Synopsis

This document provides a clear set of criteria for an astronomic worst case scenario. German guidance sets strict limits on the levels of acceptable shadow flicker effect, using two methods:

- An astronomic worst case scenario limited to a maximum of 30 hours per year or 30 minutes on the worst affected day; and
- A realistic scenario including meteorological parameters limited to a maximum of 8 hours per year.

If the above limits are exceeded, then mitigation measures should be implemented. The document makes particular reference to adopting a planning condition for automatic turbine shut-down timers, which use radiation or illumination sensors.

The following strict criteria are provided to define the astronomic worst case and realistic shadow flicker scenarios:

- There is continual sunshine and permanently cloudless skies from sunrise to sunset
- There is sufficient wind for continually rotating turbine blades
- Rotor is perpendicular to the incident direction of the sunlight
- Sun angles less than 3 degrees above the horizon level are disregarded (due to likelihood for vegetation and building screening)
- Distances between the rotor plane and the tower axis are negligible.
- Light refraction in the atmosphere is not considered.

The German guidance does not specifically refer to a distance limit for shadow flicker assessments. However, there is reference to a point where the contrast between shadow and ambient conditions are so low that the impact is excluded from assessment.

The 30 minutes per day rule for shadow flicker at any given receptor is based on a psychology academic survey by the University of Kiel (Pohl et al 2000).

This document also provides an example case study demonstrating how shadow flicker should be calculated. The methodology sets the indoor reference height at the centre of a receptor window, and a reference height of 2m above ground level if measured outside. This case study can be found in Appendix 1.

Relevant text

Please note – this text is a translation and is not quoted verbatim. Some elements of the translation may not reflect the exact wording of the original documents.

> *Scientific research* [no reference given in text] *has demonstrated experience that optical emissions in the form of periodic shadows can result in considerable harassment effects.*
>
> *Technical measurements and limits on the time of operation are based on WEA guidance. Turbine shut down is only considered in cases where the operation is an endangerment to life or health, or will result in significant damage.*
>
> *Astronomically maximum shading time (worst case) is the theoretical time when the sun is during the entire period between sunrise and sunset passing through a cloudless sky and the rotor surface is perpendicular to the solar radiation, and the wind turbine is in operation.*
>
> *Actual shading time is the realistic estimate of accumulated exposure to periodic shadows. If the irradiance of the direct solar radiation in the direction normal to the incident plane is more than 120 W/m*^{2}*, then sunshine and shadows are acceptable.*
>
> *Relevant emission figures that could occur are defined by ambient weather conditions. The effect of predicted periodic shadow is not considered a significant nuisance if the cumulative astronomical maximum loading at a reference height of 2m above ground level does not exceed 30 hours per calendar year and is not greater than 30 minutes per calendar day.*
>
> *If the time values for the astronomical maximum shading are exceeded, there are technical measures that can be considered to impose time-limit restrictions on the operation of the wind turbine. An automatic switching unit, with radiation or illumination sensors, which record the specific meteorological situation can allow terms and conditions agreed for shadow flicker time limits to be achieved. Since the value of 30 hours per calendar year was developed using the astronomical maximum loading, automatic switch-off is an appropriate solution to mitigate the actual, real time shadows. The actual real-time shadows are limited to 8 hours per calendar year (Freund 2001).*
>
> *The sun is assumed to be point-like source and appears on all day.*
>
> *There is a cloudless sky, sufficient wind to turn the turbines blades. Wind direction corresponds to the azimuth angle of the sun (ie. rotor is perpendicular to the incident direction of the sunlight). Calculations are based on geographic north. Distances between the rotor plane and the tower axis are negligible. Light refraction in the atmosphere is not considered.*
>
> *Sun angles less than 3 degrees above the horizon are removed from analysis because vegetation and buildings will remove shadow impact.*
>
> ***Annual limits***
> *Wind turbines are only approved if the maximum astronomic shading period of 30 hours per calendar year is not exceeded. A review of complaints relating to shadow flicker at*

existing systems, has informed the setting of this benchmark. When using an automatic cut off system that does not takes account metrological parameters, the maximum astronomic shading is limited to 30 hours per calendar year. For systems that do take into account metrological parameters (ie intensity of the sun), the actual shading is limited to 8 hours.

Daily Limits
Shadow flicker should be limited to a maximum of 30 minutes per day. The laboratory study by the University of Kiel (Pohl et al 2000) noted that even a one-off exposure to 60 minute duration of shadows can cause stress reactions. For precaution, shading duration is therefore limited to 30 minutes per day.

For planned plants, the astronomic maximum shading period should be used, and for existing plants, the actual shadow duration is used. When this benchmark is exceeded for at least three days, appropriate measures need to be implemented to reduce the impact to guarantee a maximum duration of shading of 30 minutes.

When siting wind turbines, there is an obligation to take precautionary measures to reduce the shadow flicker, taking account of proportionality and the requirements of the planning department.

Exceedance of the allowable emission values for a wind turbine is carried out by emission-verified compliance. Reduction of shadow is carried out by an electronic circuit which calculates the time of shadows at relevant receptors. In determining exact times, the type of receptor (eg. window) should be considered. When indoors, the reference height should be set at the centre of the window. When outdoors, the reference height is set at 2m above ground level. Sunshine duration data should cover a period of at least a year, and the data should be available by a competent authority on request.

Evidence of the amount of shadow flicker needs to be calculated in the context of planning projects and monitoring systems. This allows the shut-down timings for wind turbines to be determined.

Shadow forecast is based on an algorithm which calculates the location, day and time dependent solar position. To ensure uniform implementation, widely available computational models are recommended (DIN 5034-2 1985; VI 3789 1994).

Accuracy of geometric parameters should be ±3-10m. The determination of shadow cast times should have an accuracy of 1min per day. Absolute times are in GMT or BST.

The start and end points of shadow at each relevant receptor point needs to be calculated in relation to the receptor. In the case of several wind turbines, the cumulative contributions need to be taken into account.

As part of the calculation, excerpts are required from topographical maps, as are coordinates of plant locations and receiver points. The result from the software is iso-shadow contours (especially the 30 hour contour) for the plant.

Because of the complexities of the calculations, commercial computer programmes should be used to calculate shadow flicker. Forecast times should be presented in appropriate data tables.

2.3.4 United States

2.3.4.1 Wind Turbines and Health, American Wind Energy Association (2010)

Synopsis

The American Wind Energy Association recommends that shadow flicker impacts are mitigated by use of appropriate turbine-dwelling separation distances or screening by vegetation planting. The document also states that shadow flicker issues are less common in the United States than in Europe.

Relevant text

> *"Computer models in wind development software can determine the days and times during the year that specific buildings in close proximity to turbines may experience shadow flicker. Mitigation measures can be taken based on this knowledge and may include setbacks or vegetative buffers. Issues with shadow flicker are less common in the United States than in Europe due to the lower latitudes and the higher sun angles in the United States."*

2.3.4.2 Final Programmatic Environmental Impact Statement on Wind Energy Development on BLM- Administered Lands in the Western United States, US Department of the Interior – Bureau of Land Management (2005)

Synopsis

This document produced by the United States' Department of the Interior states that shadow flicker is not considered as significant an issue in the United States as in Europe.

However, this document does note that flickering effect may be considered an annoyance, but that modern three-bladed wind turbines are unlikely to cause epileptic seizures in the susceptible population due to the low blade passing frequencies.

Relevant text

> "*When the sun is behind the blades and the shadow falls across occupied buildings, the light passing through windows can disturb the occupants (Gipe 1995). Shadow flicker is recognized as an important issue in Europe but is generally not considered as significant in the United States (Gipe 1995). The American Wind Energy Association (AWEA 2004) states that shadow flicker is not a problem during the majority of the year at U.S. latitudes (except in Alaska where the sun's angle is very low in the sky for a large portion of the year). In addition, it is possible to calculate if a flickering shadow will fall on a given location near a wind farm and for how many hours in a year (AWEA 2004). While the flickering effect may be considered an annoyance, there is also concern that the variations in light frequencies may trigger epileptic seizures in the susceptible population (Burton et al. 2001). However, the rate at which modern three-bladed wind turbines rotate generates blade-passing frequencies of less than 1.75 Hz, below the threshold frequency of 2.5 Hz, indicating that seizures should not be an issue (Burton et al. 2001)."*
> (Section 3-20)

Canada

2.3.4.3 Draft HRM Wind Energy Generation Plan, Halifax Regional Municipality (2006)

Synopsis

This document refines the shadow flicker definition to a ‘pulsing change in light intensity’. This document does not propose any particular separation distance between turbines and dwellings, but instead outlines the various approaches adopted in three Environmental Statements, covering a fixed radius of 500-1000 m in Denmark, ’10 x rotor diameter’ rule in Aberdeenshire in Scotland, and 30 hours per year in Germany. A case study from the United States is also included that outlines a turbine shut-down mitigation measure strategy.

This document also states that even within an urban environment, careful site design in the first instance and mitigation measures thereafter may manage any potential shadow flicker impacts.

Relevant text

> *“Shadow flicker is the effect of the sun passing through the blades of the tower and creating a flickering effect or pulsing change in light intensity based on the speed of the turbine (Botha 2005). The impact of the flicker is dependent on the orientation of the tower and location of the sun. For example, if the sun is low on the horizon and the turbine blades directly face the sun the impact will cover a larger area compared to if it is parallel to the sun’s rays. In most cases the effect will fall on open countryside, however, where towers are located closer to residential properties consideration needs to be given to protect the residents from this impact. The impact is basically an annoyance and there are suggestions that it can lead to inducing epilepsy in susceptible individuals, however the study team is not aware of any recorded incidents of this actually occurring.”* (Page 16)
>
> *“A considerable amount of international research has been undertaken on the impacts and management of shadow flicker and the following summary is outlined in a comprehensive environmental impact assessment (Awhitu Wind Farm 2004):*
> *“The Danish Wind Energy Association reports that shadow flicker does not need to be assessed at distances more than 500 – 1000 metres from a wind turbine.*
> *Environmental assessments for other wind farms (e.g., by Renewable Energy Systems for the Meikle Carewe project in Aberdeenshire, Scotland) state that shadow flicker is only a potential problem at closer than 10 rotor diameters to the turbine.*
> *The ministry for the Environment of Schleswig-Holstein, a northern German region with more than 1,000 MW of installed wind power, recommend the use of flicker timer if more than 30 hours of theoretical flicker occurs per year.”* (Page 16)
>
> *“The above provides some guidance on how this impact may be managed. Based on consultations done in Alberta, the Municipality of Pincher Creek advises that operators either shut down the machines between the time the sun is rising and setting for approximately an hour, or that computers manage to control the direction of the turbine so the blades are directly parallel to the sun. Access to information on calculating and modeling the impacts of wind shadow is provided on the Danish Wind Industry Association website.* (page 16)
>
> *In an urban environment, it will be more challenging to create a sufficient clearing around the turbine. Notwithstanding this, one should not prohibit the ability to establish these structures in an urban environment because there may be site circumstances that avoid this impact (e.g., parkland area/industrial premises) or controls and technologies that manage the impact.* (page 16)
>
> *There has also been concern that wind turbines, in particular their shadow flicker, have an impact on certain grazing animals. Studies have been undertaken in a number of countries to assess this potential impact, and all indicate farm animals and horses*

adapt to the new environment within a brief acclimatization period. In relation to horses, evidence indicates that generally horses should not be ridden in these environments if they have not been acclimatized (page 16)

2.3.5 Denmark

No guidance on shadow flicker from Denmark was found during literature searches by the authors, however the following comments were noted on the Danish Wind Industry Associations website (Danish Wind Industry Association, accessed 2010):

"The hub height of a wind turbine is of minor importance for the shadow from the rotor. The same shadow will be spread over a larger area, so in the vicinity of the turbine, say, up to 1,000 m, the number of minutes per year with shadows will actually decrease."

"If you are farther away from a wind turbine rotor than about 500-1000 metres, the rotor of a wind turbine will not appear to be chopping the light, but the turbine will be regarded as an object with the sun behind it. Therefore, it is generally not necessary to consider shadow casting at such distances."

2.3.6 Australia

2.3.6.1 Planning Bulletin – Wind Farms (Draft for Consultation) Government of South Australia (2002)

Synopsis

This document states that shadow flicker is unlikely to be a significant issue if a separation distance of 500 m is maintained between the turbine and any dwelling or urban area.

Relevant text

"This occurs when the sun is low on the horizon and the blades pass between the sun and an observer, creating a flickering. This issue needs to be considered as it could cause irritation and visual impairment. This is unlikely to be a significant issue if a separation distance of at least 500 metres is maintained between the turbine and any dwelling or any defined urban area." (Page 7)

2.3.6.2 Western Australia Planning Bulletin – Guidelines for Wind Farm Development, Western Australian Planning Commission (May 2004)

Synopsis

This document states that shadow flicker can affect local amenity but is uncommon in Australia.

Relevant text

"A wind energy facility can affect local amenity due to: Shadow flicker, which occurs when the sun passes behind the blades and the shadow flicks on and off, although in Australia this is uncommon." (Page 4)

2.4 Non-governmental Organisations Guidance

2.4.1 Spatial Planning of Wind Turbines, PREDAC – European Actions for Renewable Energies

Synopsis

Predac have developed a set of recommendations for the special planning of wind energy developments, based on a survey of guidance from Belgium, Denmark, France and The Netherlands, as well as some information from Germany and Ireland.

From this document, it is clear that the approach to this issue varies across Europe, with Belgium adopting the German quantitative limits (30hrs per year and 30 min per day), and both Denmark and The Netherlands adopting similar quantitative limits (Denmark - 10 hrs per year, The Netherlands 20 minutes per day, 17 days per year – equivalent to 5 hours 40 min per year). France has no set limits on shadow flicker effect.

Additionally, there are differences between the countries in how the calculations should be carried out, with Denmark taking 'average cloud cover' into account and The Netherlands specifying that calculations should be carried out with a clear sky.

This document recommends that at neighbouring dwellings and offices that flickering shadows are not exceeding 30 hours /year or 30min. per day with normal variation in wind directions and with clear sky. (This follows the German norm of 30 hours a year at clear sky).

Relevant text

> *"It is recommended at neighbouring dwellings and offices that flickering shadows are not exceeding 30 hours /year or 30 min. per day with normal variation in wind directions and with clear sky. (This follows the German norm of 30 hours a year at clear sky)."* (Page 21)
>
> *"Belgium*
> *In Wallonie, the government recommends to apply the threshold of tolerance that are fixed on the German pattern, that is 30hrs per year and 30 min per day. In practice, they are always applied as condition to obtain the permit and must be studied in the EIA."* (Page 21)
>
> *"Denmark*
> *Recommendation: max. 10 hours/year allowed at neighbouring dwellings with average cloud cover."* (Page 21)
>
> *"France*
> *No recommendations are fixed, but the calculation of the occurrence of the shadow flicker at the nearest neighbours should be indicated in the EIA."* (Page 21)
>
> *"The Netherlands*
> *When there is more than 20 minutes per day, 17 days per year (5 hours 40 min / year calculated, with clear sky), at neighbours it is regarded as a nuisance, which is unacceptable, and a standstill device is requested."* (Page 21)

3 ACADEMIC LITERATURE

3.1 Introduction

Parsons Brinckerhoff has undertaken an academic literature review on the phenomenon of shadow flicker. Literature has been obtained from various sources, including online, direct from the authors or publishers and from the British Library. In all cases, an attempt has been made to source literature that has been referenced in guidance or other literature to provide a full review. Where necessary, Parsons Brinckerhoff has translated from the original language. Where this has been the case, it has been highlighted in the review below.

3.2 Literature

3.2.1 Shadow Hindrance by Wind Turbines, Verkuijlen E. & Westra C.A. (1984)

Synopsis

This paper is from the Interfaculty Department of Environmental Science at University of Amsterdam, and is part of the original evidence base addressing the amenity issues associated with shadow flicker effect from onshore wind turbines. The paper is set in The Netherlands and the technical drawings adopt criteria (eg. latitude and predominant wind direction) that are comparable with the United Kingdom.

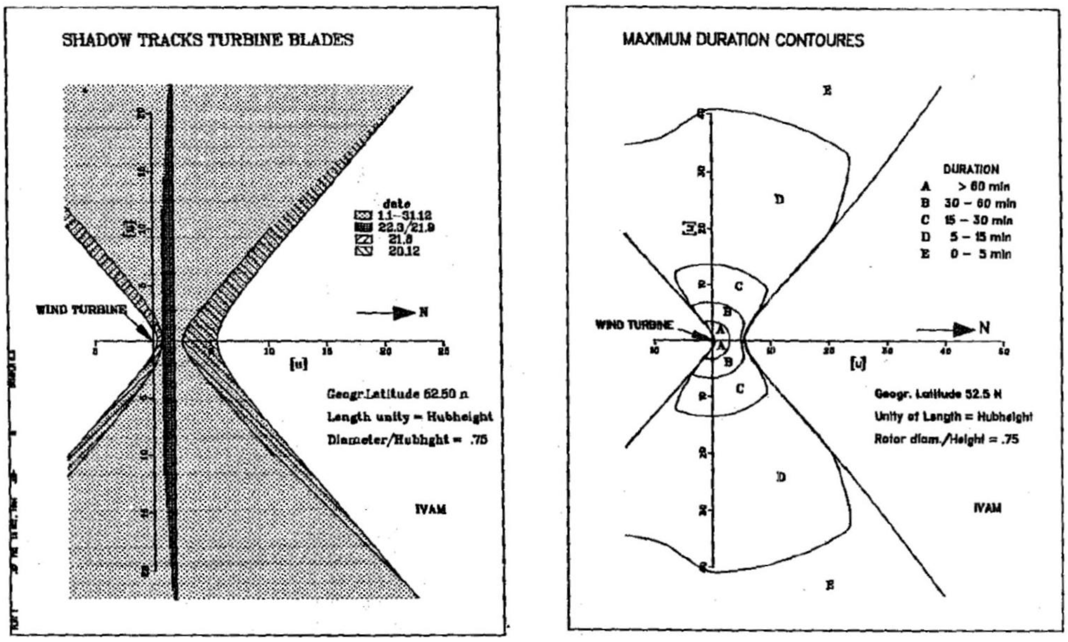
The paper states that the greatest shadow flicker impact can be expected:

- Inside a property where the change in light intensity is most noticeable
- When turbines are rotating at between 5 and 14 Hz (below 2.5 Hz and above 40 Hz will cause "hardly any nuisance").
- In areas to the east-northeast and west-northwest of a turbine

The paper suggests that three factors are important in determining the impact of shadow flicker:

1. The receptors location relative to the turbine;
2. The time at which the shadow covers a particular place;
3. The duration of exposure to shadow.

Figure 1: Shadow influence of a wind turbine (figure extracted from paper)



The paper also states that during winter, the sun is lower in the sky than in summer, so the daily track of shadow flicker effect will extend farther from the turbine.

Several mitigation measures are proposed including sensitive site design, installation of blinds, and wind turbine shut-down strategies. The paper expands on the sensitive site design aspect, suggesting that hindrance from shadow flicker would occur particularly in east-northeast and west-northwest directions from a wind turbine.

The paper concludes that further research is necessary on the impact of flicker frequencies and duration of exposure.

Relevant text extracts

> *"Indoors the effect will be far greater, because in this case (almost) all the light that reaches the observer is modulated in intensity by the turbine blades."* (Page 356)
>
> *"The effect of light flicker on an observer depends largely on its frequency. In frequencies below 1 Hz every change in light intensity is felt as such. Beyond a certain frequency flickers are no longer perceived separately. This limit is called the flicker fusion frequency and as a rule lies at 50-80 Hz."* (Page 357)
>
> *"Flicker frequencies approaching the fusion frequency may be felt to be a nuisance."* (Page 357)
>
> *"Various experiments for the lighting of traffic tunnels led to the conclusion that most persons (tested) feel flicker frequencies from 5-10 Hz as a nuisance (8-9) [Collins & Hopkinson (1957); Schreuder (1964)]. From other research projects, too, men have found to be maximally sensitive to flickers between 8 and 14 Hz. Below 2.5 Hz and beyond 40 Hz hardly any nuisance is caused."* (Page 357)
>
> *"It is well known that in some people suffering from epilepsy an epileptic seizure may be triggered by light flickers (photosensitive epilepsy). Around 2 % of the population are epileptics. In brain research about 5 % of people with epilepsy have shown*

anomalous EEG (electroencephalogram) reactions to flickers from 2.5 to 3 Hz. Higher frequencies (15-20 Hz) may even cause convulsions in epileptic persons (5) [Ginsburg (1970)]. (page 357)

"Most wind turbines give a flicker frequency between 1 and 6 Hz. The aforesaid limit of 2.5 Hz falls within this frequency range. Some wind turbines, therefore may cause hindrance (when there is wind and sunshine)." (Page 357)

"(rotor diameter/hub height = 0.75; position 52.5^o N and 4^o E)." (Page 357)

"When the sun is shining, the rotor shadow describes a track on the earth's surface from west to east as a result of the sun's daily orbit along the sky. Because the sun is lower in winter than in summer, the daily track will be farther from the turbine in winter (see Figure 1). At sunrise and sunset, the shadow shifts very fast. At sunset the shadow first becomes diffuse and then vanishes; at sunrise exactly the opposite occurs. Nevertheless it may cause nuisance during this brief spell of time. The shape of the rotor shadow depends on the relative positions of rotor and sun. The extremes are:

a) Rotor position perpendicular to the sunlight;
b) Rotor position parallel to the sunlight.

