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See p. 109 of this report for a reference to Dr. Pierpont's work on Wind Turbine Syndrome.

Read Full Report

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Use of Wind Energy in U.S. Growing, But Planning and Guidelines Are Lacking; New Report Examines Wind Energy's Impacts on Emissions, Wildlife, and Humans

WASHINGTON -- Although the use of wind energy to generate electricity is increasing rapidly in the United States, government guidance to help communities and developers evaluate and plan proposed wind-energy projects is lacking, says a new congressionally mandated report from the National Research Council. To inform the development of guidelines, the report offers an analysis of the environmental benefits and drawbacks of wind energy, along with an evaluation guide to aid decision-making about projects. As a case study, the committee that wrote the report looked at the mid-Atlantic highlands, a mountainous area that spans parts of West Virginia, Virginia, Maryland, and Pennsylvania. The report does not examine the impact of offshore wind-energy projects.

Currently, federal regulation of wind projects on private land is minimal, the report observes. And although some states have developed guidelines, wind energy is such a recent addition to the energy mix in most areas -- the nation's wind-energy capacity more than quadrupled between 2000 and 2006 -- that most states are relatively inexperienced at planning and regulation. Despite the growth in its use, wind energy still generates less than 1 percent of the nation's electricity. Some national-level policies to enhance the benefits of wind energy and minimize its harms would help guide state and local regulatory efforts, the report says.

Impacts on CO2 and Other Pollutants

A primary benefit of using wind to generate electricity is that it produces no carbon dioxide (CO2), a major greenhouse gas, or any other air pollutant. Based on U.S. Department of Energy projections for wind-energy development in the United States, the committee estimated that by 2020, wind energy will offset approximately 4.5 percent of the carbon dioxide that would otherwise be emitted by other electricity sources. In 2005, electricity generation accounted for 39 percent of the nation's total CO2 emissions.

The committee concluded that use of wind energy to generate electricity probably would not significantly reduce emissions of two other pollutants, sulfur dioxide and nitrogen oxides, because current and expected regulations of these are largely based on cap-and-trade programs. The degree to which emissions would be further reduced through special provisions to encourage wind-energy use -- such as set-asides, in which a percentage of emissions allowed under the cap are retired to the extent they can be offset by wind energy -- is uncertain, the committee added.

In the mid-Atlantic region, wind energy will likely contribute a lower proportion of electricity generation than it will in the United States overall, the report says; compared to other areas, a smaller portion of the region has strong, relatively steady winds.

Effects on Wildlife

Wind facilities can have certain adverse environmental effects on a local or regional level, by damaging habitat and killing birds and bats that fly into turbines. Among birds, the most frequent turbine fatalities are nocturnal, migrating songbirds, probably because of their abundance, the report says. However, the committee saw no evidence that fatalities from existing wind facilities are causing measurable changes in bird populations in the United States. A possible exception is deaths among birds of prey, such as eagles and hawks, near Altamont Pass, Calif. -- a facility with older, smaller turbines that appear more apt to kill such birds than newer turbines are.

Too little information is available to reliably predict how proposed new wind projects in the mid-Atlantic highlands would affect bird populations, the report says. As for bats, turbines placed on ridges -- as many are in the mid-Atlantic region -- appear more likely to kill them than turbines sited elsewhere. In fact, preliminary information indicates that in the mid-Atlantic highlands more bats are killed than expected based on experience with other regions, the committee said. Although scarce data make it hard to say how these deaths affect overall bat populations, the possibility of population effects is significant, especially if more turbines are added, given a general decline in several species of bats in the eastern United States.

Studies to evaluate possible ecological impacts should be conducted prior to choosing sites for wind facilities, the committee said, and follow-up studies should be conducted to measure actual effects. Additional basic research also is needed to help assess the short- and long-term impacts of these facilities on species at risk.

