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Introduction

In recent years, the growth of capacity to generate electricity from wind energy has been extremely rapid, increasing from 1,848 megawatts (MW) in 1998 to 11,603 MW in the United States by the end of 2006 (AWEA 2006a) (Figures 1-1, 1-2). Some of that growth was fueled by state and federal tax incentives (Schleede 2003), as well as by state renewable portfolio standards and targets. Despite that rapid growth, wind energy amounted to less than one percent of U.S. electricity generation in 2006. To the degree that wind energy reduces the need for electricity generation using other sources of energy, it can reduce the adverse environmental impacts of those sources, such as production of atmospheric and water pollution, including greenhouse gases; production of nuclear wastes; degradation of landscapes due to mining activity; and damming of rivers. Generation of electricity by wind energy has the potential to reduce environmental impacts, because unlike generators that use fossil fuel, it does not result in the generation of atmospheric contaminants or thermal pollution, and it has been attractive to many governments, organizations, and individuals. But others have focused on adverse environmental impacts of wind-energy facilities, which include visual and other impacts on humans; and effects on ecosystems, including the killing of wildlife, especially birds and bats. Some environmental effects of wind-energy facilities, especially those concerning transportation (roads to and from the plant site) and transmission (roads and clearings for transmission lines), are common to all electricity-generating facilities; others, such as their specific aesthetic impacts, are unique to wind-energy facilities. This report provides analyses to understand and evaluate those environmental effects, both positive and negative.

Like all sources of energy exploited to date, wind-energy projects have effects that may be regarded as negative. These potential or realized adverse effects have been described not only in the Mid-Atlantic Highlands (MAH) (Schleede 2003) but also in other parts of the country, such as California (CBD 2004) and Massachusetts (almost any issue of the Cape Cod Times, where the proposed and controversial wind-energy installation in Nantucket Sound is discussed).

GENERATING ELECTRICITY FROM WIND ENERGY

Two percent of all the energy the earth receives from the sun is converted into kinetic energy in the atmosphere, 100 times more than the energy converted into biomass by plants. The main source of this kinetic energy is imbalance between net outgoing radiation at high latitudes and net incoming radiation at low latitudes. The global temperature equilibrium is maintained by a transport of heat from the equatorial to the polar regions by atmospheric movement (wind) and ocean currents. The earth’s rotation and geographic features prevent the wind from flowing uniformly and consistently.

The kinetic energy of moving air that passes the rotor of a turbine is proportional to the cube of the wind speed. Hence, a doubling of the wind speed results in eight times more wind energy. Thus, the amount of air that passes through the rotor plane of a large wind turbine is sizable. A modern 1.5 MW
wind turbine with a hub height (center of rotor) and tower height of 90 meters, operating in a near-optimum wind speed of 10 m/sec (36 km/h) at hub height will create more than 1.4 MW of electricity; in eight hours it will produce the amount of electricity used by the average U.S. household in one year (about 10,600 kilowatt-hour [kWh]).

There is an upper theoretical limit (the Betz limit of 59%) to how much of the available energy in the wind a wind turbine can actually capture or convert to usable electricity. Modern wind turbines potentially can reach an efficiency of 50%. Almost all wind turbines operating today have a 3-bladed rotor mounted upwind of the hub containing the turbine. The blades have an aerodynamic profile like the wing of an aircraft. The force created by the lift on the blades result in a torque on the axis; the forces are transmitted through a gearbox, and a generator is used to transform the rotation into electrical energy, which is then distributed through the transmission grid (Figure 1-3).

Human use of wind energy has a long history (the following summary is taken from Pasqualetti et al. 2004). Wind energy has been used for sailing vessels at least since 3,100 BC. Windmills were used to lift water and grind grain as early as the 10th century AD. The first practical wind turbine was built by Charles Brush in 1886; it provided enough electricity for 100 incandescent light bulbs, three arc lights, and several electric motors. However, the turbine was too expensive at that time for commercial development.

By the 1920s, some farms in the United States generated electricity by wind turbines, and by the 1940s wind turbines sold by Sears Roebuck and Company were providing electricity for small appliances in rural American homes; in Denmark, 40 wind turbines were generating electricity. The first wind-powered turbine to provide electricity into an American electrical transmission grid was in October 1941 in Vermont. However, significant electricity generation from wind in the United States began only in the 1980s in California. Today (2006), it amounts to less than 1% of U.S. electricity generation.