In the former case the rotor casts a shadow covering a elongate strip. In the latter case the shadow has an oval shape. When the rotor plane turns from position b. to position a. the oval will become narrower till it is transformed to a narrow strip. In our further calculations of the period during which the shadow covers on particular place, we always start from case a. Three factors are important for the eventual hindrance caused by the shadow:

1) *The place covered by the shadow;*
2) *The time at which the shadow covers a particular place*
3) *The duration of the shadow covering one particular place."* (Page 357)

"It is obvious from these figures that particularly large areas in E-NE and W-NW directions from the wind turbine can be shadowed for long periods of time. In these directions, therefore, most hindrance is to be expected." (Page 358)

"From the above it can be concluded that the revolving blades of present wind turbines may inflict shadow hindrance on a number of people in a large area around the turbine, particularly if the flicker frequency is beyond 2.5 Hz. Largely because of the development of wind turbines running with variable rpm (turbines with a so-called inverter system), the number of turbines whose flicker frequency may rise above this limit of 2.5 Hz is bound to increase. This will greatly add to the change of change [sic – shadow] hindrance. It must be noted, though, that this limit was found in literature which did not refer to the shadow of wind turbine blades. Therefore, further research is necessary. This will have to go into both the impact of the resulting flicker frequency and the duration of the exposure. For the present it seems to be advisable only to install wind turbines whose resulting flicker frequency remains below 2.5 Hz. Shadow hindrance may occur particularly in east-northeast and west-northwest directions from a wind turbine. In order to reduce shadow hindrance in buildings to a minimum, this could be taken into account when siting new wind turbines. With southwest winds predominating in the Netherlands, wind turbines are often sited southwest of built-up areas. These locations, however, are most likely to suffer shadow hindrance. Siting south of buildings would therefore be a fine compromise. For numerous reasons wind turbines may still be so sited that shadow hindrance is caused in buildings. In such cases several solutions could be considered to reduce the shadow hindrance:

a) *Fitting the buildings' windows with sunblinds. This could lessen the difference in intensity between light and shadow.*
b) *Stopping the wind turbine. Whenever the shadow of a wind turbine causes nuisance, it could be stopped. Because one knows at what times shadow hindrance can be expected in a certain situation, the wind turbine could be stopped with a time switch. From exploratory calculations we have found that the annual output of wind turbines in areas of low building intensity would be reduced by a few percent only."* (Page 358)

3.2.2 A Case of Shadow Flicker / Flashing: Assessment and Solution, Clarke A.D. (1991)

Synopsis

This paper makes reference to a complaint submitted to a Local Planning Authority (LPA) relating to disturbance from shadow flicker and reflected sunlight from a wind turbine – the details of the complaint and the LPA that it was submitted to were not included in the paper. However, the rotation rate of the three-bladed turbine in question was recorded as between 33 and 44 revolutions per minute, creating a flicker frequency of between 1.65 and 2.2 Hz.

The paper also states that sunny hours are likely to lower between October and early February when shadow flicker is predicted to occur, although this is likely to be the windiest period of the year. This paper also advocates the use of the '10 x rotor diameter' rule for separation between wind turbines and habitations or occupied buildings.

The paper considers shadows cast from turbines being an issue when cast through windows of buildings, and does not make reference to impacts outside of buildings.

Relevant text extracts

"*A recommendation was made that turbines should be sited at least ten diameters distance from habitations, and more if sited to the East / Southeast or West / Southwest, and the shadow path identified."* (Page 93)

"The effect can be pronounced in rooms in buildings facing the turbine, especially if the window is the sole source of light for a room." (Page 93)

"It has been found that the frequencies of flicker that produce disturbance are between 2.5 Hz and 40 Hz." (Page 93)

"Most medium and large wind turbines have a rotation rate of between 30 r/min [rotations per minute] and 60 r/min, and smaller turbines often have a faster rotation. Most turbines in use today are two or three bladed, constant speed types, producing shadow flicker rates in the range of 1-3 Hz. Variable speed turbines may produce a 2-6 Hz flicker rate. Therefore the shadow flicker from turbines has frequencies that could in the right conditions produce light flicker effects to susceptible persons." (Page 93)

"The shadow will be most pronounced when the blades of the turbine face the building and present the largest shadow area." (Page 94)

"Residents of a neighbouring house claimed that shadow flicker and reflected sunlight from the turbine blades were causing disturbance to them (5). After complaints were made to the local Planning Authority, a study was carried out to investigate the problem." (Page 94)

"The turbine's dimensions and data were obtained:
turbine rating: 200kW
blade diameter: 25m
tower height: 30m
swept area: 491m square
rotation rate: 44 r/min & 33 r/min in light winds
number of blades: 3
flicker frequency: 2.2 Hz & 1.65 Hz." (Page 94)

"It was recommended that a timer plus photo cell should be employed to automatically switch off the turbine for the duration of the flicker period, which will not be more than about 20 minutes, if the sun is shining and the wind blowing." (Page 94).

"In addition, the number of sunny hours is likely to be small in late October, November, December, January and early February when flicker is predicted to occur, although this will be in the windiest period." (Page 95)

"Other solutions that have been suggested are that the turbine should be stopped at those hours when shadow flicker is likely to occur, or that blinds should be fitted. In one reported case the neighbours have been equipped with a switch to shut down the turbine if they are disturbed by shadow flicker." (page 95)

"Wind turbines close to habitations, eg. ten diameters distance should not be sited to the East or South East, or West or South West of habitations, unless the shadow path has been identified and does not fall on windows of habitations or occupied buildings." (Page 95)

"The minimum separation distance for wind turbines from habitations should be approximately 10 blade diameters. This is emerging from experience and research as a standard guideline, in order to reduce problems of visual impact, noise, shadow disturbance, and safety". (Page 95)

3.2.3 Wind Energy Handbook, Burton et al. (2001)

Synopsis

The Wind Energy Handbook presents a review of shadow flicker understanding at the time of publishing. This handbook states that shadow flicker frequencies between 2.5 and 20 Hertz (Hz) can cause nuisance, and restates the findings of Verkuijlen & Westra (1984) in relation to health effects relating to epilepsy.

Relevant text extracts

"Although considered to be an important issue in Europe, and recognized in the operation of traditional windmills (Verkuijlen and Westra, 1984) shadow flicker has not generally been recognized as significant in the USA (Gipe, 1995). (Page 527)

"The frequencies that can cause disturbance are between 2.5-20 Hz." (Page 527)

"In the case of shadow flicker the main concern is variations in light at frequencies of 2.5-3 Hz which have been shown to cause anomalous EEG (electroencephalogram) reactions in some sufferers from epilepsy. Higher frequencies (15-20 Hz) may even lead to epileptic convulsions. Of the general population, some 10 percent of all adults

and 15-30 percent of children are disturbed to some extent by light variations at these frequencies (Verkuijlen and Westra, 1984).” (Page 527)

“Large modern three-bladed wind turbines will rotate at under 35 r.p.m. giving blade-passing frequencies of less than 1.75 Hz, which is below the critical frequency of 2.5 Hz. A minimum spacing from the nearest turbines to a dwelling of 10 rotor diameters is recommended to reduce the duration of any nuisance due to light flicker (Taylor and Rand, 1991).” (Page 527)

3.2.4 Planning for Wind Energy in Dyfed, Taylor D. & Rand M. (1991)

Synopsis

Taylor & Rand (1991) presents details of a complaint arising in relation to shadow flicker effect in Cornwall (Cornwall County Council, 1989). Specific details relating to the origin and severity of the complaint, the dimensions of the wind turbines, and the proximity and direction of the affected receptor (etc.) were not included in the paper.

The authors of this study undertook extensive correspondence with Cornwall County Council, however it was not possible to source a copy of the original document ‘Planning Implications of Renewable Energy: Onshore Wind’.

The report concludes that at distances of greater than 10 rotor diameters between turbines and the habitation, shadow flicker effect can be reduced to relatively short periods of the year. In relation to the Cornwall case study, the short period is defined as 30 minutes a day for 10-14 weeks a year.

The paper also proposes two mitigation strategies – ‘blind installation’, and ‘turbine shut down’.

Relevant text extracts

“The effect seems to be confined to people inside buildings exposed to light from a narrow window source. The frequencies of flicker that cause disturbance, dizziness, and disorientation are between 2.5 and 40 Hertz (cycles per second). A frequency of 2.5-3 Hertz can trigger epileptic seizures in some 5% of those who are susceptible. It is estimated that about 2% of the population are susceptible to epileptic seizures.” (Page 91)

“Frequencies of flicker between 2.0 and 40 Hertz can produce disturbance. Most wind turbines produce a flicker frequency of around 1 and 6 Hertz and so are likely to induce flicker disturbance if their shadow falls on a building.” (Page 91)

“One study noted that rotor speeds of below 45 rpm for three bladed turbines and 70 rpm for two-bladed turbines should help ease the effect (Clarke, 1988).” (Page 91)

“One study in Cornwall has illustrated the effect of all these factors on the position and duration of the shadow (Cornwall County Council, 1989):

1) *The area affected forms a narrow zone on the north side of the wind turbine but elongated to the west and the east. The effect would be greater near the machines; further away the effect would be less acute and last for a shorter time.*
2) *In the direction north from the machine, the shadow would affect a building (10 metres wide) at a distance equivalent to one rotor diameter 8.5 hours a day for*

39 weeks per year; at 2 diameters 7.75 hours a day for 13 weeks; & at 3 diameters 6 hours a day for four weeks a year.”

3) *At a distance of 2 rotor diameters, in directions form south-west through north, to south-east, the shadow could affect a dwelling 2-7 hours a day for 13-26 weeks a year.*
4) *At a distance of 10 rotor diameters, again in directions from south-west, through north, to south-east, the shadow could affect a dwelling 30-45 minutes a day for 10-14 weeks a year.”* (Page 91)

“Wind turbines can cause shadow disturbance over a large area around a turbine, but the duration is likely to be limited. From the data presented above it is possible to deduce that the shadow effect can be reduced to relatively short periods of the year (30 minutes a day for 10-14 weeks a year) when spacings of 10 rotor diameters to the nearest habitation are employed.” (Page 91)

“2. The siting of wind turbines less than 10 rotor diameters from habitations should be discouraged due to the increased duration of shadow effects.” (Page 92)

“3. Should shadow disturbance generate problems then the following actions can be taken:

a) *The installation of blinds to the windows of the properties affected.*
b) *The shutting down of the wind turbine(s) during the relevant periods.”* (Page 92)

3.2.5 Harrassment by Periodic Shadow of Wind Turbines (English translation of abstract) (Belästigung durch periodischen Schattenwurf von Windenergieanlagen) Pohl et al. (1999).

Synopsis

This paper by the Institute of Psychology at Christian-Albrechts University of Kiel documents a laboratory experiment to record changes in indicators of performance, mental and physical well-being, cognitive processing and stress of the autonomic nervous system (heart rate, blood pressure, skin conductance and finger temperature) as a result of exposure to periodic shadows. The experiment was undertaken on male and female participant of varying ages. Shadows were simulated by using a system which could vary the light source and speed of shadow flicker. This was set up to simulate a shadow impact through a doorway between two laboratories, with the lighting equipment in one room and the participants in the connected room.

The study concludes that under the specific lighting conditions used in the laboratory tests, the shadow flicker effect did not constitute a significant harassment. However, the increased demands on mental and physical energy, indicated that cumulative long-term effects might cause a significant nuisance.

Relevant text extracts

Please note – this text is a translation and is not quoted verbatim. Some elements of the translation may not reflect the exact wording of the original documents.

The focus of the investigation was the question of whether periodic shadows, with a duration of more than 30 minutes from one-off performance would cause stress effects. (Page 1)

Two groups of different ages were studied, namely 32 students (average age 23 years) and 25 professionals (average age 47 years) who were each randomly assigned to two experimental conditions. In each condition was the same number of women. The experimental group (EG) received 60 minutes of periodic shadow with 80% lighting contrast. For the control group (CG) lighting conditions were the same as in the EG, but without periodic shadow. The main part of the investigation consisted of a series of six tests and measurement phases, of which two were before turning on the light, three were for a period of 20 minutes with the addition of lighting, and one phase after switching off the light. Among the variables collected included stress indicators of general performance (computing, visual search tasks), the mental and physical well-being, cognitive processing and stress of the autonomic nervous system (heart rate, blood pressure, skin conductance and finger temperature). (Page 1)

Students and professionals of the EC showed slower performance during the first 20 minutes of lighting. When the professionals were subjected to this phase there was a range of stress and performance effects, the physical condition was impaired and a greater cognitive engagement with the situation occurred. In the next 40 minutes there was compensation or even an increased performance compared to the CG. This compensating or over-compensating required additional energy due to increased physical effort, manifested in the EG students in a reduced finger temperature and in professionals in increased sweat gland activity. Younger subjects (students) compensated with other mental processes than older volunteers (professionals). The former appears to be able to shut out the stimulus and reduce the harassment, and were able to compensate even thought they were aware of the harassment. The older subjects also exhibited a stronger stress cognitive processing. The duration of stress was prolonged and there were after effects even after turning off the lights. The additional after effect that occurred in older subjects, resulted in a deterioration in their overall test performance. (Page 2)

The laboratory study showed that under specific conditions periodic shadow did not constitute a significant harassment. However, the documented increased demands on mental and physical energy, indicated that cumulative long-term effects might meet the criteria of a significant nuisance. (Page 2)

The results of this pilot study indicated that as a whole it would seem reasonable to conduct further studies with modified experimental conditions. These conditions could be various time patterns of the periodic shadow (random, intermittent, unpredictable) and the combination of periodic shadow and noise / noise (in particular, periodic noise) [It is not known whether these further studies have been carried out]. (Page 2)

3.2.6 Influences of the Opaqueness of the Atmosphere, the Extension of the Sun and the Rotor Blade Profile on the Shadow Impact of Wind Turbines (English translation of abstract) (Einflüsse der Lufttrübung, der Sonnenausdehnung und der Flügelform auf den Schattenwurf von Windenergieanlagen), Freund H-D. (2002)

Synopsis

This paper from the University of Applied Sciences at Kiel critically analyses existing geometrically calculated shadow flicker models. The paper concludes that the ambient environmental conditions that exist in reality – the finite extension of the sun; the trapezoidal structure of rotor blades; and the opaqueness of the atmosphere as a medium of radiation – reduce the shadow flicker effect of wind turbines. These inaccuracies in the modelling methodology, result in wind turbine operators facing unnecessary 'turbine shut-down' systems.

Relevant text extracts

Please note – this text is a translation and is not quoted verbatim. Some elements of the translation may not reflect the exact wording of the original documents.

> *"At present, shadow flicker periods are determined by purely geometrical models. This approach is questioned in the research project referred to in this article. The project investigates in detail the ambient conditions existing in reality. These are:*
> 1) *The finite extension of the sun*
> 2) *The trapezoidal structure of the rotor blades*
> 3) *The opaque atmosphere as a medium of radiation*
>
> *These physical parameters have a significant influence on the shadow flicker. One can see that the shadow flicker periods calculated geometrically cannot represent the worst-case periods as a matter of principle. For the distances in question, they are generally too large. For approx. 76% of the maximum range the geometric system error is 100% and gets even larger with increasing distance. Because of this system error, wind turbine operators are sometimes faced with costs for shut-off systems that are not really necessary. By using a new supplementary software in addition to the conventional computer programmes, such extra costs should be avoided."* (Page 43)

3.2.7 Wind Power Environmental Impact – Case Study of Wind Turbines Living Environment, Widing et al. (2005)

Synopsis

This paper prepared by the Centre for Wind Power Information at Gotland University presents case study information from residents living near the wind turbines in När, Klintehamn and Näsudden in Sweden. Operational experience presented suggests that 94% of persons in 69 households were not disturbed by shadow flicker effects.

The paper also indicates that it is more important on which day and in which season shadows occur, than how long the calculated/expected shadow time lasts.

In addition, a report by the Swedish Federal Housing Association (the Boverkets handbook 2003) suggests that shadow flicker duration should be assessed both on the plot of land around a house (the curtilage) as well as the façade (windows) of the property. The report states that there is a statistically significant correlation between shadow minutes per day on the façade of a property and the specified disturbance, whereas shadow minutes per day on the plot of land and disturbance are not related. However, shadow duration on the plot of land is likely, on average to be three times longer than on the façade, therefore the limits on a plot of land would need to be adjusted to make them reasonable.

Relevant text extracts

Please note – this text is a translation and is not quoted verbatim. Some elements of the translation may not reflect the exact wording of the original documents.

> *Three different wind areas on Gotland were selected for case studies: a) När; b) Klintehamn; and c) Näsudden. Only the people who live in close proximity to wind turbines have been interviewed. In När everyone living within 1100 metres from two large wind turbines, in Klintehamn a sample of those who live ESE of wind turbines*

and receiving shadows from the turbines when the sun goes down, and in Näsudden those households that are among the wind turbines on the peninsula. A total of 94 persons in 69 households were interviewed.

Of all respondents, 85 % are not disturbed by noise from wind turbines around them. In the case of shadows, the proportion who are not disrupted is even higher at 94 %.

Although none of the calculations of shadows on the facade for the respondents in Klintehamn yielded, in the worst case, more than 30 shadow hours per year and a maximum of 30 minutes per day, 24 % (of the respondents) stated that they get annoyed quite a lot or a lot by the shadows. The calculations for 17 % of the respondents in Näsudden gave 30 shadow hours per year (facade, worst case) but only 4 % were disturbed quite a lot or a lot of shadows.

In När nobody was bothered by shadows. One possible explanation why so many people are disturbed by the shadows in Klintehamn may be that the majority of the respondents live east-south-east of the power plant which, according to the calculations, results in the majority (approximately 90 % of respondents) having shadows in the evenings from April to September.

In Näsudden about half of the respondents get shadows in the evenings while the other half get the shadows in the morning or at midday. For those respondents who do not get disrupted even though the expected shadow time is long, shadows appear mainly in the morning or in winter. For those respondents who are disturbed despite the short estimated shadow time shadows occurring in the evenings. In När no respondent got shadows during summer evenings. This may indicate that it is more important on which day and in which season shadows occur, than how long the calculated/expected shadow time lasts.

In Näsudden there is no relationship what-so-ever between the estimated shadow time and the specified disturbance. However, there is a moderately-strong correlation between distance from the nearest wind turbine and stated disturbance due to shadows. This may indicate that the geometric calculation model for shadow time is not reliable when there is a large power plant that is situated far away from the current residence, as the shadow time of the power plant is included for long distances, although according to a German study the shade does not extend longer than about 1 km (Freund 2002).

Since according to the Boverkets handbook (the handbook of the "Federal Housing Agency") (Boverket 2003) a new guideline has been introduced, due to which the shadow time is calculated on the plot of land instead of on the windows, the shadow time in Klintehamn was calculated partly on land and partly on the facade. There is a statistically significant moderate correlation between shadow minutes / days on the facade and the specified disturbance. Whereas shadow minutes / days on the plot and disturbance are not related. Calculation of shadow time on the plot instead of on the facade give, on average, approximately three times longer shadow times. To introduce a new guideline that time shall be calculated on the plot/land without having adjusting the limit how long shadow time is acceptable is in this perspective not reasonable.

3.2.8 Wind Power: Renewable Energy for Home, Farm and Business, Gipe P. (2004)

Synopsis

The author of this book provides case study information on measured shadow flicker effect and experiences of local equestrians relating to operational wind farms. The author states that at an operational wind farm in Germany, research has shown that under worst –case conditions, shadow flicker would result in 100 minutes per year, however the effect in real life only equated to 20 minutes per year. Experience by an equestrian in North America, was that shadow flicker from an operational wind turbine startled horses but the shadows simply caused the horse to stop briefly until their riders urged them on.

Relevant text extracts

> *"Near Flensburg in Schleswig-Holstein, German researchers examined the effect and found that flicker, under worst-case conditions, would affect neighbouring residents a total of 100 minutes per year. Under normal circumstances the turbine in question would produce a flickering shadow only 20 minutes per year."* (Page 298)

> *"There are few recorded occurrences of concern about shadow flicker in North America. Ruth Gerath, however, notes that the flickering shadows from the turbines on Cameron Ridge near Tehachapi have startled her horse and those of others in the local equestrian club. Except for the flickering shadows, she says, the turbines seem to have no effect on the horses. The shadows simply cause the horses to stop briefly until their riders urge them on."* (Page 298)

4 COMPUTER MODELS

4.1 Introduction

As part of the development and planning process for a prospective wind farm, computer models are used by the developer in order to predict and quantify the impact shadow flicker may have on receptors within the vicinity of the prospective wind farm. The output of these models can be included in the environmental assessment of the wind farm.

There are three main computer packages which are used in the industry to model the phenomenon:

- WindFarm
- GH WindFarmer
- WindPRO

In addition to these packages, there was found to be two additional modelling tools available (add on packages to CAD and ArcGIS), however it is apparent that these tools have not been widely adopted by the industry.