Impacts on Humans

A common objection to proposed wind projects is that they will have a negative aesthetic impact. The report outlines a process to help communities and developers assess a project's likely aesthetic effects, and suggests ways to minimize them -- for example, by using uniform types and sizes of turbines, and by ensuring that each region retains some undeveloped scenic vistas. The report also offers questions to ask, to help determine whether the aesthetic impact might be great enough to render a project unacceptable.

Wind projects also can be disruptive because of noise and shadow flicker, a strobelike effect caused by rotating turbine blades. The report recommends that noise surveys be conducted before a project is sited, and that processes be set up to respond to noise complaints. Shadow flicker has generally not been a problem at wind facilities in North America, the report says; new turbines can be located so that their shadow paths avoid residences, or operations can be halted during times when troublesome flicker occurs.

The report also considers beneficial and adverse economic effects on local areas -- such as effects on landowners, the regional economy, and local government revenues -- and recommends measures to anticipate and mitigate potential problems. In addition, the report discusses possible electromagnetic interference with local installations such as radar.

Improving Planning and Regulation

Governments at the state and local levels should provide developers and the public with guidance to help them plan for wind-energy development, including guidance on procedures and information needs for assessing projects, the report says. It also recommends that regulatory agencies adopt an evaluation guide to review proposed projects, and that governments work with each other and with organizations and developers to create guidelines for weighing projects' costs and benefits at scales ranging from local to national.

The report was sponsored by the White House Council on Environmental Quality. The National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and National Research Council make up the National Academies. They are private, nonprofit institutions that provide science, technology, and health policy advice under a congressional charter. The Research Council is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering. A committee roster follows.

Copies of Environmental Impacts of Wind Energy Projects will be available from the National Academies Press; tel. 202-334-3313 or 1-800-624-6242 or on the Internet at http://www.nap.edu. Reporters may obtain a pre-publication copy from the Office of News and Public Information (contacts listed above).

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Preface

The generation of electricity from wind energy is surprisingly controversial. At first glance, obtaining electricity from a free source of energy—the wind—seems to be an optimum contribution to the nation's goal of energy independence and to solving the problem of climate warming due to greenhouse gas emissions. As with many first glances, however, a deeper inspection results in a more complicated story. How wind turbines are viewed depends to some degree on the environment and people's predilections, but not everyone considers them beautiful. Building wind-energy installations with large numbers of turbines can disrupt landscapes and habitats, and the rotating turbine blades sometimes kill birds and bats. Calculating how much wind energy currently displaces other, presumably less-desirable, energy sources is complicated, and predicting future displacements is surrounded by uncertainties.

Although the use of wind energy has grown rapidly in the past 25 years, frequently subsidized by governments at various levels and in many countries eager to promote cleaner alternative energy sources, regulatory systems and planning processes for these projects are relatively immature in the United States. At the national scale, regulation is minimal, unless the project receives federal funding, and the regulations are generic for construction and management projects or are promulgated as guidelines. Regulation at the state and local level is variable among jurisdictions, some with well-developed policies and others with little or no framework, relying on local zoning ordinances. There are virtually no policy or regulatory frameworks at the multi-state regional scale, although of course the impacts and benefits of wind-energy installations are not constrained by political boundaries.

This is the complex scientific and policy environment in which the committee worked to address its responsibility to study the environmental impacts of wind energy, including the adverse and beneficial effects. Among the specified considerations were the impacts on landscapes, viewsheds, wildlife, habitats, water resources, air pollution, greenhouse gases, materials-acquisition costs, and other impacts. The committee drew on information from throughout the United States and abroad, but by its charge, focused on the Mid-Atlantic Highlands (a mountainous region in Pennsylvania, Virginia, Maryland, and West Virginia). Using existing information, the committee was able to develop a framework for evaluating those effects; we hope this framework can inform future siting decisions of wind-energy projects. Often, there is insufficient information to provide certainty for these decisions, and thus in the process of its work the committee identified major research needed to improve the assessment of impacts and inform the siting and operational decisions of wind-energy projects.