There has been a rapid evolution of wind-turbine design over the past 25 years. Thus, modern turbines are different in many ways from the turbines that were installed in California’s three large installations at Altamont Pass, Tehachapi, and San Gorgonio (Palm Springs) in the early 1980s. A typical turbine structure consists of a pylon (tower or monopole) that can produce electricity at wind speeds as low as 12-14 km/h (3.3 – 3.9 m/sec). Generators typically reach peak efficiency at wind speeds of
approximately 45 km/h (12.5 m/sec) and shift to a safety mode when the wind exceeds a particular speed, often on the order of 80-100 km/h (22 – 28 m/sec). Smaller generators are used for individual buildings or other uses.

This report is concerned with utility-scale clusters of generators or wind-energy installations (often referred to as “wind farms”), not with small turbines used for individual agricultural farms or houses. Some of the utility-scale installations contain hundreds of turbines; for example, the wind-energy facility at Altamont Pass in California consists of more than 5,000 and those at Tehachapi and Palm Springs contain at least 3,000 turbines each, ranging from older machines as small as 100 kW installed more than 20 years ago to modern turbines of 1.5 megawatts (MW) or more (information available at www.awea.org).

Adverse effects of wind turbines have been documented: a recent Final Programmatic Environmental Impact Statement (DPEIS) (BLM 2005a) lists the following: use of geologic and water resources; creation or increase of geologic hazards or soil erosion; localized generation of airborne dust; noise generation; alteration or degradation of wildlife habitat or sensitive or unique habitat; interference with resident or migratory fish or wildlife species, including protected species; alteration or degradation of plant communities, including occurrence of invasive vegetation; land-use changes; alteration of visual resources; release of hazardous materials or wastes; increased traffic; increased human-health and safety hazards; and destruction or loss of paleontological or cultural resources. These impacts can occur at the various stages of planning, site development, construction, operation, and decommissioning or
abandonment (if applicable), although different phases tend to be associated with different impacts. Any or all of the impacts have the potential to accumulate over time and with the installation of additional generators. Beneficial environmental effects result from the reduction of adverse impacts of other sources of energy generation, to the degree that wind energy allows the reduction of energy generation by other sources. This committee’s task includes an evaluation of the importance and frequency of these effects.

The killing of bats and birds has been among the more obvious and objectively quantifiable effects. Birds can be electrocuted along transmission and distribution lines or killed by flying into them (Bevanger 1994; Erickson et. al. 2001, 2002; Stemer 2002). Thousands of birds die each year from collisions with wind-energy installations (BLM 2005a). The Altamont facility in California has caused the deaths of many raptors, which were members of protected species (CBD 2004; BLM 2005a). Several species of bats in North America also have been reported killed by collisions with wind-energy installations (Johnson 2005; Kunz et al. in press a). There were no fatalities of federally protected bat species known to this committee at this writing (early 2007).

Another widely cited impact of wind turbines is their visible effect on viewsheds and landscapes. The scale of modern turbines makes them impossible to screen from view, often making aesthetic considerations a major basis of opposition to them (Bisbee 2004). Well-established systematic methods for evaluating aesthetic impacts are available (Smardon et al. 1986; USFS 2003), but they often are misunderstood or poorly implemented, and they will need to be adapted for assessing the unique attributes of wind-energy projects. Methods also are available for identifying the particular values and sensitivities associated with recreational and cultural resources, as discussed in Chapter 4.

The regulatory system for siting and installing wind-energy projects in the United States varies widely, from a fairly thorough process in parts of California to much less rigorous processes in some other states (GAO 2005). In California, as well as in other states, the processes for evaluating and regulating wind-energy installations are evolving. In many areas of the United States, wind-energy installations have been controversial, sometimes strongly so.

THE PRESENT STUDY

Congress asked the National Academies to conduct an assessment of the environmental impacts of wind-energy installations, using the Mid-Atlantic Highlands (Pennsylvania, Virginia, Maryland, and West Virginia) as a case study.

Statement of Task

The National Academies was asked to establish an expert committee to carry out a scientific study of the environmental impacts of wind-energy projects, focusing on the Mid-Atlantic Highlands as a case example. The study was to consider adverse and beneficial effects, including impacts on landscapes, viewsheds, wildlife, habitats, water resources, air pollution, greenhouse gases, materials-acquisition costs, and other impacts. Using information from wind-power projects proposed or in place in the Mid-Atlantic Highlands and other regions as appropriate, the committee was asked to develop an analytical framework for evaluating those effects that can inform siting decisions for wind energy projects. The study also was to identify major areas of research and development needed to better understand the environmental impacts of wind-energy projects and reduce or mitigate negative environmental effects.