4.2 Current Computer Models Used

WindFarm

The Shadow Flicker module of WindFarm is one of the most used in the industry. This software predicts the times throughout the year when shadow flicker is likely to occur and predicts a worst case scenario impact at the receptor/aperture where shadow flicker would be observed. A contour map and predicted shadow flicker times can be generated as outputs from this process.

The inputs to and outputs from the WindFarm model are summarised in Table 1 and Table 2 below.

Table 1: Inputs for WindFarm software.

Inputs
Receptor locations
Site Latitude and Longitude
Angle from grid north to true north
Wind farm layout and turbine specification
Time Zone (local regional time i.e. GMT)
Wind farm layout
Size of assessment area (specified in Metres, rotor diameters or tip height)
Maximum sun height
Earth's curvature

Table 2: Outputs from WindFarm software.

Output
Map Spatial Extent of Shadow Flicker
Time at which Shadow Flicker will occur

Garrad Hassan (GH) WindFarmer

The Shadow Flicker module of GH WindFarmer calculates the occurrence of shadow flicker impact time and intervals for receptors at given locations. In addition, a map of the spatial distribution of the impact of the shadow flicker can be generated. GH state (GH Website, accessed 2010) that the module allows the user to:

- Determine the accurate shadow flicker effect for a particular year
- Represent the turbine rotor as a sphere or as a disk
- Consider the offset and orientation between turbine rotor and tower
- Model the sun as a point or a disc
- Use the topography as alternative to the simplified flat terrain assumption
- Create maps of shadow flicker occurrence on an annual or daily basis
- Analyses the shadow flicker at specific receptor points, of given elevation and orientation
- Identify the shadow flicker periods from each turbine onto each receptor

The module can also be used in 'real-time' and in conjunction with a SCADA (Supervisory Control And Data Acquisition) system, where it can be used to switch of the turbine when the shadow impact would cause disturbance.

Inputs to and outputs from the model are summarised in Table 3 and Table 4 below:

Table 3: Inputs for WindFarmer software

Inputs
Site Latitude and Longitude
Time Zone
Maximum minutes per day (constraint)
Maximum hours per year
Calculation option (calculation to a defined distance from the centre of the project or from each turbine)
Minimum Elevation Angle of the Sun
Calculation time interval (temporal resolution of model)
Model sun as a disc (yes/no)
Height above ground for shadow flicker mapping
Terrain and Visibility (options include No calculation of visibility due to terrain, use terrain to calculate turbine visibility and use terrain to calculate turbine and sun visibility)

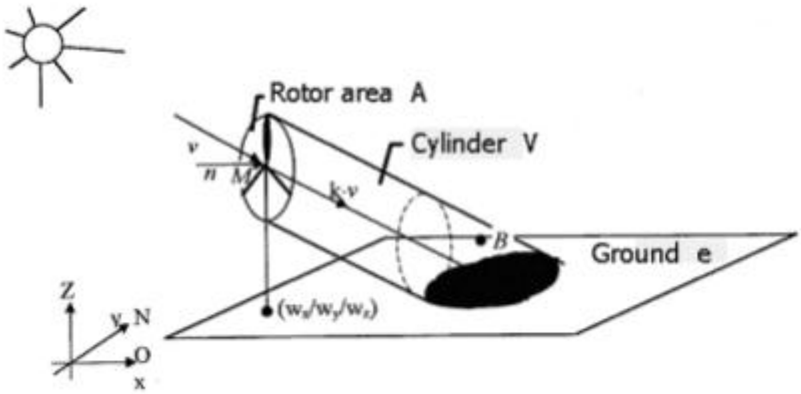
Table 4: Outputs from WindFarmer software

Output
Map of Spatial Extent of Shadow Flicker
Times at which SF is most likely to occur

WindPRO

The Shadow Flicker module (SHADOW) in WindPro calculates how often and in which intervals a specific neighbour or area will be affected by one or more wind turbines. The calculations are again 'worst case scenarios'.

The model calculates outputs using the following principles:



Source: WindPro tutorial, accessed 2010

Inputs to and outputs from the model are summarised in Table 5 and Table 6 below:

Table 5: Inputs for WindPro software

Inputs
The position of the WTGs (xyz coordinates)
Hub Height and rotor diameter
Position of the receptor (x,y,z, coordinates)
The size of the window and it's orientation, both directional(relative to south) and tilt (angle of wind pane to the horizontal)
Site Latitude and Longitude
Time Zone
A simulation model

Table 6: Outputs from WindPro software

Output	
Main Results	
Calendar for each shadow receptor	Timetable of sunrise and sunset for each day of the year in local time
	Table for when Shadow impact may occur for each day of the year, total hours of impact per day
	Number of turbines which may cause shadow impact
	Total hours of impact month by month
	Reductions due to sunshine and statistics of operational hours
Graphic calendar	
Calendar per wind turbine	
Calendar per wind turbine, graphical	

Map	

4.3 Discussion of Models

Inputs
The input parameters needed to run each of the models are essentially identical including Longitude and Latitude, Time Zone, wind turbine specification and topography. However, some differences can be observed in the entry of constraint and receptor inputs.

Defining Criteria
All of the models allow the modelling extent to be defined as either a spatial or temporal extent. These extents are set usually with reference to guidance or local planning authority advice. The spatial extent is usually defined with the wind turbine as the origin, though in WindFarmer it is possible to define the spatial extent from the centre of the project as it appears in the screen window. In addition, GL WindFarmer is the only computer model where the maximum length of time of exposure can be defined as a constraint.

Defining Receptors
The input of receptor parameters (e.g. location of receptor, size of window) slightly varies across the models and is a potential source of subjectivity and error in the output of the model since they are user defined. In addition, the way in which this data is input into the models varies. For example in WindFarm, window size, tilt and orientation are defined in the *Designer*, whereas in GH WindFarmer, location, orientation of the window, the height of the window can be defined, however the size of the window is assumed to be constant. This may lead to variations in the output of the model.

Defining sun angle
Sun angle is manually defined by the user and values are dependent on the terrain and aspect of the turbine. GH WindFarmer describe that for flat terrain a sun angle value of approximately 3° is appropriate, however for more undulating or mountainous terrain then it would be reasonable to increase the sun angle value because the terrain will have a sheltering effect on the receptors. All three models allow the sun angle variable to be defined by the user.

Digital Terrain Model Data
All packages allow the input of terrain data. The data needs to be clean of all anomalies and if possible ground truthed.

Worst Case Scenario
We have evidence to suggest that all of the models predict a 'worst case scenario' impact of the shadow on properties, as discussed already in other Sections of this report. It must be noted that this worst case scenario is not explicitly stated in the GL WindFarmer literature.

Assuming the turbine rotor as a disk
The impact of the shadow is intermittent and variable depending on the wind speed which can not be analysed in any of the software packages. The turbine rotor is assumed to be a disk which can not be penetrated by sunlight. Any shadow generated by this disc onto the receptor is classed as an impact.

Turbine Yaw Direction

It is assumed in all of the models that the rotor is yaw angle is set at 90° to the receptor to model maximum interference. In reality, the yaw of the turbine would vary with the wind direction, therefore the shadow impact would be variable.

Sunlight conditions
The sunlight conditions used in the software models are set up to result in a worst case scenario. The weather is always assumed to be sunny which would cause the greatest shadow effect. In reality sunlight intensity is dependent on factors including cloud cover and time of day.

Obstacles
All of the models allow the user to input terrain data although they do not take into account obstacles between the turbine and the receptor, for example, trees or buildings.

4.4 Applying the Computer Models

To compare these three models, Parsons Brinckerhoff has obtained versions of the software packages and has run the same scenario in each package. The results of this can be seen in Figure 2 to Figure 4 below.

An area in the Scottish Borders was chosen for the model as this area had diverse terrain, with a ridge to the north west of the turbine and undulating terrain elsewhere. A single turbine was placed in this landscape. The turbine model chosen was typical for modern onshore machines, with a 70m hub height and 80m rotor diameter. In each case, shadow flicker was calculated for a 2.5km radius around the turbine, thus far larger than the 10 rotor diameter rule. Shadow flicker receptors were added in a radial manner with an incremental spacing of 500m from the turbine as can be seen in the figures.

It should be noted that the shadow flicker calculation area can be defined in the software – 2.5 km was chosen as an indicative value so that the models could be compared with each other. The shadows are likely to be too diffuse at this distance to have an impact.

The contours used in the outputs from the model are spaced at 20 hrs/year, with the outer most (large blue) contour representing 0 – 20 flicker hrs/year. This was considered the most appropriate 'bin size' given the magnitude of flicker. Whilst it was not possible to match the contour colours between the models exactly, similar colours were chosen so that a visual comparison is possible.

It can be seen that the outputs from the three models are very similar, and whilst there are some differences at the edges of the model, the models show very similar results within 1 km from the turbine. Also, the shape of the shadow area is very similar where it interfaces with the terrain, especially to the west of the turbine.

There are differences between how Windfarm and Windpro calculate shadow start and end times. In Windfarm, the mapping data is entered in rectangular grid coordinates (for example bng grid in the UK). To calculate where on the surface of the planet the site is, (to calculate when the sun rises and sets), Latitude and Longitude coordinates need to be entered. In Wind Farm, there is an automatic conversion tool between most coordinate systems used across the world. This is used to calculate shadow times for the project which can be fed into shadow flicker timers for mitigation. In the Windfarmer 'control panel' it is also possible to set up the Latitude and Longitude values for this reason.

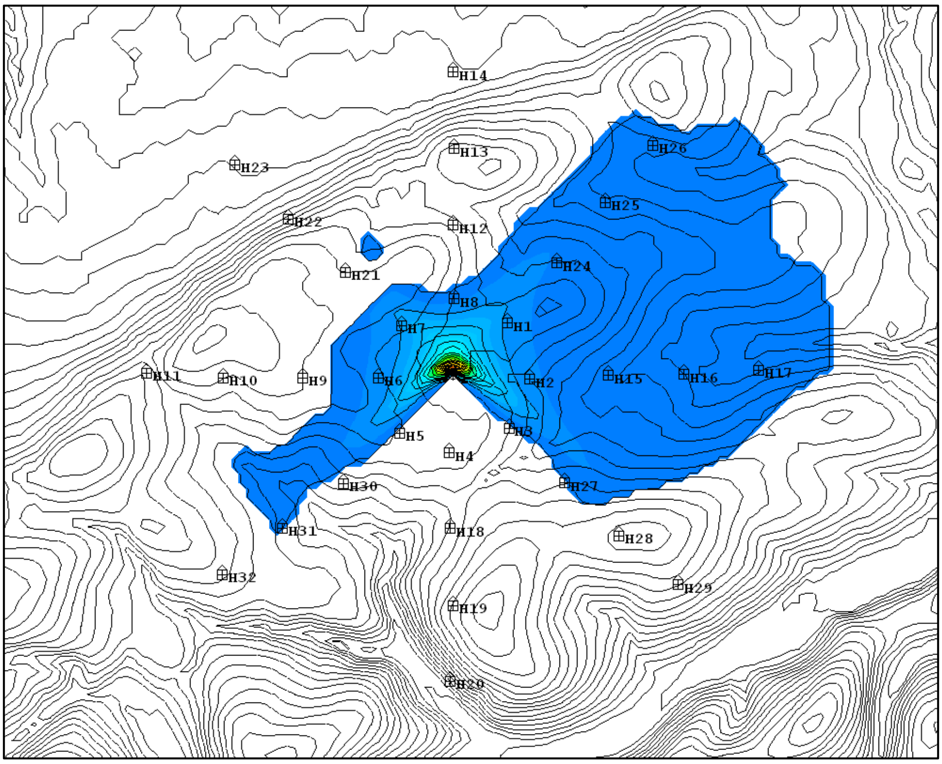


Figure 2: Output from Windfarm software

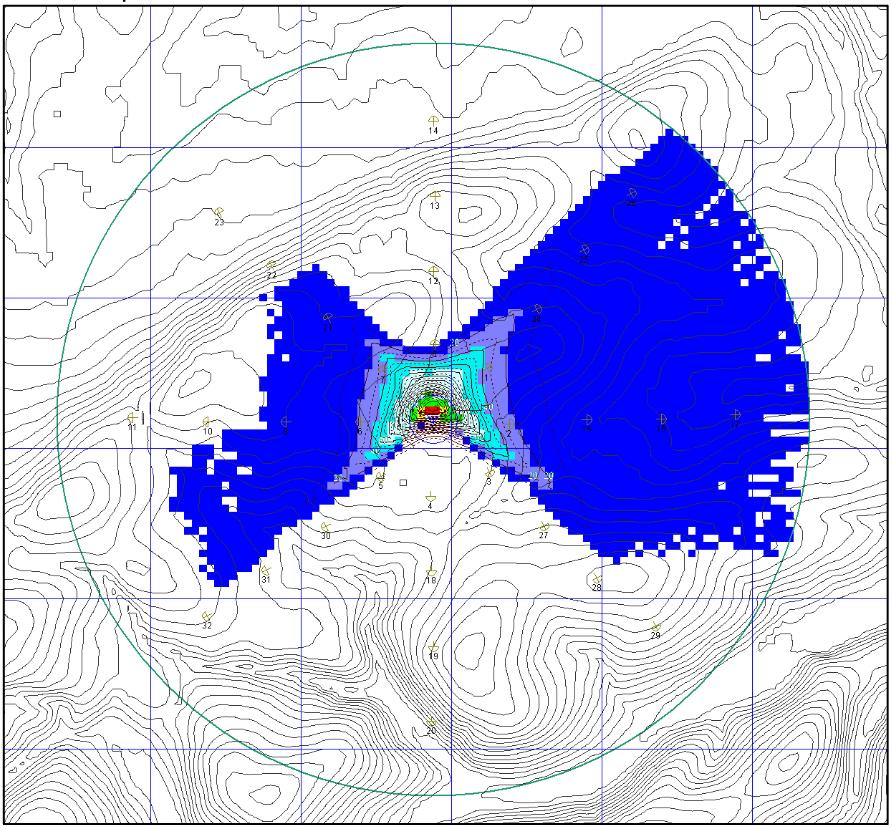


Figure 3: Output from WindFarmer software

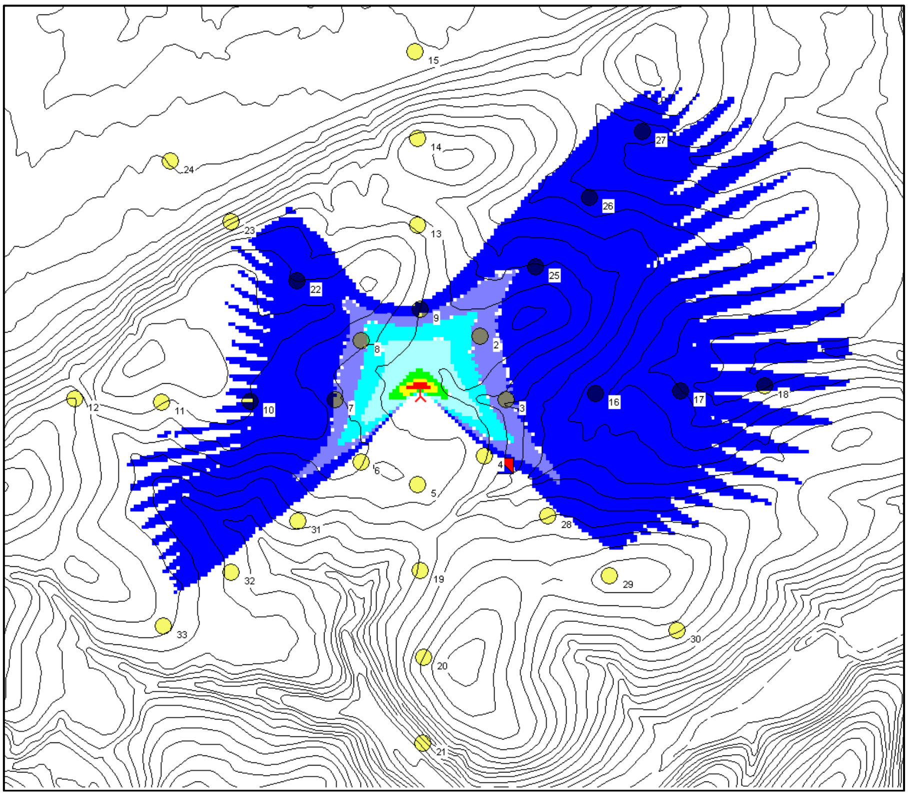


Figure 4: Output from WindPRO software

It appears that there are obvious similarities between each of the three models which have been reviewed, though it is difficult to quantify as the software vendors do not give details of the algorithms which are used to calculate the spatial and temporal extent of the flicker phenomenon.

4.5 Conclusions

This section has investigated the computer models available on the market. The three computer models investigated are similar in their approach to calculating shadow flicker around wind turbines. None of the software packages allow the input of real climatic parameters, and so can only be used to produce ‘worst case’ shadow flicker assessments.

For the purposes of demonstrating and comparing the outputs, the three computer systems were used to model simple scenario of a single wind turbine in a location in the Scottish Borders. The results from these models are displayed as contour plots which show very similar shadow flicker patterns close to the turbine with minor discrepancies between the models at distances further from the turbines.

5 STAKEHOLDER QUESTIONNAIRE SURVEY.

5.1 Introduction

In an effort to gauge the opinion of the wind energy industry on shadow flicker issues, questionnaires were distributed to industry stakeholders. Different questionnaires were produced, with one aimed at developers and consultants working in the industry and one aimed at local planning authorities (LPAs). There were four variants of this LPA questionnaire specific to planning authorities in England, Scotland Wales and Northern Ireland.

This section outlines the methods that PB employed to obtain data from these parties, and the resulting data which has been analysed to look for trends in data and parameters. This is not intended as original research but as a study into the extent of shadow flicker issues in the UK.

It must be acknowledged that the responses which are reported in this section are the viewpoint of the stakeholders consulted and thus may not be evidential based.

5.2 Methodology

The questionnaires were produced as a 'PDF form', which could be edited directly using standard adobe PDF reader software. The format allowed respondents to email the data back to PB using a dedicated email address. In case of technical issues with this method, PB provided several submission options and additionally provided contact details so that we could assist directly. This approach was developed to speed up the process, helping to ensure a high response rate, and for the environmental reason of reducing paper use.

Industry Questionnaire
The questionnaire can be found in the Appendices.

The specific aims of this questionnaire were:

- To determine the extent to which developers and consultants use the shadow flicker indicators in 'Companion Guide to Planning Policy Statement 22' (or relevant country guidance) to model shadow flicker, and to determine methodologies used to assess the occurrence of the phenomenon;
- To ascertain whether developers thought the planning guidance was sufficient for the assessment of shadow flicker, and their opinion on whether other approaches to setting guidance would be more appropriate; and,
- To improve understanding of shadow flicker impacts at operational wind farms, looking for case studies where shadow flicker was found to be causing an issue and to assess the effectiveness of current mitigation measures.

The industry questionnaire was sent out to 178 company members on the mailing list of the industry association RenewableUK. A reminder email was sent three days before the final submission deadline to help ensure the highest response rate possible. 14 responses were obtained and discussion of the results from this questionnaire can be found in the section below.

Local Planning Authority Questionnaire
The questionnaire was sent to all Local Planning Authorities and England, Wales, Scotland and Northern Ireland. Additionally, the Welsh Planning Division and the Clean Energy & Steel Production Department were invited to participate in the questionnaire. Although not

able to offer a response, staff at the Assembly Government did offer advice on relevant guidance documents and suggested key developers who should be contacted.

The specific aims of this questionnaire were:

- To determine the extent of LPAs knowledge of shadow flicker, and their opinions on 'Companion Guide to Planning Policy Statement 22' (or relevant country guidance) to model shadow flicker;
- To ascertain whether developers thought the planning guidance was sufficient for the assessment of shadow flicker, and their opinion on whether other approaches to setting guidance would be more appropriate; and,
- To improve understanding of shadow flicker impacts at operational wind farms, looking for case studies where shadow flicker was found to be causing an issue and to assess the effectiveness of current mitigation measures.

5.3 Industry Questionnaire - Response Summary

Fourteen questionnaire responses were received from developers and consultants working in the wind industry. Of these respondents, thirteen stated they have been involved in preparing shadow flicker assessments for onshore wind energy developments in the UK, five have presented evidence at public local inquiry and five are involved in 'Operation & Maintenance' of operational onshore wind farms.

Questions were split into the following four sections:

1) General assessment criteria – questions were designed to assess the degree of variance between assessment criteria methodologies for shadow flicker assessments in Environmental Statements.
2) Computer models – questions were designed to gauge the parameters that input into shadow flicker models.
3) Operational experience – collection of case study information on complaints relating to shadow flicker, operational experience in relation to mitigation measures, and anecdotal evidence of observed shadow flicker effects.
4) Current guidance – questions designed to gauge opinion on key elements of Companion Guide to PPS22 or other national guidance documents.

Please note - where a respondent has not provided comment, or stated that the question is not applicable to them, they have been excluded from the summary statistics.