The committee membership included diverse areas of expertise needed to address the committee's charge. Committee members originated from across the United States, and one hails from Denmark, adding to the international perspective of the study. Members represented the public and private sectors, and numerous natural and social science disciplines. But most important, the committee worked together as a cohesive group in deciding what issues were important and how important, examining issues from multiple perspectives, recognizing and dealing with biases, framing questions and issues in formats that would convey information effectively to decision makers, and considering, respecting and reconciling differences of opinion, judgment, and interpretation.

The committee broadly defined "environmental" impacts to include traditional environmental measures such as species, habitats, and air and water quality, but attention was also devoted to aesthetic, cultural, recreational, social, and economic impacts. The committee recognized that the planning, policy, and regulatory considerations were paramount if information about impacts was to be translated into informed decision-making. Finally, because decision-making about wind-energy projects occurs at a variety of geographic and jurisdictional levels, the committee paid careful attention to scale issues as it addressed impacts and benefits.

The benefits of wind energy depend on the degree to which the adverse effects of other energy sources can be reduced by using wind energy instead of the other sources. Assessing those benefits is complicated. The generation of electricity by wind energy can itself have adverse effects, and projecting the amount of wind-generated electricity available in the future is quite uncertain. In addition, the amount of potential displacement of other energy sources depends on characteristics of the energy market, operation of the transmission grid, capacity factor of the wind-energy generators as well as that of other types of electricity generators, and regulatory policies and practices affecting the production of greenhouse gases. Even if the amount of energy that wind energy displaces is small, it is clear that the nation will depend on multiple energy sources for the foreseeable future and reduction of environmental impacts will thereby require multiple approaches.

The committee began its work expecting that there would be measurable environmental impacts, including biological and socioeconomic impacts, and that there would be inadequate data from which to issue definitive, broadly applicable determinations. Given the complexity of the electric-power industry, the dynamics of energy markets, and the rapidity of technological change, we also expected that predicting the environmental benefits of wind energy would be challenging. On the other hand, the lack of any truly coordinated planning, policy, and regulatory framework at all jurisdictional levels loomed larger than expected throughout our deliberations. Although some predictions about future adverse environmental effects of wind-energy use can be made, the committee recognized gaps in our knowledge and recommended specific monitoring studies that will enable more rigorous siting and operational decisions in the future. Similarly, the report includes descriptions of measures of social impacts of wind-energy development, and recommends studies that would improve our understanding of these impacts.

The complexity of assessing the environmental impacts of wind-energy development can be organized in a three dimensional action space. These dimensional axes include spatial jurisdictions (local, state/regional, and federal), timing of project stages (pre-project, construction, operational, and post-operational) and environmental and human impacts, each of which include their own time and space considerations. The committee evaluated these issues in offering an evaluation guide for organizing the assessment of environmental impacts. We hope that the results of these deliberations and the evaluations and observations in this report will significantly improve the nation's ability to plan, regulate, and assess the impacts of wind-energy development.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their review of this report:

Jan Beyea, Consulting in the Public Interest
Dallas Burtraw, Resources for the Future
Michael Corradini, University of Wisconsin-Madison
Samuel Enfield, PPM Atlantic Renewable
Chris Hendrickson, Carnegie Mellon University
Alan Hicks, New York Department of Environmental Conservation
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Kevin Porter, Exeter Associates
Paul Kerlinger, Curry & Kerlinger, LLC
Ronald Larkin, Illinois Natural History Survey
Martin Pasqualetti, Arizona State University
John Sherwell, Maryland Department of Natural Resources