The committee was not asked to consider, and therefore did not address, non-environmental issues associated with generating electricity from wind energy, such as energy independence, foreign-policy considerations, resource utilization, and the balance of international trade.
The Process for This Study

The committee held five meetings: on September 19-20 2005 in Washington D.C., on December 15-16 in Charleston WV.; on March 5-7 2006 in southern California; on May 18-20 in West Virginia; and on July 17-19 in Woods Hole, MA. The first three meetings included presentations from experts and provided opportunities for public comment; at its third meeting the committee toured the wind-energy installation at San Gorgonio, near Palm Springs, CA; and at its fourth meeting it viewed the Mountaineer Wind Energy Center and the proposed Mount Storm projects near Davis, W.V. from nearby public highways (access to the Mountaineer site was not permitted). The committee’s final meeting was held in closed session and was devoted to finalizing this report. The committee gained familiarity with the relevant body of scientific knowledge through briefings and review of literature, databases, and existing studies of wind farms, both in the Mid-Atlantic Highlands and elsewhere, in addition to its own expertise.

Estimating Environmental Benefits of Wind Energy: Focus on Air Emissions

It is not conceptually difficult to estimate the adverse environmental effects of wind-energy projects, although it can be difficult in practice to quantify them. The estimation of the environmental benefits of wind energy is more difficult, because the benefits accrue through its displacement of energy generation using other energy sources, thereby displacing the adverse environmental effects of those generators. To estimate those benefits requires knowledge of what other electricity-generating sources will be displaced by wind energy, so that their adverse effects can be calculated and the offsetting advantages of wind energy can be determined. As described in detail in Chapter 2, the committee has restricted its estimates of the environmental benefits of wind energy to the reduction of air emissions that results from using wind energy for electricity instead of using other sources of electricity generation. The rationale for and limitations of this approach are discussed in detail in Chapter 2, but briefly the approach was adopted because much of the discourse about the advantages of wind energy focuses on reduction of air emissions, including greenhouse gases; because information about air emissions is extensive and readily accessible; and because wind energy has some of the same kinds of adverse impacts other than air emissions that other sources do (for example, some clearing of vegetation is required to construct either a wind-energy or a coal-fired powered plant and their access roads and transmission lines), which complicates the analysis of other adverse impacts. The committee did not conduct a full analysis of life-cycle environmental effects of wind and other sources of electricity generation. This report does, however, provide a guide to the methods and information needed to conduct a more complete analysis.

DEVELOPING AN ANALYTICAL FRAMEWORK

Part of the committee’s charge was to develop an analytical framework for reviewing environmental and socioeconomic effects of wind-energy projects. For reasons described in detail in Chapter 5, and summarized below, the committee has stopped short of a complete analytical framework, both in the report itself and in its recommendations. Instead, the committee offers an evaluation guide in Chapter 5 that, if followed, will aid coordination of regulatory review across levels of government and across spatial scales (Figure 5-1) and will help to ensure that regulatory reviews are comprehensive in addressing the many facets of the human and nonhuman environment that can be affected by wind-energy development (Box 5-4).

One reason the committee stopped short is practical: even considering only the environmental effects of wind, some effects are better documented and easier to evaluate than others. Another reason for stopping short of a full analytical treatment is that other types of energy development, and indeed most types of construction, are not currently regulated in a comprehensive and comparative way in the United States. Finally, there is no social consensus at present on how all the effects of wind-energy generation of
electricity on various aspects of the human and nonhuman environments should be evaluated as positive or negative, how the advantages and disadvantages should be traded off, or whose value systems should prevail in making such judgments. For all of these reasons, the committee focused its efforts on incrementally improving the way wind-energy decisions are made today. The evaluation guide in Chapter 5 reflects the result of those efforts.

**Placing Environmental Effects in Context**

Related to the above discussion of an analytical framework is the issue of placing environmental effects of particular electricity-generation units and other human activities in context. For example, although wind-energy projects kill tens of thousands of birds each year in the United States, other human structures and activities, including allowing domestic cats to hunt outside, are responsible for hundreds of millions, if not billions, of bird deaths each year (see Chapter 3 for more discussion of these numbers). Although wind turbines may cause visual impairments, oil-drilling rigs, coal-fired power plants, roads, buildings, and cell-telephone relay towers also may cause visual impairments. To make comparative evaluations of those impacts would imply some sort of weighting of positive and negative effects in an explicit, subjective, and systematic way, but that is not done nationally or regionally, and indeed it is not obvious what methods one would use to perform such an analysis. In addition, choosing the proper standard of comparison is difficult: should effects be calculated per turbine or structure, per energy installation, per kWh of electricity generated, or against some other standard?