General assessment criteria

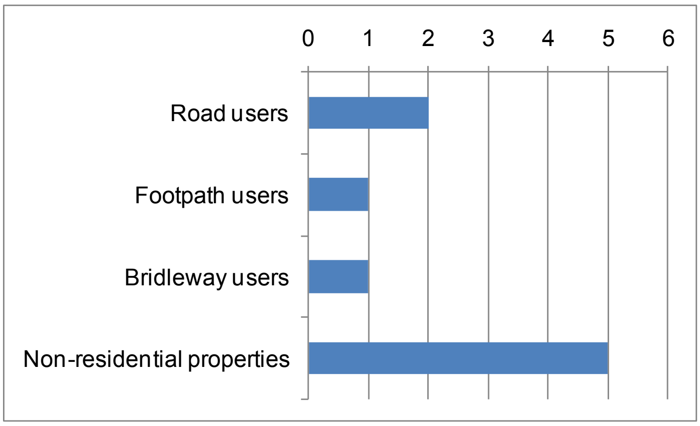
When determining the size of the assessment area, 10 out of 13 respondents adopt the 10 rotor diameter' rule. Other approaches that were adopted include:

- Using a combination of '10x rotor diameter' rule with a 2km fixed radius; and
- Assessing properties which lie just outside the '10 x rotor diameter' area.

10 out of 13 respondents only assess shadow flicker impact on users within residential properties, whilst 2 respondents assess the 'shadow flicker' impact on users both within residential properties and in the curtilage of properties. This report has is concerned only with that inside properties and through a constrained opening such as a window, however it is important that this point as part of the stakeholder responses.

Receptors that respondents include in shadow flicker assessments, are shown in Figure 5 below.

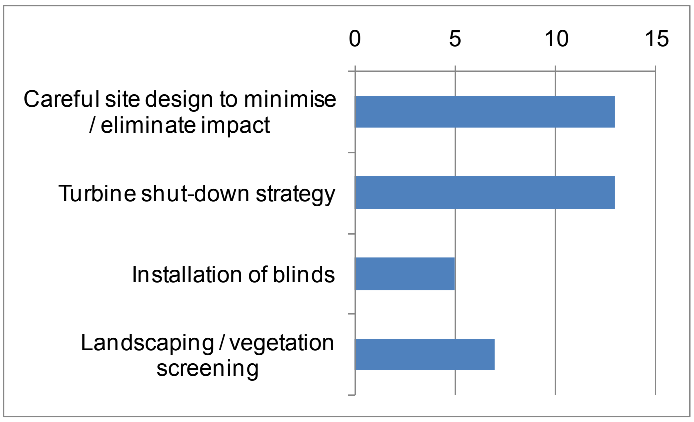
Figure 5: Results from Question 7: What receptors do you assess shadow flicker effects on?



It is clear from the responses that many developers and consultants assess shadow flicker impacts on non-residential properties, but it is not common to assess the impact of passing shadows on road, footpath, and bridleway users. Several respondents adapt their assessment methodology to meet the requirements of the LPA or specific requests from other stakeholders. Two respondents made it clear that shadow flicker is restricted to the interior of buildings.

A summary of questionnaire responses relating to various mitigation measures for shadow flicker impacts can be seen in Figure 6 below:

Figure 6: Results from Question 8: "When preparing a planning application, what mitigation strategies for predicted shadow flicker effects do you propose?"



All four mitigation options have been proposed by different respondents, with 'careful site design' and 'turbine shut down' ranking as the most popular.

Computer models

For the purposes of undertaking shadow flicker assessments, it is clear that three computer modelling software packages are used by all respondents – these programmes are WindFarm, Windfarmer, and WindPro. All three are discussed in greater detail in Section 4. With one exception, all respondents felt the respective software package was satisfactory for preparing shadow flicker assessments that are of an appropriate standard to support a planning application.

When undertaking shadow flicker assessments, 7 out of 13 respondents include field data or site-specific environmental data in their software models, while 6 out of 13 respondents do not include this data. The following comments were included elaborating on the data included in software models:

- Existing screening is taken into account;
- Topographical models (Digital Terrain Models) are included in the model;
- Location of residential properties are considered;
- Initial screening of properties by potential visibility using a Zone of Theoretical Visibility (ZTV) graphic;
- Turbine layout and dimensions;
- Wind rose information to provide idea of predominant wind direction;
- Orientation and size of receptor windows.

It is clear from the above responses that LPA's requirements for information input into software models varies, due to a lack a standard methodology for shadow flicker assessment.

The questions in this section asked respondents about whether their shadow flicker assessments adhere to the 'worst case scenario'. This was defined as:

- Continuous sunshine during daylight hours;
- Continually rotating turbine blades;
- No vegetation or other obstacles are screening the receptor;
- The wind turbine rotor plane is always perpendicular to the receptor and sun.

10 out of 12 respondents felt that their shadow flicker assessments adhered to worst case scenario criteria. Of the respondents that responded that their shadow flicker assessments did not adhere to the worst case scenario, the following comments were provided:

- Proportion of time that turbines were operational was taken into account;
- Both worst case and 'realistic' shadow flicker duration figures were considered;
- Sunshine data was included when preparing a 'realistic' shadow flicker duration figure.

Operational experience

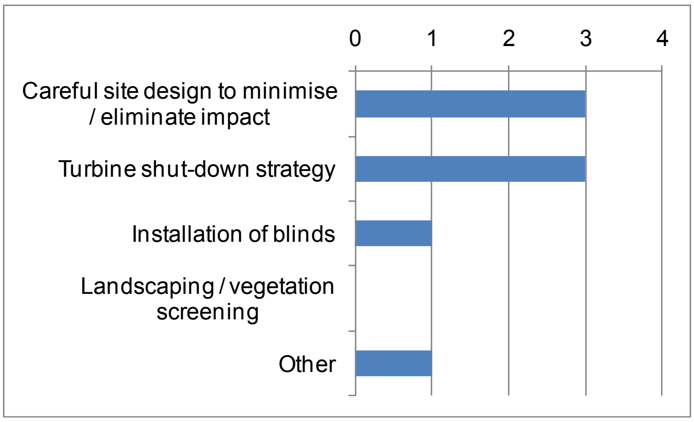
5 out of 12 respondents own or manage operational wind energy developments, of which 2 respondents were owners, four respondents were operators, and one respondent was involved in technical operations.

Three respondents noted complaints in relation to shadow flicker at their operational wind energy developments. Details of their comments are listed below.

- *A member of the landowners family has observed shadow flicker but this has not given rise to a complaint, as such no resolution was required or requested.*
- *Wind farm in flat, lowland location – complaints arose during commissioning and related to dwellings within '10 x rotor diameter' that were identified in the Environmental Statement as being potentially at risk. Sensor-triggered operational management and turbine shut-down has been implemented and is expected to resolve the situation.*
- *Complaint from a office building that was not built at the time of consent.* Please see case study information in section 5.5 below for more information.

Of the respondents who operate or manage wind energy developments, it was noted that careful site design and turbine shut-down strategies were the most popular implemented mitigation strategies, whilst installation of blinds also featured. Landscaping / vegetation screening did not feature. The results are shown in Figure 7 below.

Figure 7: Results from Question 8: What mitigation strategies for shadow flicker effects have been implemented on your operational wind energy developments?



The respondents who stated they had implemented both careful site design and turbine shut-down strategies noted that no complaints had been received and by virtue of this it could be assumed that the mitigation measures had been successful. One additional respondent stated that the turbine shut-down strategy had been ultimately successful – further case study details are provided in Section 5.5.

One respondent noted that contact details for Operation & Maintenance staff were provided to affected properties to implement turbine shut-down.

No respondents stated that they had observed shadow flicker effect occurring outside buildings or in other circumstances different from those set out in current guidance (which states "shadow flicker only occurs inside buildings where the flicker appears through a narrow window opening"). One respondent commented:

> *"Shadow flicker can only occur within properties through a restricted space. The effect through a narrow window opening is totally different to the effect out of doors where the high ambient light and diffuse shadow conditions cannot create the same level of disturbance."*

Current guidance

9 out of 13 respondents consider the '10 x rotor diameter' rule an appropriate area for shadow flicker assessments. Of the remaining respondents, most believed a combination of a fixed radius and the '10 x rotor diameter' rule would provide an appropriate alternative. One respondent provided a justification for adopting a fixed radius approach, commenting:

> *"In general for most of the UK the '10 x rotor diameter' rule is sufficient, however in higher latitudes where the sun is lower in the sky for longer, it might be appropriate to introduce a fixed radius. A study would be required to define this fixed radius as shadows become very diffuse further out and it is important not to define a radius which is too conservative."*

8 out of 12 respondents believed shadow flicker assessments should be limited to the interior of residential buildings. Of the four remaining respondents, one commented that an assessment of the impact on users of adjacent A roads and motorways is sometimes requested by the Highways Agency due to the potential for driver distraction, and three

respondents felt shadow flicker assessments should extend to non-residential properties. One respondent commented:

> *"High-occupancy non-residential buildings such as offices should be afforded similar protection to residential properties, within the context of the likely occupancy of the building at the time when shadow flicker is calculated to occur."*

There was a varied response to the value of adopting quantitative guidance on shadow flicker effects. The majority (8 out of 11 respondents) felt that quantitative guidance was inappropriate for the following reasons:

- Difficulties in quantifying acceptable levels of shadow flicker impact due to local environmental factors (eg. existing screening, cloud cover) and site specific details (eg. number of properties affected, number and nature of rooms affected, duration of effect, strength of shadowing, etc)
- Worst case scenario shadow flicker duration figures can be misinterpreted by the public as definitive impact; and
- Impacts should be assessed on a site by site basis.

The two overarching themes that emerge from this question on quantitative guidance are the difficulties in setting a level on acceptability of shadow flicker impact, and the potential for a development to be rejected where mitigation measures could provide a complete solution.

Further comments were welcomed at the end of the questionnaire. Several respondents took the opportunity to stress that shadow effects outside buildings should not be confused with shadow flicker, as the effect is much less severe. One respondent commented that there is a lack of case study data relating to shadow flicker impacts, and that an evidence base rather than limits and separation distances would be more useful. Other notable responses are included below:

> *"I think it would be a positive step to introduce some form of approach to methodology for assessing shadow flicker effects that would work in a similar way to ETSU and noise, that way it would give clarity to developers, planning authorities and communities alike that a clear and consistent framework was being worked within."*
>
> *"Guidance should be clear that shadow flicker can be accurately predicted. It should state that shadow flicker effects can be successfully mitigated and that mitigation can be successfully secured by way of a planning condition. In this respect shadow flicker issues should not be cited as a reason for refusal in a planning decision."*

5.4 Local Planning Authority (LPA) Questionnaire Responses.

Seventeen responses were received from the questionnaire that was sent to LPAs, of which ten were from councils in England, one from each of Wales and Northern Ireland and five from councils in Scotland. All of those councils who responded offer pre-planning advice to onshore wind energy developers, with the majority (13 out of 17) providing pre-planning advice specifically on shadow flicker. However, only seven of the councils offer guidance on how the shadow flicker impact could be assessed.

Please note - where a respondent has not provided comment, or stated that the question is not applicable to them, they have been excluded from the summary statistics.

Questions were split into the following four sections:

1) Current guidance – questions related to current UK guidance and are designed to gauge opinion on key elements of Companion Guide to PPS22, or relevant country specific guidance.
2) Best Practice Shadow Flicker Assessments – questions designed to assess the LPAs opinion on current shadow flicker assessment methodologies.
3) Proposed Mitigation Measures – questions on mitigation measures and planning conditions related to shadow flicker.
4) Operational experience – this section collected case study information on complaints relating to shadow flicker, operational experience in relation to mitigation measures, and anecdotal evidence of observed shadow flicker effects.

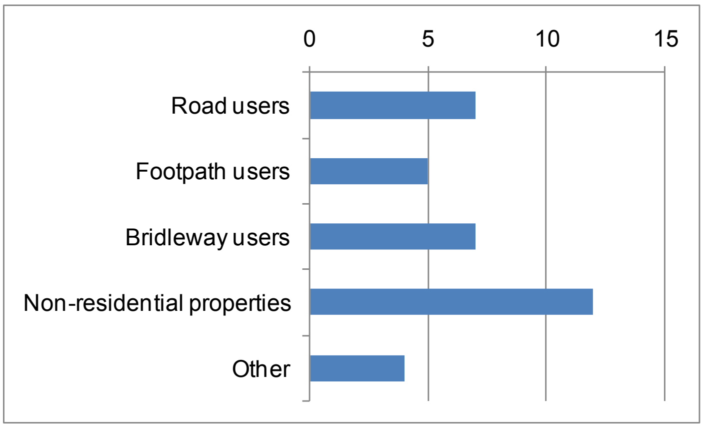
Current Guidance

This section looked at current guidance in the UK. There was general consensus among the respondents (13 out of 17) that the ten rotor diameter rule provided an appropriate area for shadow flicker assessment, with three councils having the opinion that this rule was not appropriate. Three councils had the opinion that using a combination of a fixed radius and the '10 x Rotor Diameter' would be a preferable approach, with four councils specifying alternative approaches.

Some useful comments were made on the subject of alternative approaches, especially that the assessment distance should take into account the height of turbines as well as rotor diameter, and that the 10 rotor diameter approach may not be appropriate with turbines sited on higher ground, as shadows may be thrown further. Additionally, a comment was made that the assessment distance should also be determined by the project latitude, solar elevation, height, rotational rate of turbines and cumulative impact of aligned turbines.

Although blade shadows passing across windows produce a different impact (shadow flicker) to shadows passing across open ground, a question was asked to determine opinion on whether outdoor impacts should be assessed. Four councils responded that assessment should be limited to inside buildings; with thirteen responding that the impact on other receptors should be assessed. Figure 8 shows the receptors that councils would like to see assessed.

Figure 8: Results from Question 7: If you don't think shadow flicker assessments should be limited to the interior of buildings, what receptors should be included?



Some useful comments were made on the reasons LPAs thought other receptors should be taken into account. Several comments were made that road user distraction and safety was important, with several also commenting on safety of horse riders on bridleways. There were several comments that shadow flicker has the ability to affect office / commercial workers and so it is important to assess these buildings in addition to residential buildings.

There was a generally positive attitude towards adopting quantitative guidance in the UK, although various concerns were raised about how this could be implemented in practice. Several respondents commented that having quantitative guidance would be simple to assess against. One respondent suggested that the guidance should not necessarily be carried out based on only the 'number of hours' but that also a secondary 'sensitivity' measure should be used based on the usage of affected buildings. An example of this is that early evening hours may be more valuable as 'family time' than other times of the day.

Best Practice Shadow Flicker Assessments
The four questions in this section asked respondents about whether shadow flicker assessments should adhere to the 'worst case scenario'. This was defined as

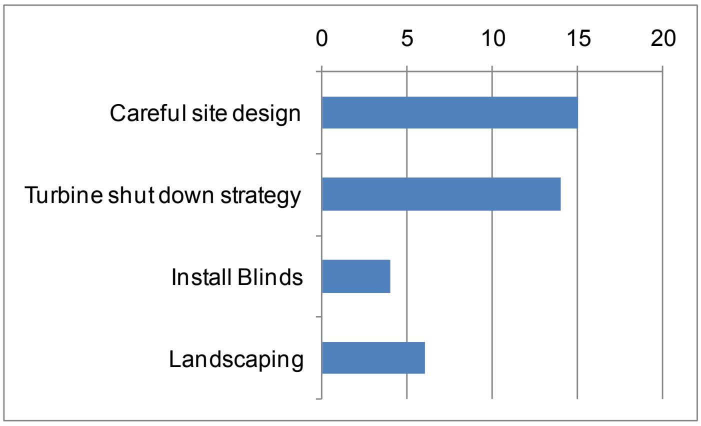
- Continuous sunshine during daylight hours;
- Continually rotating turbine blades;
- No vegetation or other obstacles are screening the receptor;
- The wind turbine rotor plane is always perpendicular to the receptor and sun.

Of the respondents, eleven had the opinion that assessments should adhere to this worst case model, with six not considering this to be suitable. Five comments were made that a likely / realistic shadow flicker assessment needs to be carried out alongside this worst case model. A concern was raised that any method used other than worse case would lead to assumptions being made that could be challenged in the planning process.

Twelve respondents thought that the addition of field data would aid the assessment process, with four not considering field data to be necessary. It was noted that the use of field data can aid an assessment by making it more realistic. It was also noted that site specific data should be included as it can help planners to make an informed decision on a development.

Proposed Mitigation Measures
Three questions were asked about mitigation measures used to limit shadow flicker from wind energy developments. Figure 9 below shows the strategies that councils consider to be appropriate when considering planning applications with potential shadow flicker issues.

Figure 9: Results from Question 15: When considering a planning application, what mitigation strategies for predicted shadow flicker effects do you consider appropriate?



It is clear that designing the development in such a way that shadow flicker does not occur is considered the most preferable option, with the implementation of a 'turbine shut down strategy' considered the next preferred option.

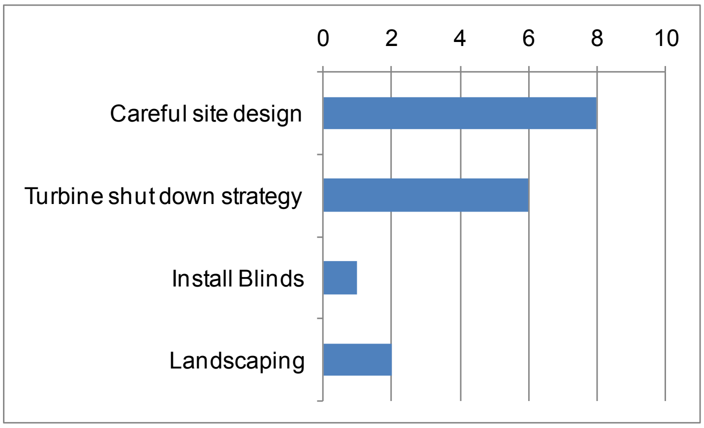
Of the councils questioned, nine have been involved with assigning a planning condition relating to shadow flicker, with eight not having assigned a planning condition related to shadow flicker. There was a range of planning conditions supplied by the councils, from the specific, (outlining the mitigation strategy to be used) to more general conditions (specifying that approved measures should be implemented should complaints be received).

Operational Experience

Of the councils who responded to the questionnaire, only one had received a complaint about a shadow flicker issue from an operational windfarm. In this case, business park workers complained of the shadow flicker effects. The issue was resolved by implementing a 'turbine shut down' protocol that acted when certain conditions of sun/alignment prevailed, or when a complaint was made from the office workers.

The mitigation strategies that have been implemented by the councils that responded are shown in Figure 10 below.

Figure 10: Results from Question 20: What mitigation strategies for shadow flicker effects have been implemented on operational wind energy developments within your planning area?



It can be seen that the most popular operational mitigation approach is to install shadow flicker timers using a turbine shut down strategy. For some of the councils, turbines have yet to be built, so it remains to be seen if the strategy has been a success, however a comment was made that this approach was successful in that no complaints had been received. It was also noted that the use of blinds and planting as mitigation approaches are considered less acceptable as they are harder to enforce, may not necessarily work and planting may not establish.

Additional Comments

A final comments box was provided for respondents to provide any additional information on shadow flicker. Whilst the majority of councils did not use this, two useful comments were raised, which reflect their experiences with the phenomenon.

The first comment was regarding the occurrence of shadow flicker, and that as it is only an issue on bright days, the occasions when it is likely to present a real problem to people in buildings nearby are likely to be few. Members of the public are often poorly informed and will assume shadow flicker to be a problem.

Another comment from one LPA was that shadow flicker has not been a major issue of concern to wind energy objectors. The visually intrusive nature of large scale proposals is the most common concern.

5.5 Operational Wind Farm Case Study

A case study has been taken from the questionnaire responses. For this wind farm, PB received information from both the developer and the Local Planning Authority involved in the development. This wind farm in Scotland has been left unnamed for reasons of confidentiality.

Complaint

Complaints were received from office users in a nearby business park, of flicker effects causing annoyance and triggering headaches. Environmental Health Officers from the local council investigated and concluded that there were adverse impacts as a result of the shadow flicker from the nearby turbines.

The office building was not in place at the time of wind farm consent or turbine installation, and was therefore not included in the shadow flicker assessment for the Environmental Statement. The first two wind turbines in the development were operational when the buildings on the site were developed for business uses. As personnel moved into the buildings, complaints were lodged over the shadow flicker effect, which especially occurred in the afternoon when the sun was from the west/ north west. Flicker became a major issue when a subsequent extension (four turbines) to the wind farm was developed and built. Both phases of development have turbines which are within ten rotor diameters of the office building.

Mitigation measures

Two mitigation measures were implemented – turbine shut-down using control modules on certain turbines that were causing the shadow flicker effect, and installation of blinds in the affected offices.

The turbine shut down strategy was deemed to have been relatively successful, although due to controller errors with the clock timer there were instances where the turbine was not shutting down at the correct times. An additional measure was implemented which allowed the complainant to contact ‘Operation & Maintenance’ staff who could remotely shut-off the turbines.

Result

The complainant was satisfied with the developer’s mitigation actions and stated that their concerns had been alleviated. Both the developer and Local Planning Authority considered that the issue had been resolved by the mitigation measures implemented.