Linda Spiegel, California Energy Commission
James Walker, enXco, Inc.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by the review coordinator, Gordon H. Orians of the University of Washington (emeritus), and the review monitor, Elsa M. Garmire of Dartmouth College. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee gratefully acknowledges the following for making presentations to the committee: Dick Anderson (WEST, Inc.), Edward Arnett (Bat Conservation International), Dinah Bear (Council on Environmental Quality), Gwenda Brewer (Maryland Department of Natural Resources), Daniel Boone (Consultant), Steve Brown (West Virginia Department of Natural Resources), Richard Cowart (The Regulatory Assistance Project), Samuel Enfield (PPM Atlantic Renewable), Ken Hamilton (Whitewater Energy), Alex Hoar (U.S. Fish and Wildlife Service), Judith Holyoke Schoyer Rodd (Friends of the Blackwater), Tom Kerr (U.S. Environmental Protection Agency), Julia Levin (California Audubon), Patricia McClure (Government Accountability Office), The Honorable Alan B. Mollohan (U.S. Representative, WV 1st Congressional District), Kevin Rackstraw (American Wind Energy Association Siting Committee), Dennis Scullion (EnXco, Inc.), John Sherwell (Maryland Department of Natural Resources), Craig Stihler (West Virginia Department of Natural Resources), Robert Thresher (National Renewable Energy Laboratory), James A. Walker (EnXco, Inc.), and Carl Zichella (Sierra Club). In addition, John Reynolds and Joseph Kerecman of PJM Interconnection and officials of Dominion Resources provided helpful information to the committee through personal communications; Laurie Jodziewicz of the American Wind Energy Association, Nancy Rader of the California Wind Energy Association, and Linda White of the Kern Wind Energy Association provided helpful information and contacts. We also thank Wayne Barwickowski and his colleagues at enXco, Inc. for their informative and helpful tour of the San Gorgonio (Palm Springs) wind-energy facility.

The committee's work was enhanced in every way by the extraordinary work of the project director, David Policansky, who provided endless sound advice, insightful expertise, and just good sense. The committee offers David its sincere gratitude for his attentive assistance and for his good fellowship throughout the project, which involved five meetings in five different locations with field trips to several wind-energy installations and public hearings. Ray Wassel and James Zucchetto also provided valuable help in framing questions, analyzing literature, and clarifying our thought processes and writings. Bryan Shipley helped to identify relevant literature and to summarize it for the committee. John Brown helped with meeting planning, including arranging field trips and helping to make sure that the committee arrived where it was supposed to be and returned in good condition. Jordan Crago supported the committee in so many ways that I cannot list them all, but they include literature searching and verification (along with Mirsada Karalic-Loncarevic), organizing drafts and committee comments, and keeping the committee housed and fed. Finally, Board Director James Reisa provided his usual wise counsel at difficult times, and his comments have improved the clarity and relevance of this report. We are grateful to them all.

Finally, I want to offer a personal note of appreciation to the committee and the staff. This was an extraordinary group of people, all with outstanding credentials but many points of view, who came together over the past two years to address an important and challenging topic. During this time they listened to each other, helped each other, and worked incredibly hard. It has been an honor to chair the committee, and my life has been enriched by the time and talents of my committee colleagues.

Paul G. Risser, Chair
Committee on Environmental Impacts of
Wind Energy Projects

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assumed to be part of evolving landscape contexts. Concerns generally would arise only when specific aesthetic or landscape attributes of the surrounding area are identified in the documentation of the site's historic value. A setting where a multi-sensory experience has been re-created, such as at Plimoth Plantation in Massachusetts, might also warrant consideration. There, the visitor expects not just to see pre-revolutionary structures but to actually experience life at the time of the early settlers. A recent and currently unresolved case in Vermont concerned a historic Civilian Conservation Corps bath-house that was documented as having been sited to take advantage of scenic views down a lake where a proposed wind-energy facility would be visible. Unlike housing developments, wind-energy projects cannot be screened from view, except behind intervening topography and vegetation. Such issues are likely to arise as wind projects are proposed in cultural landscapes, and guidance as to what constitutes an undue impact to historic or sacred sites and areas will be necessary.