It is not even obvious that doing such an analysis on a national scale would provide a useful guide to action. Our society does not always weight effects from different causes equally. To understand, evaluate, and compare various environmental impacts of a variety of human structures and activities, such as bird or bat deaths, requires an understanding of the exposures to the dangers, the societal benefits that accrue from the circumstances that lead to exposure, and many other factors, some of which might be unrecognized or unexpressed. Therefore, any systematic comparison of the environmental effects of various methods of generating electricity, especially if it is to include a broader context, would require a depth of analysis and information-gathering that would be beyond this committee’s charge, although it might have great value in helping the United States make better-informed choices about energy sources. Although a complete, systematic comparison has not been attempted in this report, the analyses that are provided here should have value pending a more comprehensive analysis.

For similar reasons, the committee also has not addressed environmental benefits related to human health. For example, wind-powered electricity generation may lessen the need for electricity generation from coal-fired power plants and thereby reduce the amount of sulfur dioxide (SO₂) and nitrogen oxides (NOₓ) emissions produced from coal combustion. SO₂ and NOₓ emissions are important contributors to concentrations of airborne particulate matter and are precursors to acid deposition, and NOₓ is an important precursor to ozone. Particulate matter and ozone are of considerable concern because of the risk they pose to public health. However, the extent to which emissions from specific electric power plants might be displaced by wind-energy facilities is unknown. Therefore making health-effects assessments of potential displacement of emissions from electricity-production facilities of unknown location would be highly uncertain (e.g., NRC 2006a).

**TEMPORAL AND SPATIAL SCALES OF ANALYSIS**

Analysis of the environmental impacts of any type of project is complicated enough, but it is exceptionally challenging for wind-energy projects. One obvious problem is how to choose the appropriate temporal and spatial scales for the analysis. A wind facility has local effects at scales of hundreds of meters to one or two kilometers: vegetation is cleared to install the turbines, local drainage patterns or can be altered, and animals can be killed by coming into contact with moving turbine blades.
At the range of one or two kilometers to a few tens of kilometers, there are visual effects on people; potential but currently unknown population effects on animals that are killed, such as bats and birds; roads are built or modified to allow the carriage of very large and heavy turbine components; and power lines are erected to transmit electricity from the turbine to the grid. At even larger scales, migratory birds and bats, which can travel hundreds to thousands of kilometers or more each way annually, suffer mortality with potential but currently unknown effects on their regional and global populations. Positive effects—the reduction of adverse effects of power generated by burning of fossil fuel, hydroelectric dams, and nuclear reactors—are more difficult to assess, because of regional and national power grids that all are influenced by the availability of wind energy and because some effects of electricity generation are truly global (the emission of greenhouse gases that influence climate change, for example). In addition, the presence or the possible construction of wind-energy installations affects people’s decisions and behavior at many levels of organization and at many spatial and temporal scales (see for example the discussion of “opportunity and threat effects” in a NRC report on the cumulative effects of oil and gas activities on Alaska’s North Slope [NRC 2003]). Finally, effects accumulate over space and time, both as a function of the number and locations of wind-energy installations, and as a function of their interactions with other perturbations (NRC 2003).

UNDERSTANDING AND ASSESSING CUMULATIVE ENVIRONMENTAL EFFECTS

When numerous small decisions about related environmental issues are made independently, the combined consequences of those decisions often are not considered (Odum 1982). As a result, the patterns of the environmental perturbations or their effects over large areas and long periods are not adequately analyzed. This is the basic issue of cumulative effects assessment. The general approach to identifying and assessing cumulative effects evolved after passage of the National Environmental Policy Act (NEPA) of 1969, and this committee, like an earlier NRC committee (NRC 2003), has followed that approach. This discussion is adapted from that committee’s report.