6 RESULTS ANALYSIS

A number of themes have arisen during the course of the guidance and literature review that warrant further discussion. This section separates out individual overarching themes and provides a summary of variations and common understanding between national guidance and academic literature. The key themes that are discussed in greater detail below are as follows:

- Section 6.1 - Assessment area – geometrics of study area
- Section 6.2 - Assessment area – radius of study area
- Section 6.3 - Quantitative guidance
- Section 6.4 - Shadow flicker in offices
- Section 6.5 - Indoor assessment versus outdoor assessment
- Section 6.6 - Proposed mitigation
- Section 6.7 - Health effects - epilepsy
- Section 6.8 - Health effects and nuisance
- Section 6.9 - Environmental and site-specific factors
- Section 6.10 - Planning conditions

The authors also note that during the literature searches, no regulatory policy relating to shadow flicker was found; in all countries where it is a perceived issue, shadow flicker falls under the remit of best-practice guidelines.

It is clear from our literature searches that much of the academic research on the subject of shadow flicker was carried out in the 1980s and 1990s. Since then, turbines have got larger with lower blade rotational frequencies, so some of the results may not be directly applicable to modern turbines found on the market today.

6.1 Assessment area – geometrics of study area

England's Companion Guide to PPS22 (2004) and BERR (2007), and Northern Ireland's Best Practice Guidance to PPS18 (2009) state that only properties within 130 degrees either side of north of a particular turbine can be affected by shadows. Verkuijlen & Westra (1984) confirm this assertion, stating that particularly large areas to the east-northeast and west-northwest of the turbine experience shadows for long periods of time. Both German guidance (2002) and Verkuijlen & Westra (1984) provide figures demonstrating the azimuth extent of the shadow flicker zone.

The concept of limiting the assessment to within 130 degrees either side of north is not contested (nor are any alternative assessment methodologies proposed) in any guidance documents or academic literature.

6.2 Assessment area – radius of study area and 10 x rotor diameter

England's Companion Guide to PPS22 (2004) and BERR (2007) state that shadow flicker only occurs within '10 x rotor diameters' of a turbine. Northern Ireland's Best Practice Guidance to PPS18 (2009) is not as explicit in this regard, stating instead that the potential for shadow flicker at distances greater than ten rotor diameters is very low. Similarly Scotland's PAN 45 (2002) guidance refers to the '10 rotor diameter' as a general rule and infers that outside this area shadow flicker should not be problematic. The Irish Planning Guidelines (undated) state that at distances greater than '10 x rotor diameter', the potential for shadow flicker is very low.

Based on case study evidence from an operational wind farm, Cornwall County Council (1989) concluded that for properties at a distance of 2 rotor diameters, maximum shadow duration is calculated as 2 – 7 hours per day for 13 – 26 weeks per year. For properties at a distance of 10 rotor diameters, maximum shadow duration is calculated as 30 – 45 minutes per day for 10-14 weeks per year. Clarke (1991) and Taylor & Rand (1991) recommend that turbines should be sited at least ten diameters distance from habitation, and Clarke (1991) states that greater separation may be necessary if properties are sited to the east - southeast or west – southwest.

Other international guidance documents adopt a fixed radius. The Danish Wind Industry Association website (2010) suggests that at distances greater than 500-1000 m from a wind turbine, the rotor will not appear to be 'chopping' the light, but the turbine will be regarded as an object with the sun behind it, and it is therefore not necessary to consider shadow casting at such distances. The South Australian Planning Bulletin (2002) notes that shadow flicker is unlikely to be a significant issue at distances greater than 500 m.

The majority of industry respondents who completed the questionnaire as part of this study both used the '10 x rotor diameter' rule when preparing a shadow flicker assessment, and considered it an appropriate survey distance. Of particular note is the potential need for a differentiation between impacts at different latitudes, as the sun is lower in the sky for longer at higher latitudes, an assertion that is supported by an LPA respondent.

Similarly to industry responses, there was general consensus among LPA respondents that the '10 x rotor diameter' rule was an appropriate assessment area.

It is worth noting the Danish Wind Energy Association website comments that the hub height of a wind turbine is of minor importance in determining the shadows cast from the rotor. The same shadow will be spread over a larger area resulting in a reduced intensity of shadow in the vicinity of the turbine.

6.3 Quantitative guidance

England's Companion Guide to PPS22 (2004), Northern Ireland's Best Practice Guidance to PPS18 (2009), and Scotland's PAN45 (2002) (among others) require shadow flicker impacts to be quantified by the assessor, however only Northern Ireland's Best Practice Guidance to PPS18 (2009) and Irish Planning Guidelines (undated) set quantitative limits for acceptable duration at 30 hours per year or 30 minutes per day at neighbouring offices and dwellings. In addition, Predac (2004) recommends that shadow flicker should not exceed an astronomic worst case figure of 30 hours per year or 30 minutes per day at neighbouring offices and dwellings, however there is considerable variation between the limits set in Germany, Denmark, and the Netherlands.

German guidance (2002) adopts two maximum limits:

- An astronomic worst case scenario limit of 30 hours per year or 30 minutes on the worst affect day; and
- A realistic scenario taking account of meteorological parameters limited to 8 hours per year.

Gipe (1995) states that operational experience from the Untied States suggests shadow flicker has generally not been recognised as a significant issue. In addition, a survey by Widing et al. (2005) of residents in Swedish towns near an operational wind farm concludes that respondents who claim not to be impacted by shadow flicker were exposed to the phenomenon mainly in the morning or in winter. Contrastingly, those who do experience shadow flicker are mainly exposed in the evenings (Widing et al., 2005).

The majority of respondents to the industry questionnaire expressed concerns that quantifying acceptable levels of shadow flicker duration would be problematic due to latitudinal variations of impact, and the potential for wind energy developments to be rejected where, in reality, mitigation measures could provide a complete solution. Conversely to the developer's response, LPAs were generally in favour of adopting quantitative guidelines, although concerns were raised about the practicalities of implementation, in particular the need to characterize the sensitivity of receptors in order to determine appropriate levels of shadow flicker. It is thought that LPAs favour a quantitative solution as it is straightforward to assess when developments are taken through the planning process.

6.4 Shadow flicker in offices

Several guidance documents recommend that in addition to residential properties, shadow flicker impacts at offices neighbouring a wind energy development should also be assessed. Northern Ireland's Best Practice Guidance to PPS18 (2009), Predac (2004), and Irish Planning Guidelines (undated) all state that shadow flicker impacts should not exceed 30 hours per year or 30 minutes per day at neighbouring offices, with Irish Planning Guidelines (undated) limiting the survey area to within a 500m fixed-radius. Of the literature review carried out, no academic references to assessing shadow flicker in offices were found.

The shadow flicker case study (*Section 5.5*) received from our consultation was a complaint at an office premises, that was developed after the wind farm was built. In this situation, it was decided that no level of shadow flicker was acceptable, and shadow flicker timers were installed to shut down the turbines that caused the issue. This successful mitigation strategy solved the shadow flicker problem in this instance.

6.5 Shadow flicker – indoor assessment versus outdoor assessment

England's Companion Guide to PPS22 (2004), Northern Ireland's Best Practice Guidance to PPS18 (2009), and Scotland's PAN45 (2002) state categorically that shadow flicker impacts are limited to the interior of buildings. This assertion is also supported by Western United States guidance (2005), and Taylor & Rand (1991) who state that shadow flicker effect is confined to people inside buildings exposed to light from a narrow window source. Clarke (1991) claims that shadow flicker effect is pronounced in rooms facing the turbine especially if the window is the sole source of light.

German guidance (2002), however, suggests that shadow flicker assessments may need to be extended to outdoor locations, suggesting a reference height of 2m above ground level. Widing et al. (2005) state that a recent Federal Housing Agency document entitled Boverket (2003) recommends that shadow flicker should be assessed both on the façade of a building (eg. indoors), as well as on the plot of land (eg. the curtilage of the property). Widing et al. (2005) raise concerns that appropriate shadow flicker duration limits for interior and exterior locations would need to be adopted.

No industry respondents to the questionnaire have observed shadow flicker occurring outside buildings or in circumstances different from those set out in Companion Guide to PPS22. The majority of developers and consultants only assess shadow flicker impacts on users within residential properties, with two also assessing the impact on users within the curtilage of a property. It is also clear from the questionnaire, that developers and consultants are receptive to assessing non-residential properties, but have reservations (albeit with a few exceptions) about assessing road, footpath and bridleway users. One issue that was raised repeatedly by developers and consultants is the need to distinguish between the shadow flicker phenomenon that occurs inside a property through constrained openings, and an entirely different phenomenon, referred to as passing shadows in outdoor locations.

A number of LPA respondents (14) would like to see shadow assessments extended to cover users other than those inside residential buildings. Conversely to the industry responses, LPAs considered that the assessment should include road and bridleway users for safety reasons, as well as users of offices and commercial premises.

Canadian guidance (2006) states that farm animals and horses adapt to shadow flicker impacts within a brief acclimatization period. Gipe (2004) suggests that experience in North America has shown that shadow flicker may cause a horse to stop briefly until the rider urges them on.

6.6 Proposed mitigations

A summary of recommended mitigation measures from UK and international guidance documents is included in Table 7 below.

Table 7: Summary of mitigation measures in International guidance.

	Careful site design	Turbine shut-down	Installation of blinds	Landscaping / vegetation screening
United Kingdom guidance				
England	Yes			
Northern Ireland	Yes	Yes		
Wales	Yes	Yes	Yes	Yes
International guidance				
Ireland	Yes	Yes		Yes
Germany		Yes		
United States	Yes			Yes
Canada		Yes		
Non-governmental organisation guidance				
International Finance Corporation	Yes			

It is clear that the most commonly recommended mitigation measures in guidance are careful site design to minimise and where possible eliminate potential impacts, and implementation of a turbine shut-down strategy if necessary. Introduction of screening of wind turbines by landscaping and vegetation planting also feature strongly among recommendations, however installation of blinds in affected properties is exclusively advised by the Welsh guidelines (2010).

Verkuijlen & Westra (1984) state that in order to reduce shadow flicker effect, siting of new turbines is an important consideration. Verkuijlen & Westra (1984) also propose that in the Netherlands where the predominant wind direction is southwesterly (the same predominant wind direction as the UK), siting to the south of buildings would be a good compromise between maximising wind resource and minimising shadow flicker impact. Additional mitigation measures proposed by Verkuijlen & Westra (1984), Clarke (1991), and Taylor & Rand (1991) include installation of blinds and turbine shut-down strategies.

Of the questionnaire responses received from both industry and LPAs, the clear preference for mitigation options proposed at the pre-consent stage is careful site design, and implementation of a turbine shut-down strategy if required. Other mitigation measures that feature relatively strongly are introduction of screening through landscaping / vegetation planting, and installation of blinds. It was noted from the LPA questionnaire that installation of blinds and landscaping / vegetation screening are less acceptable as mitigation measures as they are harder to enforce and may not necessarily work.

The respondents who stated they had implemented both careful site design and turbine shut-down strategies noted that no complaints had been received and by virtue of this it could be assumed that the mitigation measures had been successful. In the case study (*Section 5.5*) relating to a complaint at an office premises, a dual approach was implemented involving a turbine shut-down strategy with radiation sensors and a direct shut-down request system between the complainant and Operation & Maintenance staff at the wind farm.

Freund (2002) notes that inaccuracies in shadow flicker modelling methodologies may result in wind turbine operators facing unnecessary turbine shut-down systems. It is important that a refined methodology is used to determine the necessity for turbine shut-down to ensure mitigation strategies are proportionate to the potential impact.

6.7 Health effects - epilepsy

UK advice relating shadow flicker to health effects vary in their finer detail but essentially suggest that approximately 0.5% of the UK's population suffers from epilepsy, and of these between 3.5% (BERR,2007) and 5% (Companion Guide to PPS22, 2004) are photo-sensitive. Less than 5% of photo-sensitive epileptics are sensitive to the lowest frequencies of 2.5 – 3 Hz (Companion Guide to PPS22, 2004; and Verkuijlen & Westra, 1984), although the remainder are sensitive to higher frequencies extending up to 30 Hz (BERR 2007). Verkuijlen & Westra (1984) state that higher frequencies of 15-20 Hz may also cause convulsions in some epileptics (Ginsburg, 1970).

Canadian guidance (2006) notes that shadow flicker can lead to inducing epilepsy in susceptible individuals, however the study team is not aware of any recorded incidents of this actually occurring. This statement is also supported by Verkuijlen & Westra (1984).

BERR (2007) also states that most commercial wind turbines in the UK rotate much more slowly than this, at between 0.3 and 1.0 Hz. Clarke (1991) distinguishes between single speed turbines with shadow frequencies of 1-3 Hz and variable speed turbines which may produce shadows of 2-6 Hz.

Parsons Brinckerhoff - Note to reader on turbine frequencies
Frequency of shadow flicker is related to the rotational speed of a wind turbine's blades and the number of blades. Commercial scale wind turbines being deployed on developments across the UK tend to have three blades. The rotational speed of a turbine depends on the generator technology used within the nacelle. Older turbine models used asynchronous generators which were essentially '**fixed speed**'. Modern turbines tend to use a generation technology that allows a limited degree of change in rotational speed – '**variable speed**'. Many of the major manufacturers are now developing '**direct drive**' wind turbines which can have a much larger range of speeds to optimise the energy that can be captured. Due to technical constraints, larger turbines tend to rotate slower than smaller turbines.

6.8 Health effects and nuisance

Several guidance documents – BERR (2007), Western United States (2005), Canada (2006) -make a distinction between health effects related to epileptic seizures and impacts on residential amenity.

Burton et al. (2001) note that of the general population, some 10% of adults and 15-30% of children are disturbed to some extent by light variations at frequencies of 15-20 Hz. The range of nuisance frequencies in most people who were tested is between 5 and 14 Hz (Collins & Hopkinson, 1957; Schreuder, 1964), and below 2.5 Hz and above 40 Hz, hardly any nuisance is caused. A typical wind turbine rotation frequency is 0.3 – 1Hz (BERR, 2007).

Psychology research by Pohl et al. (1999) into the impact of shadow flicker on indicators of performance, mental and physical well-being, cognitive processing and stress of the autonomic nervous system, demonstrates that shadow flicker effect does not constitute a significant harassment. However, under specific conditions the increased demands on mental and physical energy indicated that cumulative long term effects might meet the criteria of a significant nuisance. In this study, shadows were simulated using an lighting system set up to produce a similar effect to wind turbine blades.

6.9 Environmental and site-specific factors

As a general rule, most best practice guidance documents suggest that an astronomic worst case scenario is adopted when preparing shadow flicker assessments, and that no environmental and site-specific factors are built into the modelling stage.

However, there are exceptions to this rule, with several guidance documents suggesting that ameliorating factors should be taken into account during the modelling stage. Gipe (2004) provides evidence from Germany that shadow flicker duration under a worst case calculation would be 100 minutes per year, but under normal circumstances, the turbine only produces 20 minutes per year.

BERR (2007) (now DECC) states that the following factors should be considered in shadow flicker assessments:

- Window widths;
- Uses of the affected rooms;
- Intervening topography; and
- Intervening vegetation.

Best Practice Guidance for the Irish Wind Energy Industry (2008) also advocates that it is reasonable to include ambient environmental conditions such as wind direction and general climatic data in shadow flicker models. Furthermore, Predac (2004) notes that Danish guidance takes into account 'average cloud cover'. German guidance (2002) stipulates that sun angles less than 3 degrees above the horizon should be removed from the analysis due to the likelihood that vegetation and buildings will remove the shadow impact. In addition, Clarke (1991) comments that the number of sunny hours is likely to be lower in October through to early February although this will likely be the windiest period.

German guidance (2002) proposes a methodology for undertaking a realistic shadow flicker assessment taking into account meteorological information such as luminosity.

There are obvious difficulties when introducing meteorological conditions into shadow flicker modelling. In particular, there would be a need to establish a clear set of guidelines detailing an assessment methodology and suitable data sources.

From the industry questionnaire, the vast majority of developers and consultants carry out assessments that adhere to the worst case scenario. A number of developers currently carry out realistic assessments. The industry questionnaire also revealed that when undertaking shadow flicker assessments, over half of the respondents introduced environmental data into their software models. It is clear from the questionnaire however that there is no consistent approach to developer methodologies. Environmental and site specific parameters that developers introduce include:

- Existing screening.
- Intervening topography
- Window widths;
- Wind direction;
- Orientation and size of the affected window;
- Uses of the affected rooms.

Of the LPA respondents, a significant majority considered that shadow flicker assessments based on the worst case scenario criteria are appropriate, with several commenting that a realistic assessment should also be carried out. A significant majority of LPA respondents also felt that introduction of field data would aid the assessment by making it more realistic and helping planners to make an informed decision.

6.10 Planning conditions

BERR (2007) proposes the following planning condition where shadow flicker may have a potentially significant impact:

> *"The operation of the turbines shall take place in accordance with the approved shadow flicker mitigation protocol unless the Local Planning Authority gives its prior written consent to any variation."*

German guidance also makes reference to adopting a planning condition for installation of automatic turbine shut-down timers.

Over half of the LPA respondents to the questionnaire have been involved with assigning a planning condition relating to shadow flicker. The wording of planning condition vary considerably, with some planning conditions providing prescriptive requirements for shadow flicker mitigation strategies, whilst others are more general and lack detail. This could be due to project specifics and the requirements of individual LPAs. Example planning conditions provided by LPAs during the questionnaire process are included below:

> *"At the request of the occupant of the affected property, any turbine producing shadow flicker at any occupied dwelling which existed at the time that this permission was granted shall be shut down and the blades remain stationary until the conditions causing those shadow flicker effects have passed. The development shall be carried out in accordance with the approved details."*

> *"The wind turbines hereby approved shall not begin operation until a scheme for the avoidance of any shadow flicker effect for dwellings within 10 rotor diameters of any turbine in the development has been submitted in writing to and approved by the Local Planning Authority. The approved scheme shall be implemented as approved."*

7 CONCLUSIONS

This report has looked at the issue of shadow flicker from wind turbines, and presents data from a literature review, survey of international guidance and the results of a questionnaire sent to industry stakeholders.

The extent of the impact that shadow flicker causes is given in a psychology study (Pohl, 1999). This study concludes that the shadow flicker effect did not constitute a significant harassment. However, under specific conditions the increased demands on mental and physical energy, indicated that cumulative long-term effects might meet the criteria of a significant nuisance. This demonstrates the need to reduce the impact where possible.

A key finding of this study is that in the UK there have not been extensive issues with shadow flicker, and the results of a questionnaire survey to the industry and planning authorities has yielded few complaints. In these cases, shadow flicker issues were resolved using turbine shut down systems which are the standard mitigation approach adopted across Europe.

Current guidance to assess shadow flicker in the Companion Guide to PPS22 (2004) states that impacts occur within 130 degrees either side of north from a turbine. This has been found to be an acceptable metric. Additionally, the 10 rotor diameter rule has been widely accepted across different European countries, and is deemed to be an appropriate assessment area, although there is potentially a need to differentiate between appropriate assessment areas at different latitudes. This is an area where the scientific evidence base could be readdressed.

Across Europe and further afield, different countries have varying guidance on shadow flicker assessment. In all countries investigated where shadow flicker is a perceived issue, it falls under the remit of ‘best practice’ guidelines rather than regulatory policy. Some countries have adopted quantitative guidance, with limits on the flicker that can result from a development. During our consultation with the wind industry and LPAs, concerns were raised about the practicalities of implementing such a system in the UK.

Mitigation measures adopted by developers have been successful. Careful site design to eliminate shadow impacts is important, with mitigation measures such as turbine shut down systems being used regularly. These systems are acceptable for all parties, and by virtue of their success, the issue of shadow flicker appears to be minor. Mitigation measures are often put into planning conditions.

It is clear that there is no standard methodology that all developers adopt when carrying out shadow flicker assessments, and different developers and local authorities have different ways of approaching the assessment. Developers tend to use a ‘worst case’ assessment, with some developers using environmental or site specific factors to produce a ‘realistic’ case. Whilst the industry software that we reviewed can only be used to carry out worst case shadow flicker assessments, there is perhaps a need to address worst-case and realistic shadow flicker in assessments.

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9 APPENDICES

Appendix 1	Case study demonstrating Shadow Flicker Assessment – Taken from Notes on the Identification and Evaluation of the Optical Emissions of Wind Turbines, States Committee for Pollution Control – Nordrhein-Westfalen (2002)
Appendix 2	Industry Questionnaire
Appendix 3	LPA Questionnaire (England)
Appendix 4	LPA Questionnaire (Scotland)
Appendix 5	LPA Questionnaire (Wales)
Appendix 6	LPA Questionnaire (Northern Ireland)

Appendix 1

Case study demonstrating Shadow Flicker Assessment – Taken from Notes on the Identification and Evaluation of the Optical Emissions of Wind Turbines, States Committee for Pollution Control – Nordrhein-Westfalen (2002)

This literature document from Germany (detailed in Section 3) provides an example case study demonstrating how shadow flicker should be calculated.

To calculate the actual duration of shading, meteorological information needs to be taken into account. The first parameter taken into account is luminosity – see Table 8 and Table 9 for luminosity data from the German weather service.