Evaluating Impacts on Historic, Sacred, and Archeological Sites

Historic, sacred, and archeological sites and settings must be regarded as sensitive sites. In most states, key historic sites are well documented and rated regarding their local, state, or national significance. State Offices of Historic Preservation, along with local historical societies, provide detailed information on historic sites and properties, and usually are involved in the review of proposed wind-energy projects. State archaeologists generally recommend specific guidelines for archaeological surveys, depending on the site involved. Archeological and sacred sites may be less well known. Documentation of these sites is essential. Good descriptive documentation will identify the particular values involved and the extent to which the context or setting contributes to the structure or landscape and in what way. Generally, the documentation of historic sites offers useful guidance to the value of the surrounding landscape to the interpretation of the resource, although the final determination probably should be done by experts. Most states are only now beginning to develop methods for reviewing on-site and offsite impacts of wind-energy facilities on historic sites (e.g., Vermont Division for Historic Preservation 2007). Siting wind-energy projects in the vicinity of identified and documented historic or sacred landscapes as well as historic, sacred, and archeological sites is likely to "raise red flags." The impacts of viewing wind facilities from historic or sacred landscapes will require similar kinds of analyses to those noted in Appendix D for aesthetic impacts; however, additional guidance from relevant experts is needed in this area.

IMPACTS ON HUMAN HEALTH AND WELL-BEING

Wind-energy projects can have positive as well as negative impacts on human health and well-being. The positive impacts accrue mainly through improvements in air quality, as discussed previously in this report. These positive impacts (i.e., benefits) to health and well-being are diffuse; they are experienced by people living in areas where conventional methods of electricity generation are used less because wind energy can be substituted in the regional market.

In contrast, to the extent that wind-energy projects create negative impacts on human health and well-being, the impacts are experienced mainly by people living near wind turbines who are affected by noise and shadow flicker.

Noise

As with any machine involving moving parts, wind turbines generate noise during operation. Noise from wind turbines arises mainly from two sources: (1) mechanical noise caused by the gearbox and generator; and (2) aerodynamic noise caused by interaction of the turbine blades with the wind. As described below (see "Noise Levels"), noise of greatest concern can be generally classified as being of one of these three types: broadband, tonal, and low-frequency.

The perception of noise depends in part on the individual—on a person's hearing acuity and upon his or her subjective tolerance for or dislike of a particular type of noise. For example, a persistent "whoosh" might be a soothing sound to some people even as it annoys others. Nevertheless, it appears that subjective impressions of the noise from wind turbines are not totally idiosyncratic. A 1999 study (Kragh et al. 1999) included a laboratory technique for assessing the subjective unpleasantness of wind-turbine noise. Preliminary findings indicated that *noise tonality* and *noise-fluctuation strength* were the parameters best correlated with unpleasantness (Kragh et al. 1999).

Broadband, tonal, and low-frequency noise have all been addressed to some degree in modern upwind horizontal wind turbines, and turbine technologies continue to improve in this regard. With regard to the design of a wind-energy project, one is generally interested in assessing whether the additional noise generated by the wind turbines (relative to the ambient noise) might cause annoyance or a hazard to human health and well-being.

Noise impacts also can result from project construction and maintenance. These are generally of relatively short duration and occurrence but can include equipment operation, blasting, and noise associated with traffic into and out of the facility. These are not addressed in detail in this section. In the following, a brief review of wind-turbine noise and its impacts is presented along with suggested methods for assessing such impacts and mitigation measures.