The NEPA requires environmental review for all federal actions and Environmental Impact Statements (EISs) for federal actions with potentially significant environmental effects. In 1978, the Council on Environmental Quality promulgated regulations implementing the NEPA that are binding on all federal agencies (40 CFR Parts 1500-1508 [1978]). A cumulative effect was defined as “the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions. . . . Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.” For example, an EIS might conclude that the environmental effects of a single power plant on an estuary might be small and, hence, judged to be acceptable. But the effects of a dozen plants on the estuary are likely to be substantial, and perhaps of a different nature than the effects of a single plant—in other words, the effects are likely to accumulate and may interact. Even a series of EISs might not identify or predict the cumulative effects that result from the interaction of multiple activities.

The accumulation of effects can result from a variety of processes (NRC 1986). The most important ones are:

- Time crowding—frequent and repeated effects on a single environmental medium. An example related to wind-energy development might be repeated effects on multiple individuals within a local population of birds or bats before the population had time to recover.
- Space crowding—high density of effects on a single environmental medium, such as a concentration of turbines or installations in a small region so that the areas affected by individual turbines or installations overlap. Space crowding can result even from actions that occur at great distances from one another. An example related to wind energy might be that impacts from widely separated wind facilities could accumulate on a single migratory population of birds or bats.
• Compounding effects—effects attributable to multiple sources on a single environmental medium, such as the combined effects of turbines, cell-phone towers, transmission lines, and other structures that could kill flying animals.

• Thresholds—effects that become qualitatively different once some threshold of disturbance is reached, such as when eutrophication exhausts the oxygen in a lake, converting it to a different type of lake. The first industrial structure in an otherwise undeveloped environment might cross a visual threshold or a threshold of wilderness values. Another example might be the existence of a threshold in terms of the number of turbines and risk of bird and bat fatalities, or habitat fragmentation.

• Nibbling—progressive loss of habitat resulting from a sequence of activities, each of which has fairly innocuous consequences, but the consequences on the environment accumulate, perhaps causing the extirpation of a species from the area.

These examples illustrate why recognizing and measuring the accumulation of effects depends on the correct choice of domain—temporal and spatial—for the assessment. Although the assessment of cumulative effects has a history of several decades (e.g., NRC 1986), it still is a complex task. The responses of the many components of the environment likely to be affected by an action or series of actions differ in nature and in the areas and periods over which they are manifest. An action or series of actions might have effects that accumulate on some receptors (e.g., target organisms or populations) but not on others, or on a given receptor at one time of the year but not at another. Therefore, a full analysis of where, when, how and why effects accumulate requires multiple assessments.

To address this problem, an earlier National Research Council committee (NRC 2003) attempted to identify the essential components of such an assessment:

• Specify the class of actions whose effects are to be analyzed.
• Designate the appropriate temporal and spatial domain in which the relevant actions occur.
• Identify and characterize the set of receptors to be assessed.
• Determine the magnitude of effects on the receptors and whether those effects are accumulating.

These criteria cannot always be applied because of data limitations. Also, the effects of individual actions range from brief or local to widespread, persistent, and sometimes irreversible.

To conduct an analysis of how effects accumulate, one must understand what would occur in the absence of a given activity. The accumulated effects are the difference between that probable history and the actual history. To predict how effects may accumulate for a proposed action, it is essential to have good baseline data and data about the same kinds of receptors in similar areas that were and were not influenced by comparable actions. In some cases, the lack of such information prevented the committee from identifying and assessing possible cumulative effects of some activities or structures related to wind-energy development. Even if accumulating effects are identified, their magnitude and their biological, economic, and social importance must be assessed.

As noted above, it is difficult to assess cumulative effects in the absence of a comprehensive, broad-scale regulatory and assessment framework. The discussion above is presented in the expectation that it, along with the recommendations for development of an evaluation guide presented in Chapter 5, will be useful for future planning and assessment efforts.

ORGANIZATION OF THE REPORT

Chapter 2 sets the context for wind energy in the United States and analyzes the committee’s approach to estimating the environmental benefits of wind energy. It describes the considerations involved in understanding under what conditions and to what degree wind energy can displace electricity generation by other sources, and hence reduce the adverse environmental effects of those sources, in particular their air emissions. Chapter 3 provides an evaluation of the literature on the effects of wind
turbines on ecosystems and their components, and discusses methods that would be valuable in future evaluations; it also identifies research needs. Chapter 4 deals with effects on humans of wind-energy projects, including aesthetic, noise, cultural, health, economic, and related effects. Chapter 5 compares a variety of extant regulatory and evaluative regimes and extracts their strong points for consideration in other places and at larger (e.g., national) scales, and draws the information together in an evaluation guide that would be most useful for evaluating the effects of existing wind-energy installations and for assessing—and managing—the effects of proposed installations at various scales.