Table 8: Data from the German Weather Service (taken directly from paper)

Sun [°]	Illuminance [lx]	Radiation Equivalent [lx/Wm^{-2}]
3	389	62
60	10.912	105

Table 9: A linear interpolation of the above metrological data. (taken directly from paper)

Sun [°]	Illuminance [lx]
3	389
5	664
10	1402
15	2207
20	3071
25	3986
30	4942
35	5929
40	6935
45	7949
50	8959
55	9951
60	10912

Day length is then calculated by using representative sunrise and sunset data for different locations across Germany and during different months of the year – see Table 10.

Table 10: Day lengths for different locations and months of year (taken directly from paper)

	Berlin	Essen	Hanover	Karlsruhe	Munchen	Schleswig	Schwerin
01-Jan	8:17; 16:03	8:37; 16:34	8:32; 16:18	8:21; 16:40	8:04; 16:31	8:44; 16:07	8:32; 16:05
01-Apr	5:41; 18:41	6:08; 19:07	5:56; 18:56	6:04; 18:59	5:52; 18:44	5:54; 18:58	5:48; 18:50
01-Jul	3:48; 20:32	4:20; 20:52	4:03; 20:47	4:26; 20:34	4:18; 20:17	3:51; 21:00	3:49; 20:47
01-Oct	6:07; 17:44	6:33; 18:10	6:22; 17:59	6:26; 18:06	6:13; 17:53	6:24; 17:58	6:16; 17:51

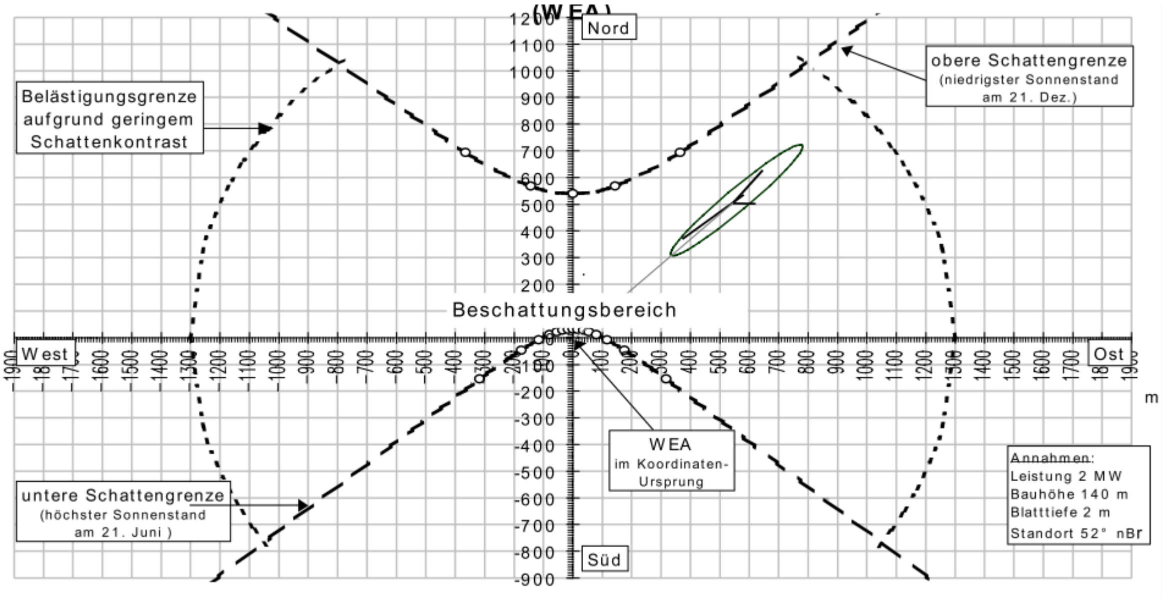
The shadow flicker study area is then calculated using variables such as hub height and rotor diameter of the turbine. The following table and figure have been produced for sample data with a turbine located in flat terrain in central Germany. The receptor is 2m above ground level and has an area of 0.1 x 0.1 m^2. Table 11 below summarises the parameters and results of the sample study.

Table 11: Summary of parameters and results for the sample study. (taken directly from paper)

ID No.	Hub height [m]	Rotor diameter [m]	Azimuth from north to east [°]	Distance between Turbine and receptor [m]	Hours / year	Days / year	Minutes / day
1	60	40	0°	150	90	124	60
2			40°	300	25	62	32
3			120°	450	15	49	22
4	90	60	0°	250	83	111	56
5			40°	400	28	61	36
6			120°	650	14	46	22
7	100	80	0°	300	98	108	62
8			40°	500	37	76	38
9			120°	750	20	54	26

Figure 11 shows the potential shading area of a large wind turbine. The dashed lines to the north represent the shadow limit on 21st December and the south dashed line represents the shadow limit on 21st June. The dotted lines to the east and west show the limit of impact due to shadow contrast. It can be seen that the shading region is symmetrical due to the path of the sun.

Figure 11: Possible shading area of a large wind turbine



APPENDIX 2

APPENDIX 3

APPENDIX 4

APPENDIX 5

APPENDIX 6

Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered

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The *Community Noise and Health Study* conducted by Health Canada included randomly selected participants aged 18–79 yrs (606 males, 632 females, response rate 78.9%), living between 0.25 and 11.22 km from operational wind turbines. Annoyance to wind turbine noise (WTN) and other features, including shadow flicker (SF) was assessed. The current analysis reports on the degree to which estimating high annoyance to wind turbine shadow flicker (HA_{WTSF}) was improved when variables known to be related to WTN exposure were also considered. As SF exposure increased [calculated as maximum minutes per day (SF_m)], HA_{WTSF} increased from 3.8% at $0 \leq SF_m < 10$ to 21.1% at $SF_m \geq 30$, $p < 0.0001$. For each unit increase in SF_m the odds ratio was 2.02 [95% confidence interval: (1.68,2.43)]. Stepwise regression models for HA_{WTSF} had a predictive strength of up to 53% with 10% attributed to SF_m. Variables associated with HA_{WTSF} included, but were not limited to, annoyance to other wind turbine-related features, concern for physical safety, and noise sensitivity. Reported dizziness was also retained in the final model at $p = 0.0581$. Study findings add to the growing science base in this area and may be helpful in identifying factors associated with community reactions to SF exposure from wind turbines. [http://dx.doi.org/10.1121/1.4942403]

[JFL] Pages: 1480–1492

I. INTRODUCTION

There are a growing number of studies that have assessed community annoyance to wind turbine noise (WTN) exposure using modeled WTN levels and/or proximity to wind turbines (WTs) (Pedersen and Persson Waye, 2004, 2007; Pedersen *et al.*, 2007; Pedersen *et al.*, 2009; Pedersen, 2011; Verheijen *et al.*, 2011; Pawlaczyk-Łuszczyńska *et al.*, 2014; Tachibana *et al.*, 2014). Adding to these findings are the results from the Health Canada *Community Noise and Health Study* (CNHS) where it was found that the prevalence of self-reported high annoyance to several WT features, including noise, vibrations, visual impact, blinking lights, and shadow flicker (SF) increased with increasing exposure to modeled outdoor A-weighted WTN levels (Michaud *et al.*, 2016b).

This suggests that in addition to providing an estimate of WTN annoyance, modeled WTN levels could also be used to estimate annoyance from other WT-related variables. Although there is a benefit to using WTN to estimate multiple community reactions, the advantages of a more parsimonious exposure assessment may not necessarily be the best approach for estimating annoyance responses that are based on visual

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perception. These reactions may be estimated with more accuracy with an exposure model that estimates the visual exposure that is presumably causing annoyance. In this regard, there was an opportunity in the CNHS to investigate the prevalence of high annoyance to wind turbine shadow flicker (HA_{WTSF}) using a commercially available model for SF exposure.

WT SF is a phenomenon that occurs when rotating blades from a WT cast periodic shadows on adjacent land or properties [Bolton, 2007; Department of Energy and Climate Change (DECC), 2011; Saidur *et al*., 2011]. The occurrence of SF is determined by a specific set of variables that include the hub height of the turbine, its rotor diameter and blade width, the position of the Sun, and varying weather patterns, such as wind direction, wind speed, and cloud cover [Harding *et al*., 2008; Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH), 2012; Katsaprakakis, 2012]. As the onset of shadow flickering will only occur when the WT blades are in motion, it will always be associated with at least some level of WTN emissions. When studying the effects of SF, it is therefore important to also consider personal and situational variables that have been assessed in relation to WTN annoyance. These include, but are not limited to, noise sensitivity, concern for physical safety, reported health effects, property ownership, presence of WTs on property, type of dwelling, personal benefit, etc. (Michaud *et al*., 2016a). Unlike annoyance reactions, conceptually, "*concern for physical safety*" from having WTs in the area was not considered to necessarily be a response to operational WTs. Rather, this is more likely to reflect an attitudinal variable that could exert an influence on the response to SF. This would align with the research that has repeatedly demonstrated that "*fear of the source*," but not its associated noise, has been found to have an influence on noise annoyance (Fields, 1993).

The current analysis follows the approach presented by Michaud *et al*. (2016a). Two multiple regression models are provided for HA_{WTSF}. The first model is *unrestricted*, with variables retained in the model based solely on their statistical strength of association with HA_{WTSF}. In contrast, the second model can be viewed as *restricted*, insofar as variables that are *reactions* to WT operations are not considered. The rationale for two models is that while the unrestricted model reports on all of the variables that were found to be most strongly associated with HA_{WTSF} in the current study, the restricted model may yield information that could be used to identify annoyance mitigation measures and other methods of accounting for HA_{WTSF}, over and above reducing SF exposure levels.

II. METHODS

A. Sample design

1. Target population, sample size and sampling frame strategy

A detailed description of the study design and methodology, the target population, final sample size, and allocation of participants, as well as the strategy used to develop the sampling frame has been described by Michaud *et al*. (2013) and Michaud *et al*. (2016b). Briefly, the study locations were drawn from areas in southwestern Ontario (ON) and Prince Edward Island (PEI) having a relatively high density of dwellings within the vicinity of WTs. Preference was also given to areas that shared similar features (i.e., rural/semirural, flat terrain, and free of significant/regular aircraft exposure that could confound the response to WTN). There were 2004 potential dwellings identified from the ON and PEI sampling regions which included a total of 315 and 84 WTs, respectively. The WT electrical power outputs ranged between 660 kW and 3 MW, with hub heights that were predominantly 80 m. To optimize the statistical power[1] of the study in order to detect an association between WTN and health effects, all identified dwellings within 600 m from a WT were sampled, as occupants in these dwellings would be exposed to the highest WTN levels. Dwellings at further distances were randomly selected up to 11.22 km from a WT. This distance was selected in response to public consultation, and to ensure that exposure-response assessments would include participants unexposed to WTN. The target population consisted of adults aged 18 to 79 yrs.

This study was approved by the Health Canada and Public Health Agency of Canada Review Ethics Board (Protocol Nos. 2012-0065 and 2012-0072).

B. Data collection

1. Questionnaire content and administration

A detailed description of the questionnaire content, pilot testing, administration, and the approaches used to increase participation have been described in detail by Michaud *et al*. (2016b), Michaud *et al*. (2013), and Feder *et al*. (2015). Briefly, the questionnaire instrument included modules on basic demographics, noise and shadow annoyance, health effects (e.g., tinnitus, migraines, dizziness), quality of life, sleep quality, perceived stress, lifestyle behaviours, and chronic diseases.

Data were collected by Statistics Canada who communicated all aspects of the study as the CNHS. This was an attempt to mask the study's true intent, which was to assess the community response to WTs. This approach is commonly used to avoid a disproportionate contribution from any group that may have distinct views toward the study subject. Sixteen (16) interviewers collected study data through in-person interviews between May and September 2013 in southwestern ON and PEI. Once a roster of all adults aged 18 to 79 yrs living in the dwelling was compiled, a computerized method was used to randomly select one adult from each household. No substitution was permitted under any circumstances.

2. Defining percent highly annoyed by SF exposure

As part of the household interview, participants were asked if they could see WTs from anywhere on their property. Participants that indicated they could see WTs were then asked to rate their magnitude of annoyance with "*shadows or flickers of light*" (hereafter referred to as SF annoyance) from WTs by selecting one of the following categories: "*not at all*," "*slightly*," "*moderately*," "*very*," or "*extremely*." Consistent with the approach recommended in ISO/TS-15666 (2003), the top two categories were collapsed to create a "*highly annoyed*" group (i.e., HA_{WTSF}). This group was compared to a group defined as "*not highly annoyed*" which consisted of all other categories, including those who did not see WTs. The same approach was taken for defining the percentage highly annoyed by WTN (Michaud *et al*., 2016a).

C. Modeling WT SF

SF exposure was calculated for all dwellings with WindPro v. 2.9 software (EMD International®, 2013a,b). The model estimated SF exposure from all possible visible WTs from a particular dwelling. WindPro sets the maximum default distance that is used to create this exposure area to be 2 km from a WT, based on available German nationwide requirements (German Federal Ministry of Justice, 2011; EMD International®, 2013a,b). Beyond this distance, the model assumes that shadow exposure will dissipate before reaching dwellings. At 2 km an object must be at least 17.5 m wide to be able to fully cover the Sun's disk and thus cause a maximum variation in light intensity. As WT blades are much narrower, the sunlight will only be partially blocked and the variation in light intensity will be considerably decreased. Other calculation parameters were set for the astronomical maximum shadow durations (i.e., worst case) including: solar elevation angles greater than 3° above the horizon; no clouds; constant WT operation; and rotor and dwelling facade perpendicular to the rays of the Sun (German Federal Ministry of Justice, 2011). Base maps set within the appropriate UTM grid zones for the studied areas were fitted with local height contours and land cover data for forested areas (Natural Resources Canada, 2016). Average tree heights for the most common tree species were estimated for both provinces (Gaudet and Profitt, 1958; Peng, 1999; Sharma and Parton, 2007; Schneider and Pautler, 2009; Ontario Ministry of Natural Resources, 2014) as vegetation can block the line of sight of a turbine and thus may reduce SF exposure [Massachusetts Department of Environmental Protection (MassDEP) and Massachusetts Department of Public Health (MDPH), 2012; EMD International®, 2013a,b]. The model calculates SF exposure at the dwelling window, which factors in window dimensions, window height above ground, and window distance from room floor for all dwellings. In the current study, the WindPro default window dimension ($1\,m \times 1\,m$) and distance from the bottom of the window to the room floor (1 m) were considered to be representative of the dwellings in the CNHS. With regards to dwelling height, the default value in WindPro is 1.5 m from the ground; however, in order to be consistent with modeled WTN and standard practice in Canada (ONMOE, 2008; Keith *et al*., 2016), a dwelling height of 4 m was chosen. The "*greenhouse*" mode for SF exposure calculation was used, which considers that the dwelling window can be affected by SF from all possible directions by all WTs within the line of sight of a dwelling. As a result, the calculations provided worst-case SF exposure for all dwelling windows from each facade.

As mentioned above, SF occurs together with noise emissions. Therefore, WTN levels considered in this analysis are based on the calculations presented by Keith *et al*. (2016).

D. Model uncertainties

There are some limitations associated with the current available SF calculation models, which may have an influence on the analysis of the study responses. With regards to this particular model, there are uncertainties regarding the specific distance from a WT where SF ceases to be visible, when the worst-case scenario method is employed (EMD International, 2013a,b). However, when applying Weber's Law of Just Noticeable Difference (Ross, 1997) to the turbines in this study, the distance at which the shadow flickering ceases to be noticeable falls within the 2 km exposure range, which is in line with the software default parameters. Even the combined uncertainty of ± 55 m that is associated with using GPS to estimate the location of the dwellings and the location of the WTs in the study (Keith *et al*., 2016), is not likely to have a large impact on SF exposure near the WindPro 2 km default exposure limit. The impact of this uncertainty increases with decreasing distance between the dwelling and WT (Fig. 1). This is especially the case in the North to South orientation relative to the WT (e.g., dwelling H, Fig. 1). In a worst case scenario, due to the nature of SF exposure, at close distances to the WT it is possible that dwellings could be misclassified as having no exposure when they may in fact receive high levels of SF exposure or vice-versa (e.g., dwelling E, Fig. 1).

Shadow areas as well as turbine and dwelling points were plotted using WindPro v. 3.0 (EMD International®, 2015) and Global Mapper v.14 (Blue Marble Geographics®, 2012). These plots indicate that approximately 10% of the dwellings included in the analysis are at risk of being misclassified with regards to their respective SF exposure groups (Sec. II E).

E. Statistical analysis

The analysis for categorical outcomes follows very closely the description as outlined in Michaud *et al*. (2013). SF exposure groups were delineated in the following manner:

- in hours per year (SF_h): (i) $0 \le SF_h < 10$, (ii) $10 \le SF_h < 30$, and (iii) $SF_h \ge 30$;
- in days per year (SF_d): (i) $0 \le SF_d < 15$, (ii) $15 \le SF_d < 45$, and (iii) $SF_d \ge 45$;
- in maximum minutes per day (SF_m): (i) $0 \le SF_m < 10$, (ii) $10 \le SF_m < 20$, (iii) $20 \le SF_m < 30$, and (iv) $SF_m \ge 30$.

The Cochran-Mantel-Haenszel (CMH) chi-square test was used to detect associations between sample characteristics and SF exposure groups while controlling for province. As a first step to develop the best predictive model, univariate logistic regression models for HA_{WTSF} were fitted, with SF_m categories as the exposure of interest, adjusted for province and a predictor of interest. It should be emphasized that potential predictors considered in the univariate analysis have been previously demonstrated to be related to the modeled endpoint and/or considered by the authors to conceptually have a potential association with the modeled endpoint. In the absence of other possibly important predictors, the interpretation

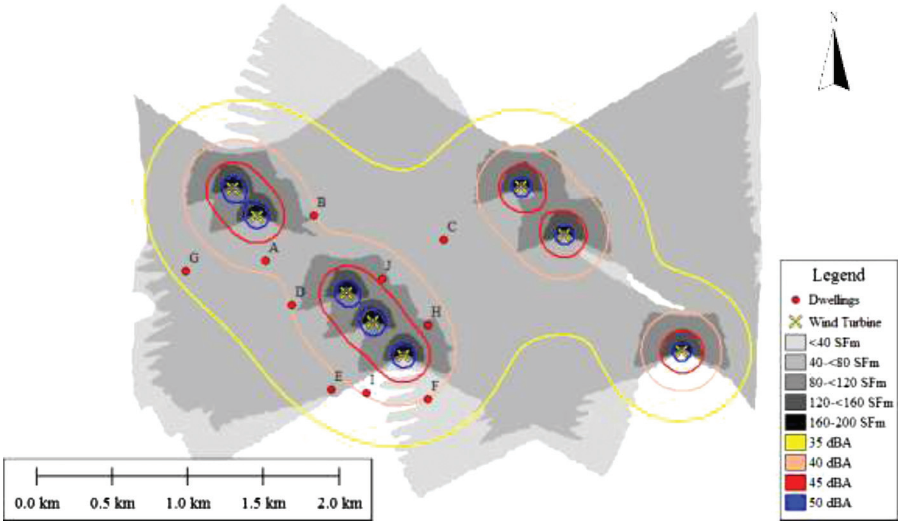

FIG. 1. A theoretical illustration of co-exposure to modeled WT SF and WTN levels. This figure presents a simulation of SF and noise exposure generated by eight WTs on flat terrain, with shadow coverage and WTN level contours described by the sequential color palettes in the legend box. The particular shape of the shadow coverage is created as the Sun moves behind the turbines throughout the day, generating a bowtie-shaped coverage area that is due to longer shadows at sunrise and sunset and shorter shadows at mid-day. In an actual WT park, dwellings are exposed to the combination of SF exposure from multiple turbines, as illustrated in this figure. As can be seen in the case of dwelling I, it is theoretically possible for a dwelling to be located relatively close to a WT, where WTN levels exceed 40 dBA, but outside the SF exposure area. For this demonstration, calculations were carried out with WindPro 3.0 (EMD International®, 2015) and projected with Global Mapper v.14 (Blue Marble Geographics®, 2012). WindPro 3.0 is used here in order to simultaneously present both WTN levels and shadow exposure. Shadow exposure is quantified in SF_m, while WTN noise levels are expressed in A-weighted decibels (dBA).

of any individual relationship in the univariate analysis must be made with caution as it may be tenuous.

The unrestricted and restricted multiple logistic regression models for HA_{WTSF} were developed using stepwise regression with a 20% significance entry criterion for predictors (based upon univariate analyses) and a 10% significance criterion to remain in the model. The stepwise regression was carried out in three different ways: (1) the base model included exposure to SF_m categories and province; (2) the base model included exposure to SF_m categories, province, and an adjustment for participants who reported receiving personal benefit from having WTs in the area; and (3) the base model included exposure to SF_m categories and province, conditioned on those who reported receiving no personal benefit. In all models, SF_m categories were treated as a continuous variable. The unrestricted model aimed to identify variables that have the strongest overall association with HA_{WTSF}. In the restricted model, the variables not considered for entry were those that were subjective responses to WT operations, such as high annoyances to visual, blinking lights, noise, vibrations, the World Health Organization (WHO) domain score, as well as the two standalone WHO questions (Quality of Life and Satisfaction with Health) and the perceived stress scale (PSS) scores.