Noise Levels

Noise from wind turbines, at the location of a receptor, is described in terms of sound pressure levels (relative to a reference value, typically 2×10^{-5} Pa) and is typically expressed in dB(A), decibels corrected or A-weighted for sensitivity of the human ear. Note that there is a difference between sound *power* used to describe the source of sound and sound *pressure* used to describe the effect on a receptor. The sound power level from a single turbine is usually around 90-105 dB(A); such a turbine creates a sound pressure of 50-60 dB(A) at a distance of 40 meters (this is about the same level as conversational speech). Noise (sound pressure) levels from an onshore wind project are typically in the 35-45 dB(A) range at a distance of about 300 meters (BWEA 2000; Burton et al 2001). These are relatively low noise or sound-pressure levels compared with other common sources such as a busy office (~60 dB(A)), and with nighttime ambient noise levels in the countryside (~20-40 dB(A)). While turbine noise increases with wind speed, ambient noises—for example, due to the rustling of tree leaves—increase at a higher rate and can mask the turbine noise (BLM 2005a).

In addition to the amplitude of the noise emitted from turbines, its frequency content is also important, as human perception of sounds is different at different frequencies. Broadband noise from a wind turbine typically is a "swishing" or "whooshing" sound resulting from a continuous distribution of sound pressures with frequencies above 100 Hz. Tonal noise typically is a "hum" or "pitch" occurring at distinct frequencies. Low-frequency noise (with frequencies below 100 Hz) includes "infrasound," which is inaudible or barely audible sound at frequencies below 20 Hz.

Mechanical sounds from a turbine are emitted at "tonal" frequencies associated with the rotating machinery, while aerodynamic sounds are typically broadband in character. Mechanical noise is generated from rotating components in the nacelle, including the generator and gearbox, and to a lesser extent, cooling fans, pumps, compressors, and the yaw system. Aerodynamic noise, produced by the flow of air over blades, is created by blades interacting with eddies created by atmospheric inflow turbulence. This broadband aerodynamic noise is generally the dominant type of wind-turbine noise, and it generally increases with tip speed. Both mechanical and aerodynamic noise often are loud enough to be heard by people.

With older downwind turbines, some infrasound also is emitted each time a rotor blade interacts with the disturbed wind behind the tower, but it is believed that the energy at these low frequencies is insufficient to pose a health hazard (BWEA 2005). Nevertheless, a recent study by van den Berg (2004, 2006) suggests that, especially at night during stable atmospheric conditions, low-frequency modulation (at around 4 Hz) of higher frequency swishing sounds is possible. Note that this is not infrasound, but van den Berg (2006) states that it is not known to what degree this modulated fluctuating sound causes annoyance and deterioration in sleep quality to people living nearby.

Low-frequency vibration and its effects on humans are not well understood. Sensitivity to such vibration resulting from wind-turbine noise is highly variable among humans. Although there are opposing views on the subject, it has recently been stated (Pierpont 2006) that "some people feel disturbing amounts of vibration or pulsation from wind turbines, and can count in their bodies, especially their chests, the beats of the blades passing the towers, even when they can't hear or see them." More needs to be understood regarding the effects of low-frequency noise on humans.

Assessment

Guidelines for measuring noise produced by wind turbines are provided in the standard, IEC 61400-11: Acoustic Noise Measurement Techniques for Wind Turbines (IEC 2002), which specifies the instrumentation, methods, and locations for noise measurements. Wind-energy developers are required to meet local standards for acceptable sound levels; for example, in Germany, this level is 35 dB(A) for rural nighttime environments. Noise levels in the vicinity of wind-energy projects can be estimated during the design phase using available computational models (DWEA 2003a). Generally, noise levels are only computed at low wind speeds (7-8 m/s), because at higher speeds, noise produced by turbines can be (but is not always) masked by ambient noise.

Noise-emission measurements potentially are subject to problems, however. A 1999 study involving noise-measurement laboratories from seven European countries found, in measuring noise emission from the same 500 kW wind turbine on a flat terrain, that while apparent sound power levels and wind speed dependence could be measured reasonably reliably, tonality measurements were much more variable (Kragh et al. 1999.) In addition, methods for assessing noise levels produced by wind turbines located in various terrains, such as mountainous regions, need further development.