Exact tests were used in cases when cell frequencies were <5 in the contingency tables or logistic regression models (Stokes *et al.*, 2000; Agresti, 2002). All models were adjusted for provincial differences. Province was initially assessed as an effect modifier. Since the interaction between modeled SF exposure and province was never statistically significant, province was treated as a confounder in all of the regression models. The Nagelkerke pseudo R^2 and Hosmer-Lemeshow (H-L) p-value are reported for all logistic regression models. The Nagelkerke pseudo R^2 indicates how useful the explanatory variables are in predicting the response variable. When the p-value from the H-L goodness of fit test is >0.05, it indicates a good fit.

Statistical analysis was performed using Statistical Analysis System (SAS) version 9.2 (2014). A 5% statistical significance level was implemented throughout unless otherwise stated. In addition, Bonferroni corrections were made to account for all pairwise comparisons to ensure that the overall Type I (false positive) error rate was less than 0.05.

III. RESULTS

A. Response rates, WT SF and WTN levels at dwellings

Of the 2004 potential dwellings, 1570 were valid dwellings[2] and 1238 individuals agreed to participate in the study (606 males, 632 females). This produced a final response rate of 78.9%. Table I presents information about the study population by the SF_m categories, as this exposure parameter was found to be the most strongly associated with HA_{WTSF} when compared to shadow exposure in hours per year (SF_h) and total shadow days per year (SF_d) (see Sec. III B). The majority of respondents were located in the two lowest SF exposure groups, i.e., $0 \leq SF_m < 10$ ($n = 654$, 53.0%) and $10 \leq SF_m < 20$ ($n = 233$, 18.9%), and the least number of respondents ($n = 161$, 13.1%) were situated in areas where $SF_m \geq 30$. Employment ($p = 0.0186$), household annual income ($p = 0.0002$), and ownership of property in PEI ($p < 0.0001$) were significantly related to SF categories (Table I). Participants receiving personal benefits from having WTs on their properties were not equally distributed between SF categories ($p < 0.0001$) with the greatest proportion of these participants situated in areas with $SF_m \geq 20$. Self-reported prevalence of health effects such as migraines/

TABLE I. Sample characteristics by SF exposure.

Variable	$0 \leq SF_m < 10$	$10 \leq SF_m < 20$	$20 \leq SF_m < 30$	$SF_m \geq 30$	Overall	CMH p-value[a]
	Shadow flicker exposure (SF_m)					
n	657[b]	234[b]	185[b]	162[b]	1238[b]	
SF_h min–max[c]	0–4.5	1.67–24.10	6.07–62.65	15.05–136.67		
SF_d min–max[d]	0–62	14–133	28–228	39–242		
Distance between dwellings and nearest WT (km) min–max	0.40–11.22	0.44–1.46	0.33–1.18	0.25–0.84		
Distance between dwellings and nearest WT (km) 50th, 95th percentiles	1.38, 8.54	1.02, 1.38	0.81, 1.05	0.60, 0.78		
WTN level (dB) min–max	<25–43	29–43	32–45	35–46		
WTN level (dB) 50th, 95th percentiles	33, 41	36, 41	38, 42	40, 45		
Do not see WT n (%)	133 (20.3)	11 (4.7)	3 (1.6)	2 (1.2)	149 (12.1)	
Highly annoyed to WTSF[e] n (%)	25 (3.8)	12 (5.2)	25 (13.5)	34 (21.1)	96 (7.8)	<0.0001
Highly annoyed by WTN (either indoors or outdoors)[e] n (%)	38 (5.8)	14 (6.0)	18 (9.7)	19 (11.8)	89 (7.2)	0.0013
Highly annoyed by WTN indoors[e] n (%)	20 (3.1)	10 (4.3)	6 (3.2)	11 (6.8)	47 (3.8)	0.0275
Highly annoyed by WTN outdoors[e] n (%)	44 (6.7)	15 (6.4)	22 (11.9)	21 (13.0)	102 (8.3)	0.0012
Highly annoyed by WT blinking lights[e] n (%)	54 (8.3)	21 (9.0)	26 (14.1)	21 (13.0)	122 (9.9)	0.0033
Highly annoyed visually by WT[e] n (%)	70 (10.7)	33 (14.1)	30 (16.2)	26 (16.2)	159 (12.9)	0.0054
Highly annoyed by WT vibrations[e] n (%)	8 (1.2)	0 (0.0)	5 (2.7)	6 (3.8)	19 (1.5)	0.0147
Sex n (%males)	318 (48.4)	120 (51.3)	95 (51.4)	73 (45.1)	606 (49.0)	0.9432
Age mean (SE)	51.91 (0.71)	50.71 (1.13)	50.44 (1.21)	51.01 (1.25)	51.61 (0.44)	0.5854[f]
Marital Status (PEI) n (%)						0.0724[g]
Married/Common-law	73 (60.3)	16 (80.0)	29 (87.9)	38 (71.7)	156 (68.7)	
Widowed/Separated/Divorced	22 (18.2)	2 (10.0)	1 (3.0)	8 (15.1)	33 (14.5)	
Single, never been married	26 (21.5)	2 (10.0)	3 (9.1)	7 (13.2)	38 (16.7)	
Marital Status (ON) n (%)						0.1939 [g]
Married/Common-law	371 (69.5)	137 (64.0)	110 (72.8)	74 (67.9)	692 (68.7)	
Widowed/Separated/Divorced	103 (19.3)	38 (17.8)	21 (13.9)	20 (18.3)	182 (18.1)	
Single, never been married	60 (11.2)	39 (18.2)	20 (13.2)	15 (13.8)	134 (13.3)	
Employment n (%employed)	359 (54.7)	149 (63.7)	111 (60.0)	103 (63.6)	722 (58.4)	0.0186
Agricultural employment n (%)	50 (14.0)	25 (16.9)	6 (5.5)	17 (16.7)	98 (13.7)	0.6272
Level of education n (%)						0.8435
≤High School	357 (54.4)	130 (55.6)	100 (54.1)	91 (56.2)	678 (54.8)	
Trade/Certificate/College	254 (38.7)	87 (37.2)	72 (38.9)	56 (34.6)	469 (37.9)	
University	45 (6.9)	17 (7.3)	13 (7.0)	15 (9.3)	90 (7.3)	
Household income (×$1000) n (%)						0.0002
<60	300 (53.3)	111 (55.5)	70 (45.5)	50 (37.3)	531 (50.5)	
60–100	155 (27.5)	56 (28.0)	43 (27.9)	46 (34.3)	300 (28.5)	
≥100	108 (19.2)	33 (16.5)	41 (26.6)	38 (28.4)	220 (20.9)	
Property ownership (PEI) n (%)	83 (68.6)	20 (100.0)	31 (93.9)	48 (90.6)	182 (80.2)	<0.0001[e]
Property ownership (ON) n (%)	471 (87.9)	188 (87.9)	134 (88.2)	101 (92.7)	894 (88.4)	0.5419[e]
Receive personal benefits n (%)	37 (6.0)	19 (8.4)	23 (12.6)	31 (19.5)	110 (9.3)	<0.0001

[a]The CMH chi-square test is used to adjust for province unless otherwise indicated.
[b]Totals may differ due to missing data.
[c]SF_h, maximum number of hours of SF in hours per day.
[d]SF_d, maximum amount of SF exposure in days per year.
[e]Highly annoyed includes the ratings *very* or *extremely*.
[f]Two-way analysis of variance adjusted for province.
[g]Chi-square test of independence.

headaches, chronic pain, dizziness, and tinnitus were all found to be equally distributed across SF categories (data not shown). The corresponding A-weighted WTN levels and proximity to the nearest WT are also shown in Table I.

B. Percentage highly annoyed by SF exposure from WTs

Regardless of the parameter used to quantify SF exposure, in all cases the predictive strength of the base model was statistically weak. Nevertheless, an analysis based on SF_m had the largest R^2 ($R^2 = 11\%$, compared to 10% for SF_h and 8% for SF_d; data not shown). Therefore, results are presented for HA_{WTSF} with respect to SF_m.

A statistically significant exposure-response relationship was found between SF_m and reporting to be HA_{WTSF}. As such, the prevalence of HA_{WTSF} increased from 3.8% in the lowest modeled SF exposure group ($0 \leq SF_m < 10$) to 21.1% when modeled shadow exposure was above or equal to 30 min per day, which represents almost a six-fold increase in the prevalence of HA_{WTSF} from the lowest exposure category to the highest. In comparison to an exposure duration of $0 \leq SF_m < 10$, the OR for HA_{WTSF} was statistically similar to

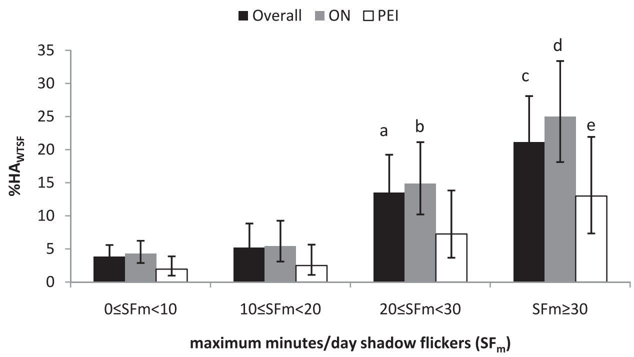

FIG. 2. Illustrates the percentage of participants that reported to be either very or extremely (i.e., highly) bothered, disturbed, or annoyed over the last year or so while at home (either indoors or outdoors) by shadows or flickers of light from WTs. Results are presented by province and as an overall average as a function of modeled SF exposure time (SF_m). Fitted data are plotted along with their 95% CIs. The models fit the data well (H-L test p-value >0.9). Bonferroni corrections were made to account for all pairwise comparisons. [(a), (b), (c)] Significantly different from $0 \leq SF_m < 10$ and $10 \leq SF_m < 20$; respective p-values for pairwise comparisons, $p \leq 0.0138$, $p \leq 0.0012$, and $p < 0.0006$. (d) Significantly different compared to all other categories, $p \leq 0.0126$; (e) Significantly different compared to $0 \leq SF_m < 10$, $p = 0.0162$.

that for $10 \leq SF_m < 20$ [1.29, 95% confidence interval (CI): (0.50, 3.33)]; and then significantly increased with increasing SF_m from 3.94 [95% CI: (1.80, 8.63)] at $20 \leq SF_m < 30$ to 7.51 [95% CI: (3.54, 15.96)] for $SF_m \geq 30$. Significant increases were also observed between the two highest SF exposure groups ($20 \leq SF_m < 30$, $SF_m \geq 30$) and those exposed to $10 \leq SF_m < 20$ (see Fig. 2).

1. Univariate analysis of variables related to HA_{WTSF}

Several variables were considered for their potential association with HA_{WTSF} (see Table II). A cautious approach should be taken when interpreting univariate results as these models do not account for the potential influence from other variables. The base model had an R^2 of 11%, compared to a base model of 10% when modeled using outdoor A-weighted WTN as a surrogate of SF exposure (data not shown). Prior to adjusting for other factors, the prevalence of HA_{WTSF} was significantly higher in ON ($p = 0.0193$). As WTN exposure and SF can occur simultaneously, the interaction between WTN levels and SF_m was also tested to assess the possible influence that such an interaction may have on HA_{WTSF}. As can be seen from Table II, the interaction between WTN levels and SF exposure was statistically significant ($p = 0.0260$), and increased the R^2 to 15%. This is somewhat better than the 11% obtained from the base model.

Factors beyond SF and WTN exposure were also considered for their potential influence on HA_{WTSF}. Participants who owned their property had 6.38 times higher odds of reporting HA_{WTSF} compared to those who were renting property [95% CI: (1.54, 26.39)]. Those who did not receive a personal benefit from having WTs in the area were found to have 4.03 times higher odds of being HA_{WTSF} compared to those who did receive personal benefits [95% CI: (1.42, 11.44)]. Those who reported to have migraines, dizziness, and tinnitus had 3 times higher odds of reporting HA_{WTSF} compared to those who did not report these health conditions. Participants that reported having chronic pain, arthritis, or restless leg syndrome had at least one and a half times the odds of reporting HA_{WTSF} compared to those who did not report suffering from these conditions (Table II). Participants who self-identified as being highly sensitive to noise had 3.49 times higher odds of being HA_{WTSF} compared to those who did not self-identify as being highly sensitive to noise [95% CI: (2.14, 5.69)]. Those who reported that WTs were audible had 10.68 times higher odds of HA_{WTSF} compared to those who could not hear WTs [95% CI: (5.07, 22.51)]. This variable was further categorized into the length of time that the participant heard the WT (do not hear, <1 year, ≥1 year); it was found that both those who heard WTs for less than 1 year and 1 year or greater had higher odds of being HA_{WTSF} compared to those who could not hear the WTs. Furthermore, there was no statistical difference in the proportion HA_{WTSF} among those who heard the WTs for less than 1 year or greater than or equal to 1 year ($p = 0.0924$). People who did not have a WT on their property had higher odds of reporting HA_{WTSF} compared to those who had at least one WT on their property [OR = 11.07, 95% CI: (1.49, 82.14)]. Annoyance variables were significantly correlated (Table III) and participants who were highly annoyed to any of the aspects of WT (noise, blinking lights, visual, and vibrations) tended to be also HA_{WTSF}.

The OR for these annoyances ranged from 13 to 34, with annoyance to vibrations and blinking lights having the lowest and highest OR, respectively. Concern for physical safety due to the presence of WTs in the studied communities (i.e., *concern for physical safety* variable) was also highly associated with HA_{WTSF}; participants who were highly concerned about their physical safety had 14.15 times higher odds of HA_{WTSF} compared to those who were not highly concerned about their physical safety [95% CI: (8.17, 24.53)]. Those who identified that their quality of life was "*Poor*" or were "*Dissatisfied*" with their health had 2 times higher odds of reporting HA_{WTSF} compared to their counterparts. Both the physical health domain and the environmental domain from the abbreviated World Health Organization Quality of Life questionnaire were negatively associated with being HA_{WTSF} (Feder *et al.*, 2015). That is to say that as the domain value increased (indicating an improved domain value), the prevalence of HA_{WTSF} decreased. Additionally, as the PSS scores of participants increased, so did the prevalence of HA_{WTSF} by 3% [95% CI: (1.00, 1.07)] (Table II).

2. Multiple logistic regression analyses of variables related to HA_{WTSF}

Table IV presents the unrestricted multiple logistic regression model for HA_{WTSF}. The first variable to enter the model was annoyance with WT blinking lights, which increased the R^2 from 11% at the base model level to 42%. This was followed by annoyance to WTN when outdoors, annoyance to the visual aspect of WTs, concern for physical safety, audibility of WTs, and annoyance to vibrations caused by WTs, which together increased the R^2 of the final model to 53%. Personal economic benefit associated with WTs has been found to have a strong impact on reducing

TABLE II. Univariate analysis of variables related to HA_{WTSF}.

Variable	Groups in variable[a]	Nagelkerke pseudo R^2	SF_m[b] OR (CI)[d]	SF_m[b] p-value	Explanatory variable OR (CI)[d]	Explanatory variable p-value	Province[c] OR (CI)[d]	Province[c] p-value	H-L test[e]
Base model[f,b]		0.11	2.02 (1.68, 2.43)	<0.0001			2.16 (1.13, 4.12)	0.0193	0.7699
SF_m × WTN level[g]		0.15	—[h]		—[h]		2.03 (1.04, 3.98)	0.0381	0.4851
Sex	Male/Female	0.11	2.02 (1.68, 2.43)	<0.0001	1.10 (0.72, 1.70)	0.6527	2.15 (1.13, 4.10)	0.0203	0.6015
Age group	≤24	0.12	2.03 (1.69, 2.45)	<0.0001	0.55 (0.15, 1.98)	0.3611	2.23 (1.17, 4.27)	0.0153	0.5879
	25–44				1.40 (0.74, 2.65)	0.3002			
	45–64				1.47 (0.83, 2.62)	0.1901			
	65+				reference				
Education	≤High School	0.11	2.02 (1.68, 2.43)	<0.0001	1.19 (0.48, 2.92)	0.7112	2.12 (1.11, 4.05)	0.0225	0.8936
	Trade/Certificate/College				1.40 (0.56, 3.50)	0.4695			
	University				reference				
Income (×$1000)	<60	0.12	1.99 (1.63, 2.44)	<0.0001	0.71 (0.39, 1.29)	0.2617	1.68 (0.85, 3.33)	0.1390	0.1722
	60–100				1.08 (0.59, 1.98)	0.8041			
	≥100				reference				
Marital Status	Married/Common-law	0.12	2.02 (1.68, 2.43)	<0.0001	1.76 (0.85, 3.65)	0.1274	2.20 (1.15, 4.21)	0.0169	0.5600
	Widowed/Separated/Divorced				1.21 (0.50, 2.97)	0.6746			
	Single, never been married				reference				
Property ownership	Own/rent	0.13	1.99 (1.65, 2.39)	<0.0001	6.38 (1.54, 26.39)	0.0105	2.11 (1.10, 4.04)	0.0246	0.8715
Type of dwelling	Single detached/Other	0.11	1.99 (1.65, 2.40)	<0.0001	1.67 (0.51, 5.52)	0.3969	2.10 (1.10, 4.02)	0.0246	0.6535
Employment	Employed/not employed	0.12	2.00 (1.67, 2.41)	<0.0001	1.43 (0.91, 2.26)	0.1247	2.18 (1.14, 4.16)	0.0183	0.3034
Type of employment	Agriculture/ Other	0.13	2.03 (1.61, 2.57)	<0.0001	0.95 (0.43, 2.12)	0.9017	3.27 (1.34, 7.98)	0.0094	0.8071
Personal benefit	No/Yes	0.13	2.09 (1.73, 2.52)	<0.0001	4.03 (1.42, 11.44)	0.0088	2.16 (1.13, 4.13)	0.0205	0.7111
Migraines	Yes/No	0.16	2.06 (1.70, 2.48)	<0.0001	3.15 (2.02, 4.94)	<0.0001	1.91 (1.00, 3.68)	0.0518	0.4864
Dizziness	Yes/No	0.15	2.03 (1.69, 2.45)	<0.0001	2.81 (1.79, 4.41)	<0.0001	2.19 (1.14, 4.20)	0.0190	0.6998
Tinnitus	Yes/No	0.15	2.09 (1.73, 2.52)	<0.0001	2.91 (1.85, 4.58)	<0.0001	2.21 (1.15, 4.25)	0.0170	0.6902
Chronic Pain	Yes/No	0.13	2.06 (1.71, 2.48)	<0.0001	2.16 (1.37, 3.42)	0.0010	2.01 (1.05, 3.84)	0.0355	0.5661
Asthma	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	1.19 (0.55, 2.60)	0.6606	2.16 (1.13, 4.12)	0.0194	0.6215
Arthritis	Yes/No	0.12	2.06 (1.71, 2.48)	<0.0001	1.57 (1.01, 2.45)	0.0461	2.20 (1.15, 4.21)	0.0170	0.5660
High Blood Pressure	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	0.90 (0.56, 1.45)	0.6710	2.17 (1.14, 4.14)	0.0186	0.3444
Medication for high blood pressure, past month	Yes/No	0.12	2.02 (1.68, 2.43)	<0.0001	0.74 (0.45, 1.21)	0.2251	2.20 (1.15, 4.19)	0.0171	0.3238
History of high blood pressure in family	Yes/No	0.11	2.02 (1.67, 2.44)	<0.0001	1.03 (0.67, 1.60)	0.8926	2.03 (1.06, 3.88)	0.0334	0.7739
Chronic bronchitis/ emphysema/ COPD	Yes/No	0.11	2.01 (1.67, 2.42)	<0.0001	0.55 (0.16, 1.82)	0.3240	2.18 (1.14, 4.16)	0.0178	0.8001
Diabetes	Yes/No	0.12	2.02 (1.68, 2.44)	<0.0001	0.61 (0.25, 1.45)	0.2587	2.12 (1.11, 4.05)	0.0227	0.6111
Heart disease	Yes/No	0.11	2.02 (1.68, 2.43)	<0.0001	1.22 (0.56, 2.68)	0.6137	2.15 (1.13, 4.10)	0.0198	0.7954
Diagnosed sleep disorder	Yes/No	0.12	2.02 (1.68, 2.43)	<0.0001	1.57 (0.82, 2.98)	0.1716	2.11 (1.11, 4.03)	0.0236	0.7696
Restless leg syndrome	Yes/No	0.13	2.01 (1.67, 2.42)	<0.0001	2.12 (1.26, 3.55)	0.0044	2.01 (1.05, 3.85)	0.0342	0.5256
Sensitivity to Noise	High/Low	0.15	2.04 (1.69, 2.46)	<0.0001	3.49 (2.14, 5.69)	<0.0001	2.03 (1.06, 3.91)	0.0335	0.4659
See WT	Yes/No	0.14	1.88 (1.56, 2.27)	<0.0001	>999.999 (< 0.001, > 999.999)	0.9658	2.06 (1.08, 3.92)	0.0290	0.7480
Audible WT	Yes/No	0.23	1.66 (1.37, 2.02)	<0.0001	10.68 (5.07, 22.51)	<0.0001	2.42 (1.26, 4.67)	0.0083	0.7198
Number of years turbines audible	less than 1 year	0.23	1.66 (1.37, 2.02)	<0.0001	5.04 (1.56, 16.25)	0.0068	2.51 (1.30, 4.85)	0.0063	0.8472
	1 year or more				11.51 (5.45, 24.33)	<0.0001			
	Do not hear WTs				reference				

TABLE II. (*Continued*.)

Variable	Groups in variable[a]	Nagelkerke pseudo R^2	SF_m[b] OR (CI)[d]	SF_m[b] *p*-value	Explanatory variable OR (CI)[d]	Explanatory variable *p*-value	Province[c] OR (CI)[d]	Province[c] *p*-value	H-L test[e]
At least 1 WT on property	No/Yes	0.14	2.14 (1.77, 2.58)	<0.0001	11.07 (1.49, 82.14)	0.0187	2.07 (1.08, 3.95)	0.0279	0.4544
Visual annoyance to WTs	High/Low	0.37	2.17 (1.75, 2.71)	<0.0001	20.29 (12.24, 33.64)	<0.0001	1.68 (0.79, 3.56)	0.1785	0.9285
Annoyance with blinking lights	High/Low	0.42	2.22 (1.76, 2.80)	<0.0001	34.27 (19.68, 59.67)	<0.0001	1.23 (0.57, 2.66)	0.5984	0.7649
Annoyance to WTN	High/Low	0.30	2.02 (1.65, 2.48)	<0.0001	18.18 (10.58, 31.25)	<0.0001	1.72 (0.85, 3.48)	0.1336	0.3863
Annoyance to WTN from indoors	High/Low	0.23	2.05 (1.68, 2.50)	<0.0001	19.58 (9.80, 39.11)	<0.0001	1.65 (0.85, 3.21)	0.1388	0.4867
Annoyance to WTN from outdoors	High/Low	0.32	2.04 (1.66, 2.52)	<0.0001	19.49 (11.54, 32.93)	<0.0001	2.02 (0.99, 4.12)	0.0545	0.4643
Annoyance to vibrations/rattles	High/Low	0.16	2.01 (1.66, 2.43)	<0.0001	13.07 (4.71, 36.30)	<0.0001	2.07 (1.07, 4.01)	0.0309	0.9413
Concerned about physical safety	High/Low	0.26	1.92 (1.57, 2.34)	<0.0001	14.15 (8.17, 24.53)	<0.0001	2.09 (1.04, 4.18)	0.0379	0.6700
Quality of Life	Poor/Good[i]	0.12	2.04 (1.69, 2.45)	<0.0001	2.31 (1.14, 4.71)	0.0208	2.13 (1.12, 4.06)	0.0218	0.5909
Satisfaction with health	Dissatisfied/Satisfied[j]	0.12	2.04 (1.69, 2.45)	<0.0001	1.84 (1.07, 3.18)	0.0280	2.12 (1.11, 4.04)	0.0227	0.5133
Medication for anxiety/depression	No/Yes	0.11	2.02 (1.68, 2.43)	<0.0001	1.28 (0.62, 2.65)	0.5128	2.19 (1.15, 4.18)	0.0177	0.2842
Continuous scale explanatory variables									
Physical health domain (range 4–20)		0.13	2.06 (1.71, 2.48)	<0.0001	0.90 (0.85, 0.96)	0.0012	2.04 (1.07, 3.90)	0.0313	0.7547
Psychological domain (range 4–20)		0.11	2.02 (1.68, 2.43)	<0.0001	0.98 (0.90, 1.07)	0.6738	2.17 (1.14, 4.14)	0.0187	0.6490
Social relationships domain (range 4–20)		0.11	2.02 (1.68, 2.42)	<0.0001	0.98 (0.91, 1.06)	0.5701	2.14 (1.13, 4.09)	0.0205	0.7782
Environment domain (range 4–20)		0.13	2.05 (1.70, 2.47)	<0.0001	0.88 (0.80, 0.96)	0.0056	2.27 (1.19, 4.34)	0.0134	0.6815
Perceived stress scale (range 0–37)		0.12	2.01 (1.67, 2.42)	<0.0001	1.03 (1.00, 1.07)	0.0386	2.07 (1.08, 3.96)	0.0276	0.6513

[a]Where a reference group is not specified it is taken to be the last group.
[b]The exposure variable, SF_m, is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure.
[c]PEI is the reference group.
[d]Odds ratio (OR) and 95% CI based on logistic regression model, an OR $>$ 1 indicates that annoyance levels were higher, relative to the reference group.
[e]H-L test, $p > 0.05$ indicates a good fit.
[f]The base model includes the modeled shadow exposure (SF_m) and province.
[g]WTN level is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in WTN level, where a unit reflects a 5 dB WTN category.
[h]The interaction between WTN levels and modeled shadow exposure was significant ($p = 0.0260$). When fitting separate logistic regression models to each shadow exposure group, it was observed that there was a positive significant relationship between high annoyance to SF and WTN levels only among those in the lowest shadow exposure group [OR and 95% confidence interval: 2.62 (1.64, 4.20)]. The relationship in the other three shadow exposure groups ($10 \le SF_m < 20$, $20 \le SF_m < 30$, and $SF_m \ge 30$) was not significant ($p > 0.05$, in all cases).
[i]"Poor" includes those that responded "poor" or "very poor."
[j]"Dissatisfied" includes those that responded "dissatisfied" or "very dissatisfied."

TABLE III. Spearman correlation coefficient (p-value) between annoyance variables.

Type of annoyance[a]	WTN inside	WTN outside	Visual	Blinking lights	SF	Vibrations inside
WTN in or out	0.98 ($p < 0.0001$)	0.99 ($p < 0.0001$)	0.49 ($p < 0.0001$)	0.48 ($p < 0.0001$)	0.51 ($p < 0.0001$)	0.25 ($p < 0.0001$)
WTN inside		0.98 ($p < 0.0001$)	0.46 ($p < 0.0001$)	0.46 ($p < 0.0001$)	0.50 ($p < 0.0001$)	0.23 ($p < 0.0001$)
WTN outside			0.49 ($p < 0.0001$)	0.48 ($p < 0.0001$)	0.51 ($p < 0.0001$)	0.25 ($p < 0.0001$)
Visual				0.79 ($p < 0.0001$)	0.70 ($p < 0.0001$)	0.19 ($p < 0.0001$)
Blinking lights					0.75 ($p < 0.0001$)	0.17 ($p < 0.0001$)
SF						0.18 ($p < 0.0001$)

[a]Participants were asked to indicate how bothered, disturbed, or annoyed they were over the last year or so while at home. Unless the participants' location was specified as indoors or outdoors, at home was defined as either indoors or outdoors. Vibrations were identified as being present during WT operations.

reported annoyance to WTN (Pedersen *et al.*, 2009). In the current study, directly or indirectly receiving personal benefit from having WTs in the area could include receiving payment, rent, or benefiting from community improvements ($n = 110$). When this variable was forced into the final model, it had no influence on the variables that entered the model, nor did it have any impact on the final R^2 (data not shown). Similarly, removing these participants had no influence on the strength of the overall final model (i.e., R^2 remained at 53%). The one change observed when participants receiving personal benefit were removed was that annoyance to vibrations was discarded and restless leg syndrome entered the model at a p-value of 0.0540 (data not shown). The statistically significant interaction between WTN levels and SF_m (see Sec. III B 1) was not found to be related to HA_{WTSF} after adjusting for the variables shown in Table IV.

Table V presents the restricted multiple logistic regression model for HA_{WTSF}. In this restricted model, the first variable to enter the model was concern for physical safety, increasing the R^2 from 11% at the base model level to 26%. The following variables then entered the model: audibility of WTs, sensitivity to noise, having at least one WT on the property, property ownership, and dizziness. The overall fit of the final restricted model was 37%. The last three variables (having at least one WT on the property, property ownership, and dizziness) collectively contributed only an additional 2% to the overall model and were all only significant at the 10% level, and not at the 5% level. Receiving personal benefits does not enter the final model, due to its redundancy given the other variables that did enter the model. However, when it is forced into the model it is significant at $p = 0.0343$ level (data not shown). In this case, the variable "*is there at least one wind turbine on your property*" is dropped in place of "*employment status*," which comes into the model with a p-value of 0.0722 (data not shown). The overall fit of the model improves slightly to 38% (data not shown). Finally, when conditioning on only those who do not receive benefits, the overall fit of the model drops slightly to 36%, with neither of the "*employment status*" nor the *"is there at least one wind turbine on your property"* variables coming into the final model (data not shown).

IV. DISCUSSION

The accumulated research on the potential health effects associated with SF from WTs has concluded that SF from WTs is unlikely to present a risk to the occurrence of seizures, even among individuals that have photosensitive epilepsy (Harding *et al.*, 2008; Knopper *et al.*, 2014; Smedley *et al.*, 2010). The knowledge gap that persists is the extent to which WT SF causes annoyance. Also unknown is how this annoyance may result from an interaction between SF and WTN levels, given that SF and at least some level of WTN emissions occur simultaneously. To date, there have been very few assessments that have evaluated the effect of SF on community response. A German field study performed by Pohl *et al.* (1999) investigated methods for the evaluation of SF exposure, which ultimately led to current SF exposure

TABLE IV. Multiple logistic regression analysis (unrestricted) of variables related to HA_{WTSF}.

		Stepwise Model 1		
Variable	Groups in variable[a]	OR (CI)[b]	p-value	Order of entry into model: R^2 at each step
HA_{WTSF} versus not HA_{WTSF}		($n = 1147$, $R^2 = 0.53$, H-L $p = 0.7536$)		
SF_m[c]		2.04 (1.56, 2.66)	<0.0001	Base: 0.11
Province	ON/PEI	1.20 (0.50, 2.89)	0.6811	Base: 0.11
Annoyance with blinking lights	High/Low	7.67 (3.84, 15.34)	<0.0001	Step 1: 0.42
Annoyance to WTN from outdoors	High/Low	2.25 (1.09, 4.66)	0.0287	Step 2: 0.47
Visual annoyance to WT	High/Low	4.09 (2.09, 7.99)	<0.0001	Step 3: 0.50
Concerned about physical safety	High/Low	2.89 (1.39, 6.01)	0.0045	Step 4: 0.51
Audible WT	Yes/No	3.15 (1.35, 7.34)	0.0080	Step 5: 0.52
Annoyance to vibrations/rattles	High/Low	3.49 (1.00, 12.23)	0.0503	Step 6: 0.53

[a]Where a reference group is not specified it is taken to be the last group.
[b]OR and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The exposure variable SF_m is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure.

TABLE V. Multiple logistic regression analysis (restricted) of variables related to HA_{WTSF}.

Variable	Groups in variable[a]	Stepwise Model 1		Order of entry into model: R^2 at each step
		OR (CI)[b]	p-value	
HA_{WTSF} versus not HA_{WTSF}		($n = 1159$, $R^2 = 0.37$, H-L $p = 0.7294$)		
SF_m[c]		1.70 (1.37, 2.11)	<0.0001	Base: 0.11
Province	ON/PEI	2.07 (1.00, 4.27)	0.0494	Base: 0.11
Concerned about physical safety	High/Low	7.01 (3.90, 12.60)	<0.0001	Step 1: 0.26
Audible WT	Yes/No	6.33 (2.90, 13.81)	<0.0001	Step 2: 0.32
Sensitivity to noise	High/Low	2.81 (1.57, 5.05)	0.0005	Step 3: 0.35
At least 1 WT on property	No/Yes	6.87 (0.88, 53.73)	0.0663	Step 4: 0.36
Property ownership	Own/rent	4.78 (0.95, 24.01)	0.0574	Step 5: 0.37
Dizziness	Yes/No	1.68 (0.98, 2.86)	0.0581	Step 6: 0.37

[a]Where a reference group is not specified it is taken to be the last group.
[b]OR and 95% CI based on logistic regression model, an OR > 1 indicates that annoyance levels were higher, relative to the reference group.
[c]The exposure variable SF_m is treated as a continuous scale in the logistic regression model, giving an OR for each unit increase in shadow exposure. Model is restricted insofar as variables that are reactions to WT operations are not considered.

limits in Germany, while a conference paper presented by Pedersen and Persson Waye (2003) assessed annoyance with SF as a function of modeled SF exposure. The conclusion from this conference paper was that modeled WTN levels were a better predictor of annoyance to SF from WTs than modeled SF exposure. A similar conclusion was reached in the current study wherein it was found that, regardless of how SF exposure was modeled, the R^2 for HA_{WTSF} by modeled SF was statistically weak and essentially the same as that found using WTN levels (i.e., 10% and 9%, respectively). Some improvement was found when the interaction between WTN levels and SF_m was considered, which increased the R^2 to 15%. However, after adjusting for other factors that were statistically related to HA_{WTSF}, this interaction was no longer significant in the final multiple regression models.

In spite of the obvious deficiencies in estimating HA_{WTSF} using either A-weighted WTN levels or SF_m alone (or together as an interaction term), a statistically significant exposure-response relationship was found between HA_{WTSF} and SF modeled as SF_m. The strength of the base model was markedly improved from 11% to 53% when adjusting for other factors. In this case, these other factors included those which are subjective and/or could be viewed as reactions to operational WTs (e.g., other annoyances). When the final model was restricted to variables conceptually viewed as objective and/or not contingent upon WT operations, the strength of the final model improved from 11% for the base model to 37%. Both of these models have merit, but as discussed below, the restricted model may be more valuable in situations where a wind farm is not yet operational.

It is not surprising that in the unrestricted model, the variables related to the visual perception of WTs were among those which had the strongest statistical association with $HA_{WTSF,}$ as these were found to be more highly correlated with each other than annoyance reactions mediated through tactile and/or auditory senses (see Table III). Their presence in the final model indicates that there were no issues related to multicollinearity. This should be interpreted to mean that each of these annoyance variables is a significant predictor of HA_{WTSF}. In this regard, most of the increase in the predictive strength of the model for HA_{WTSF} was observed once annoyance to blinking lights on WTs entered the model. This step increased the R^2 from 11% at the base level to 42%. Participants that reported being highly annoyed by blinking lights on WTs had almost 8 times higher odds of being HA_{WTSF}. In a study performed by Pohl *et al.* (2012), it was found that respondents were comparably as strongly annoyed by WT blinking lights as they were by SF, a finding which may also be reflected in this study. It is also worth mentioning that in the CNHS, annoyance to blinking lights on WTs was found to be related to actigraphy-measured sleep disturbance (Michaud *et al.*, 2016c). It is therefore possible that poorer sleep quality at night among these participants is associated with a heightened response to SF during the day.

In the current study, participants reported how annoyed they were by WTN while they were at home (either indoors or outdoors), indoors only, and outdoors only. Annoyance to WTN when inside does not make it into the final models; however, the finding that annoyance to WTN when outside had the stronger association with HA_{WTSF} seems to suggest that SF annoyance is more likely an outdoor phenomena. The results of the unrestricted multiple logistic regression model show that estimating HA_{WTSF} using SF_m can be significantly improved when considering these other annoyances.

Further improvements can be expected when concern for physical safety associated with having WTs in the area and the audibility of WTs are also accounted for. Although *concern for physical safety* may in some cases reflect a response to operational WTs, it could just as readily be treated as an attitudinal response triggered by the anticipated physical presence of industrial WTs. Although extremely rare, there have been reports of catastrophic failure that could exacerbate the level of concern for one's physical safety in the same way rare aircraft accidents are known to increase the fear of aircraft (Fields, 1993; Moran *et al.*, 1981; Reijneveld, 1994). As discussed below, concern for physical safety also appears in the restricted multiple regression model.

In the restricted model (see Table V), which only included variables that were not direct responses to WT operations, it was found that concern for physical safety was the variable that contributed the most to R^2, as it increased the base model R^2 from 11% to 26%. In this case, respondents that declared being highly concerned for their physical safety had, on average, 7 times higher odds of reporting HA_{WTSF}. The observation that this variable was present in both models suggests that actions taken to identify and reduce this concern at the planning stages of a WT facility may reduce HA_{WTSF}.

As already mentioned, exposure to SF from WTs will always occur with at least some level of WTN exposure. It is therefore not surprising that the audibility of WTs and noise sensitivity were also found to be statistically related to HA_{WTSF}. Noise sensitivity has long been known to have an influence on community noise annoyance. At equivalent noise levels, annoyance reactions are higher among people who report to be noise sensitive (Job, 1988).

Although property ownership, having a WT on one's property, and experiencing dizziness appear in the final model, together they only contribute an additional 2% to the overall strength of the model and all three variables are significant only at the 10% level. Therefore, only a very cautious interpretation of their influence on HA_{WTSF} can be made. Property ownership could reflect a greater attachment to one's property and heightened response to any exposure that is perceived to have negative impacts on one's property. The negative association between having a WT on one's property and HA_{WTSF} may be an indication that these participants are more likely to directly or indirectly benefit from having WTs in the area. While personal benefit does not enter any of the final multiple regression models, this is because only 110 participants received personal benefits. When considered alone, personal benefit had an influence on HA_{WTSF}. The presence of dizziness in the final model might be explained by the notion that dizziness can be a sensory-related variable and as such may have an influence on a visually-related parameter, such as HA_{WTSF}. Although both the unrestricted and restricted multiple regression models improved the strength of their corresponding base models substantially, their predictive strength for HA_{WTSF} was still rather limited.

Possible explanations for this limited predictive strength could stem from the uncertainties in the model used to quantify SF_m, as discussed in Sec. II D, or from additional limitations. First and foremost, it should be emphasised that the SF model employed for this study was developed to quantify SF exposure for a specific period of time. Therefore, there may have been a mismatch between the parameter used to quantify SF exposure (i.e., maximum minutes per day at the dwelling window) and the subjective perception of SF from WTs assessed in the current study. Annoyance to SF exposure is not limited to dwelling window façades. It is much more likely to reflect an integrated response to shadow over one's entire property, or to any location where SF is perceived. Additionally, the current SF model presents worst-case SF exposure. A more refined assessment that included precise meteorological conditions, such as cloud coverage as well as wind speed and wind direction, could provide a more accurate evaluation of WT SF exposure. This may in turn provide a stronger association with community response to this variable. Finally, it is important to mention that the SF model only accounts for SF duration, and not shadow intensity. An assessment of SF intensity could potentially strengthen the association between SF exposure and community annoyance.

A careful examination of the SF annoyance question in the CNHS questionnaire itself is also warranted. There was ambiguity in the question used to assess HA_{WTSF} that may have contributed to the weak association observed between SF_m and HA_{WTSF}. The question probed one's annoyance towards *shadows or flickers of light* from WTs while they are at home, where "*at home*" means either indoors or outdoors. This wording could have led the respondent to assess their annoyance from shadows caused by WTs with either stationary or rotating blades. By contrast, the wording of the question could also have led the respondent to assess their annoyance from flickers of light generated by rotating WT blades. However, the model used to quantify SF exposure only considers moving shadows and as such, there may have been a discrepancy between the modeled exposure, and the participants' response. Although improvements will only come as this research area matures, as a starting point the authors recommend that future research in this area refine the SF annoyance question to the following: *Thinking about the last year or so, while you are at home, how much do shadows created by rotating wind turbine blades bother, disturb or annoy you*?

V. CONCLUDING REMARKS

For reasons mentioned above, when used alone, modeled SF_m results represent an inadequate model for estimating the prevalence of HA_{WTSF} as its predictive strength is only about 10%. This research domain is still in its infancy and there are enough sources of uncertainty in the model and the current annoyance question to expect that refinements in future research would yield improved estimates of SF annoyance. In addition to addressing some of the aforementioned shortcomings, future research may also benefit by considering variables that were not addressed in the current study. These may include, but not be limited to, personality types, attitudes toward WTs, and the level of community engagement between WT developers and the community. In the interim, this study identifies the variables, that when considered together with modeled SF exposure, improve the overall estimate of HA_{WTSF}. The applicability of these variables to areas beyond the current study sample will only become known as this research area matures.

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[1]Overall statistical power for the CNHS was based on the study's primary objective to assess WTN associated impacts on sleep quality. Based on an initial sample size of 2000 potential dwellings, it was estimated that there

would be 1120 completed questionnaires. For 1120 respondents there should be sufficient statistical power to detect at least a 7% difference in the prevalence of sleep disturbances with 80% power and a 5% false positive rate (Type I error). There was uncertainty in the power assessment because the CNHS was the first to implement objectively measured endpoints to study the impact that WTN may have on human health in general, and on sleep quality, in particular. In the absence of comparative studies, a conservative baseline prevalence for reported sleep disturbance of 10% was used (Tjepkema, 2005; Riemann *et al.*, 2011). Sample size calculation also incorporated the following assumptions: (1) approximately 20%–25% of the targeted dwellings would not be valid dwellings (i.e., demolished, unoccupied seasonal, vacant for unknown reasons, under construction, institutions, etc.); and (2) of the remaining dwellings, there would be a 70% participation rate. These assumptions were validated (Michaud *et al.*, 2016b).

[2]Four hundred and thirty-four potential dwellings were not valid locations; upon visiting the address Statistics Canada noted that the location was inhabitable but unoccupied at the time of the visit, newly constructed not yet inhabited, unoccupied trailer in trailer park, a business, a duplicate address, an address listed in error, summer cottage, ski chalet, hunting camps, or a location where residents were all above 79 yrs of age. See Michaud *et al.* (2016b) for more details.

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