Mitigation Measures and Standards

Noise produced by wind turbines generally is not a major concern for humans beyond a half mile or so because various measures to reduce noise have been implemented in the design of modern turbines. The mechanical sound emanating from rotating machinery can be controlled by sound-isolating techniques. Furthermore, different types of wind turbines have different noise characteristics. As mentioned earlier, modern upwind turbines are less noisy than downwind turbines. Variable-speed turbines (where rotor speeds are lower at low wind speeds) create less noise at lower wind speeds when ambient noise is also low, compared with constant-speed turbines. Direct-drive machines, which have no gearbox or high speed mechanical components, are much quieter.

Acceptability standards for noise vary by nation, state, and locality. They can also vary depending on time of day—nighttime standards are generally stricter. In the United States, the U.S. Environmental Protection Agency (EPA) only provides noise guidelines. Many state governments issue their own regulations (e.g., Oregon Department of Environmental Quality 2006), and local governments often enact noise ordinances. Standards of acceptability need to be understood in the context of ambient (background) noise resulting from all other nearby and distant sources.

Shadow Flicker

As the blades of a wind turbine rotate in sunny conditions, they cast moving shadows on the ground resulting in alternating changes in light intensity. This phenomenon is termed shadow flicker. Shadow flicker is different from a related strobe-like phenomenon that is caused by intermittent chopping of the sunlight behind the rotating blades. Shadow flicker intensity is defined as the difference or variation in brightness at a given location in the presence and absence of a shadow. Shadow flicker can be a nuisance to nearby humans, and its effects need to be considered during the design of a wind-energy project.

In the United States, shadow flicker has not been identified as causing even a mild annoyance. In Northern Europe, on the other hand, because of the higher latitude and the lower angle of the sun, especially in winter, shadow flicker can be a problem of concern.

Assessment

Shadow flicker is a function of several factors, including the location of people relative to the turbine, the wind speed and direction, the diurnal variation of sunlight, the geographic latitude of the location, the local topography, and the presence of any obstructions (Nielsen 2003). Shadow flicker is not important at distant sites (for example, greater than 1,000 ft from a turbine) except during the morning and evening when shadows are long. However, sunlight intensity is also lower during the morning and evening; this tends to reduce the effects of shadows and shadow flicker. The speed of shadow flicker increases with wind-turbine rotor speed.

Shadow flicker may be analytically modeled, and several software packages are commercially available for this purpose (e.g., WindPro and GH WindFarmer). An online tool for simple shadow calculations for flat topography is also available (DWEA 2003b). These software packages generally provide conservative results as they typically ignore the numerous influencing factors listed above and only consider a worst-case scenario (i.e., no shadow or full shadow). Inputs to a shadow-flicker model in WindPro, for example, include a description of the turbine and site, the topography, the joint wind speed and wind direction distribution, and an average or distribution of sunshine hours. Typical output results include the number of shadow-hours per year; these are often represented by iso-lines or contours of equal annual shadow-hours on a topographical map. Daily and annual shadow variations may also be a part of the result (DWEA 2003b). A typical result might indicate, for example, that a house 300 meters from a 600kW wind turbine with a rotor diameter of 40 meters will be exposed to moving shadows for approximately 17-18 hours annually, out of a total of 8760 hours in a year (Andersen 1999.)

Impacts

Shadow flicker can be a nuisance to people living near a wind-energy project. It is sometimes difficult to work in a dwelling if there is shadow flicker on a window. In addition to its intensity, the frequency of the shadow flicker is of importance. Flicker frequency due to a turbine is on the order of the rotor frequency (i.e., 0.6-1.0 Hz), which is harmless to humans. According to the Epilepsy Foundation, only frequencies above 10 Hz are likely to cause epileptic seizures. (For reference, frequencies of strobe lights used in discotheques are higher than 3 Hz but lower than 10 Hz.) If a turbine is close to a highway, the movement of the large rotor blades and possible resulting flicker can distract drivers. Irish guidelines, for example, recommend that turbines be set back from the road at least 300 meters (MSU 2004).